Proceedings of the 8th US/German Workshop on Salt Repository Research, Design, and Operation

Spent Fuel and Waste Disposition

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SUMMARY

The 8th US/German Workshop on Salt Repository Research, Design, and Operation was hosted by 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, an excellent venue to present, discuss, and advance the basis for disposal of radioactive waste in salt formations.

This collaboration has come a long way since reconvening United States (US)/German salt repository collaboration in 2010. The international collaboration is productive and successful and continues to identify prominent salt research that either emerges as the science and research agendas develop or continues to mature from existing, ongoing partnerships. This is mirrored and documented by annual Proceedings, updated mutual research agendas, and advancement of salt repository science across a forefront of issues.

This document records the Proceedings of the 2017 gathering of salt repository nations. In a spirit of mutual support, technical issues are dissected, led capably by subject matter experts. As before, it is not possible to explore all contemporary issues regarding nuclear waste disposal in salt formations. Instead, the group focused on a few selected issues to be pursued in depth, while at the same time acknowledging and recording ancillary issues.

To distribute the burden of creating the annual Proceedings, lead scientists in certain areas of research volunteered to write cogent summaries, which are presented as chapters in this document. Contributing authors are listed in the Acknowledgement Section. As always, these Proceedings include appendices containing the Final Agenda, List of Participants, Abstracts, Presentations, and Biographical Information, if provided. A primary objective for producing Proceedings of each workshop is to sustain a track-record of ongoing collaboration and thereby provide continuity of long-term research, summarize and publish status as issues mature, and develop appropriate research by consensus in a workshop environment. The workshop Proceedings are also a great resource for background material, photographs, and history of salt repository experience.

Major topics and findings constitute individual chapters in these Proceedings. The scientific breadth continues to be larger than can be accomplished by single investigators, as will become apparent in this document. Presentations and abstracts provided by participants are included in appendices, while summary write-ups are provided so the reader can understand clearly where our collaborations are focused and heading. Notably, the following topics are emphasized here:

- 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) testing of WIPP salt—Chapter 2
- Creep at low deviatoric stress—Chapter 3
- Reconsolidation of granular salt—Chapter 4
- KOSINA (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)—Chapter 5
- Operational safety—Chapter 6
- Special topics – Chapter 7

The Proceedings will conclude (Chapter 8) with a look toward the next workshop to be held in Hannover, Germany in September 2018.

Continuity of purpose has been established over recent years of the US/German collaboration on salt repository research, design and operation. Themes and emphases arise naturally because advancing investigations, discussion, and new test results lead to creation of a yearly or relatively short-term focus for salt repository research. A contemporary agenda has been documented periodically in external publications, in annual Proceedings, and is often integrated into requests to the German Ministry and the US Department of Energy for financial support. Research themes frequently interrelate or feed information between and among activities, as can be readily discerned in the content of these Proceedings.

Specific research in definitive areas probes deeply into fundamental material properties, which makes it practical to break-out separate chapters for certain case studies. For example, WEIMOS, testing of the Waste Isolation Pilot Plant (WIPP) salt, and creep at low stress conditions are directly linked. These relationships are well known to participants, but presentation of scientific advancement is sometimes more clearly conveyed by either combination or separation into individual chapters. Chapter 2 on WEIMOS, which emphasizes modeling also includes testing of WIPP salt because specific testing has been identified to support model development and assessment. A deeper examination of testing at low deviatoric stress warrants its own chapter, which is developed sequentially after WEIMOS.

Chapter 3 dives deeper into what appears to be accelerated salt creep deformation at low deviatoric stress, which means that steady-state deformation by salt under low stress conditions appears to be much faster than extrapolated rates from commonly used constitutive relationships. Essentially, there were no experiments with precise instrumentation and absolute control over state variables at the low strain rates of interest. The experimental door was opened by Bérest and coworkers and similar investigations now constitute significant emphasis in our collaborative research.

Chapter 4 reviews reconsolidation of granular salt and takes note of progress and uncertainties to define emphasis for future investigations. This extremely important research issue has also been recognized for several decades, as backfilling and reconsolidation are industry practice for structural integrity, stowing, and other purposes, which can be extending to affect seal systems for repositories. In salt repositories, reconsolidation of granular salt has profound implications—in terms of operational safety and long-term performance. Collaborators are looking at how best to advance current understanding and how to solidify practices to ensure safety by design.

Chapter 5 highlights the progress of work and results of a research and development project called KOSINA, which is a joint undertaking of Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany)) (BGR), Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) GmbH (GRS), Institut für Gebirgsmechanik (Institute for Rock Mechanics), and DBE TECHNOLOGY (a wholly owned subsidiary of a German Company for Construction and Operation of Waste Repositories (DBE) and funded by the German Federal Ministry for Economic Affairs and Energy. KOSINA is an acronym for *Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept*. KOSINA was launched in the summer of 2015 A bedded salt formation was not considered previously as a possibility to host a high-level-waste repository in Germany. The project has been going on for nearly three years and will be concluded in April 2018. KOSINA foci include development of generic geologic models, including derivation of model parameters, development of a safety demonstration concept, development of technical repository designs for four different emplacement alternatives, analysis of geomechanical integrity, evaluation of operational safety, as well as analysis of radiological consequences. The main achievements are four different repository designs, two per each generic geologic model (flat-bedded salt and salt pillow) based on thermomechanical calculations. This includes implementation of a safety concept that provides containment of radioactive materials with regard to the technical designs of waste packages, transport and emplacement technologies, and backfilling and sealing concepts. Integrity of the geologic barriers could be demonstrated for all four repository designs, and the long-term predictions showed no radiological releases during the demonstration period of one million years. Presentations given by the partners showed details of the achievements.

Chapter 6 concerns the vital topic of Operational Safety. The workshop emphasizes recent WIPP experience, because of unexpected interruption of disposal operations owing to a fire and a radiological release. Operations ceased for three years, and underground access was severely limited. Ground control was not possible during this period, giving rise to unsafe working conditions in some areas of the repository. A recovery plan was developed and implemented and WIPP is once again disposing of transuranic waste. These real-life experiences are informative to Project BASAL, which includes assessment and documentation of interactions between operational safety and post-closure safety.

Chapter 7 covers the session of special topics from the final afternoon of the workshop. This included discussion of the actinide brine chemistry workshop, an ongoing GRS/Sandia National Laboratories collaboration on regional density-dependent groundwater flow around a salt repository, and a German study on deep borehole disposal.

Chapter 8 looks ahead. After eight years of annual workshops, our collaborations have matured in many ways, but most importantly the engaged colleagues know how to work together. This is essential and key for being *erfolgreiche collaboration*. The German word *erfolgreich* cannot be improved by translation into English—it means successful. Scientific and technical teamwork cooperation is also acknowledged by funding organizations.

A clear research agenda has been established, providing essential workshop topics. Next year (2018) the US/German Workshop will be held coincidentally with the 9th Conference on the Mechanical Behavior of Salt (SaltMechIX). The SaltMechIX will take place at the BGR in Hannover on September 12-14, 2018. The conference will be organized jointly by the Federal Institute for Geosciences and Natural Resources Hannover, the Institute of Geomechanics Leipzig, and the Technical University of Clausthal. Because the global salt research community enjoys close ties, coordination and added value should materialize between the salt repository workshop and the larger venue of the SaltMechIX conference.

The technical emphasis of ongoing workshops remains on issues pertaining to salt repository research, design, and operation. The group strives to advance the technical basis for salt repository systems, and provides a forum to evaluate and address arising issues and support the Nuclear Energy Agency Salt Club. A secondary emphasis of the ongoing workshops is to ensure early-career salt researchers can collaborate with and learn from experts in the field who may soon be retiring, helping to ensure a degree of continuity in each of the participant countries’ technical programs. Proceedings of all workshops and other pertinent information are posted on several websites (e.g., Sandia National Laboratories, the Nuclear Energy Agency Salt Club, Karlsruhe Institute of Technology/Projektträger Karlsruhe). Proceedings can also be obtained via a simple web search.

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The 8th US/German Workshop on Salt Repository Research, Design, and Operations was hosted by the Central Organisation for Radioactive Waste (Centrale Organisatie Voor Radioactief Afval, COVRA) in Nieuwdorp, The Netherlands. Hospitality extended by COVRA operations, especially Ewoud Verhoef, Erica Neeft, Marianne Cornet, and Laura Waterman was outstanding. The facilities for presentations and discussion were excellent for a group of our size, while catering and logistics made the entire exchange wonderful. The Netherlands has been a solid contributor to our technical program, as well.

Special thanks to Laura A. Connolly of Sandia National Laboratories for helping organize the COVRA meeting logistics, urging participants to provide material on time and in good order, gathering and assembling all the abstracts, presentations and other program materials included in these Proceedings.

Each country's organizations gain from collaborations that have now enjoyed 8 years of consistent achievement. Though we have historically worked together for many years (since the 1970s), national programs were not always synchronous regarding priorities or funding. That condition still exists to some extent, but progress and comradery in recent years helped build these workshops into a sustainable structure. Sharing responsibility as well as technical contributions is reflected by chapter authorship. Virtually every attendee contributed to dialogue and debate, which augurs a future continuity of US/German Workshops on Salt Repository Research, Design and Operations multiplying benefits to involved parties. These Proceedings comprise the following main chapters:

CONTRIBUTING AUTHORS		
Chapter	**Title**	**Authors**
Chapter 1	INTRODUCTION	F. Hansen, W. Bollingerfehr, and W. Steininger
Chapter 2	WEIMOS AND TESTING WIPP SALT	A. Hampel, T. Popp, K. Herchen and F. Hansen
Chapter 3	CREEP AT LOW DEVIATORIC STRESS	T. Popp and F. Hansen
Chapter 4	RECONSOLIDATION OF GRANULAR SALT	K. Wieczorek, N. Mueller-Hoeppe, and F. Hansen
Chapter 5	KOSINA	W. Bollingerfehr, J. Kindlein, T. Popp, and T. Kühnlenz
Chapter 6	OPERATIONAL SAFETY	S. Dunagan, J. Wolf, N. Bertrams, W. Bollingerfehr, D. Buhmann, C. Fahrenholz, W. Filbert, A. Lommerzheim, U. Noseck, and S. Prignitz
Chapter 7	SPECIAL TOPICS	K. Kuhlman
Chapter 8	CONCLUDING REMARKS	F. Hansen, W. Bollingerfehr, and W. Steininger

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to RESPEC who made it possible for the first author (Hansen) to attend, contribute, write, and edit these Proceedings.

Going forward, the Proceedings will be compiled by the hosting organization. That means in 2018, the Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany)) will compile the Proceedings. The successful assembly process undertaken the past few years should facilitate this transition. Subsequently, in 2019 for example, the hosting organization will also assume production of the Proceedings. In this modern-day electronic environment, the Proceedings will be posted on several websites.

If you don't show appreciation to those who deserve it, they'll learn to stop doing the things you appreciate.

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REVISION HISTORY

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ACRONYMS

ABC	Actinide Brine Chemistry
AIB	WIPP accident investigation board
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany))
BMU	Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety of Germany
BMWi	Bundesministerium für Wirtschaft und Energie (German Federal Ministry for Economic Affairs and Energy)
CBFO	US Department of Energy Carlsbad Field Office
CORR	Contractor Operational Readiness Review
COVRA	Central Organisation for Radioactive Waste (Centrale Organisatie Voor Radioactief Afval, Dutch nuclear waste processing and storage company)
CRZ	containment-providing rock zone
DAEF	Deutsche Arbeitsgemeinschaft für Endlagerforschung (German Association for Repository Research)
DBE TEC	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE Technology is a wholly owned subsidiary of German Company for Construction and Operation of Waste Repositories (DBE))
DOE	US Department of Energy
DORR	DOE Operational Readiness Review
DRZ	damaged rock zone
EDZ	excavation damaged zone
FEPs	features, events, and processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) GmbH
HEPA	high-efficiency particulate air
HLW, HAW	high-activity waste, high-level radioactive waste
IAEA	International Atomic Energy Agency
IfG	Institut für Gebirgsmechanik (Institute for Rock Mechanics)
INE	Institute for Nuclear Waste Disposal
IVS	WIPP interim ventilation system
KIT	Karlsruhe Institute of Technology
KOSINA	Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept
LANL	Los Alamos National Laboratory
NEA	OECD Nuclear Energy Agency
NWP	nuclear waste partnership (WIPP management and operations contractor)
OECD	Organisation for Economic Co-operation and Development
PTKA-WTE	Projektträger Karlsruhe / Abteilung Entsorgung (Project Management Agency Karlsruhe, (Department Waste Management)

R&D	research and development
RepoTREND	(Transport and REtention of Non-decaying and Decaying contaminants in final REPOsitory)
RGI	Radiologischer Geringfügigkeits-Index (index of marginal radiological impact)
SaltMechIX	9th Conference on the Mechanical Behavior of Salt
SMRI	Solution Mining Research Institute
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TSC	Transport and Storage Cask
TUC	Technische Universität Clausthal, Germany
US/USA	United States/United States of America
WEIMOS	Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (Collaborative project: Further development and qualification of rock mechanicsl modeling for final storage of HAW in rock salt).
WIPP	DOE Waste Isolation Pilot Plant
WP	Work Package

Proceedings of the 8th US/German Workshop on Salt Repository Research, Design, and Operation

1 INTRODUCTION

Research, design and operation of salt repositories have advanced appreciably over the past several years through collaboration between scientists, engineers, stakeholders, regulators, and researchers predominantly from Germany and the United States (US). Repository programs in The Netherlands have contributed significantly over this period, as well, and with their blessings the branding of these collaborations remains under the moniker: US/German Workshop on Salt Repository Research, Design, and Operation. Although the workshops focus on salt repositories for nuclear waste, the underlying testing and modeling research and development (R&D), seal systems, materials and performance, geomechanics, operations, and a variety of topics at the forefront of salt behavior and applications are of great interest to the larger salt community. These Proceedings can serve as a resource in terms of identifying the state-of-the-art in many areas as well as a reserve of figures, photographs, and records. This document has been created for each annual meeting since 2010, and can be readily obtained from many sources, including a simple web search.

These international workshops were reinitiated in 2010 to address salt repository applications. Several collaborative investigations have been ongoing for a long time. Scientists and engineers have increasingly better tools and insight into the challenges of salt behavior. Interrogation of salt geomechanics is sharpened through collaboration, which identifies those areas of greatest value or most significant impact to repository considerations. The group often looks critically at existing baseline information and summarizes the state of the practice in joint publications.

The workshop forum provides well-informed scientists an opportunity to deliberate contemporary issues that may or may not affect salt repositories. Because the workshop emphasis is on nuclear waste disposal, there is often a need to respond to sensational claims of one type or another that challenge the robustness of salt isolation and storage of materials placed therein. All technical issues are openly discussed and questions that remain are addressed systematically.

2 WEIMOS TESTING WIPP SALT

2.1 WEIMOS Project

Our flagship collaboration effort (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) – WEIMOS – addresses modeling of salt deformation. Historically, salt scientists and practitioners have employed many methods to model salt deformation, from response models, to power-law functions, to more sophisticated models of today. Salt response is complicated and strongly influenced by state variables, while natural environments offer non-laboratory conditions and further challenges for proper characterization and modeling. With burgeoning computational capability comes a parallel trial to provide constitutive properties for various physical phenomena, as discussed in this WEIMOS chapter and related, separate chapters.

Collaborative geomechanical modeling preceding the current WEIMOS efforts simulated field experiments that progressed from relatively simple heated boreholes to contemporary efforts to model Rooms B & D at the Waste Isolation Pilot Plant (WIPP), which were full-scale experiments representing size and geometry of possible disposal vaults. Room D closure occurred under ambient temperature, while Room B experienced thermal profiles expected with certain configurations of defense high-level waste. The

WEIMOS collaboration is actively addressing historical modeling of Rooms B&D while maintaining transparent treatment of decision bases.

Modelers and laboratory scientists have worked closely within the WEIMOS project and its predecessors. This collaboration highlights how the current salt-repository research agenda has evolved. To gain perspective, it should be noted that modelers have been performing finite-element calculations of WIPP underground response and other similar applications for 30-40 years. Computational capabilities have advanced tremendously over this time, while laboratory techniques continued to improve precision, control, and basic micromechanical understanding of salt deformational processes. Fundamental issues are not new; more than 30 years ago, early computer models of ambient WIPP deformation under-predicted actual underground closure by a factor of three at 3.7 years after the excavation (Munson et al., 1986). Under-prediction was easily compensated at that time by simply reducing the modulus of elasticity by 12.5; whereupon, computer models simulated room closure more closely (Munson et al., 1987). This rather un-mechanistic approach achieved a match between field-test results and computer models.

Attempts at a more fundamental reconciliation between underground test results and simulations followed a winding path. From the WIPP side, a long series of modeling choices was made such that computer models would match field-test data. These included changes of the flow potential from von Mises to Tresca, change of frictional coefficient for interfaces, change of stratigraphy, change of material properties (clean and argillaceous salt), and change to material model calibrations. After significant reconfiguration of model parameters, the much-adjusted model could match field experiments at WIPP acceptably well for immediate programmatic needs (Munson et al., 1989). Over decades that followed, WIPP licensing went forward, and operational issues became paramount with concomitant decrease in research interest or necessity. However, collaboration between German salt researchers and US colleagues recently revisited WIPP field-test results from Rooms B & D, and despite possessing vastly improved computational capability and an increased laboratory data base, once again under-predicted closure by a factor of two to three at 3.7 years. Therefore, it should be clear that the finely tuned model for WIPP room closure was successful because many parameters were adjusted to allow models to match field-test results. The WEIMOS project and preceding collaborations were vital in this discovery.

Collaborations such as these demonstrate clear and sometimes striking value. The objective and transparent process undertaken in current collaborations leads to the present-day research agenda, as discussed below. Salt simulations require fundamental input to behavior of layered interfaces, such as anhydrite/clay or anhydrite/salt. Constitutive models for salt under conditions of low deviatoric stress are essential because most of the simulated area in a finite-element grid as well as the actual underground situation, resides in regions of low deviatoric stress. Therefore, the current research agenda includes shear of inhomogeneous layers and testing of salt under low stress conditions.

Other tuning of model parameters, such as introduction of a free variable called lost transient strain, would be suitable for further research. Previous modeling of WIPP room closure also invoked vast changes to WIPP reference stratigraphy, which warrants peer review and reconciliation. These discoveries were made by way of collaborations on the modern WEIMOS efforts. Adjusting models in various ways may be an acceptable engineering approach, but research embraced by the US/German collaborators on salt repository science is dedicated to examining open questions, such as identified here.

The Joint Project WEIMOS (2016-2019) is a collaboration of the following partners:

- Dr. Andreas Hampel, Scientific Consultant, Mainz, Germany (coordinator);
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig, Germany;
- Leibniz Universität Hannover, Germany;
- Technische Universität Braunschweig, Germany;

- Technische Universität Clausthal, Germany (TUC);
- Sandia National Laboratories (SNL), Albuquerque and Carlsbad, New Mexico, USA.

The German partners are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and managed by the Project Management Agency Karlsruhe. The US partners are funded by the US DOE, through the offices of Nuclear Energy and Environmental Management.

In this project, the rock mechanical modeling for the final disposal of heat-generating high-level radioactive waste (HLW, HAW) in rock salt is developed further and qualified for the application in numerical simulations. It builds on three previous Joint Projects on the "Comparison of Constitutive Models for the Thermo-mechanical Behavior of Rock Salt" (2004-2016). In these studies, four topics were identified by the partners for a necessary further development of the modeling. The progress in the four work packages (WPs) 1 to 4 shall be demonstrated with simulations of a complex model of a typical underground situation in salt in work package 5:

WP 1. Deformation behavior at small deviatoric stresses
WP 2. Temperature and stress dependence of damage reduction
WP 3. Deformation behavior resulting from tensile stresses
WP 4. Influence of inhomogeneities (layer boundaries, interfaces) on deformation
WP 5. Virtual demonstrator
WP 6. Administrative work

At the 8th US/German Workshop recent results and the status of research in WPs 1 to 5 were reported.

WP 1: Small deviatoric stresses

Reliable extrapolations of the creep behavior of natural salt over a long period of time and at low deformation rates with constitutive equations require a well-derived experimental data base and an understanding of the acting deformation mechanisms. This theme was thus an important topic in the geomechanical section at the workshop and addressed also by the invited speaker Pierre Bérest (École Polytechnique, Paris, France) and Stuart Buchholz (RESPEC Inc., Rapid City, South Dakota, USA) in their presentations.

In WEIMOS, triaxial lab creep tests at small deviatoric stresses, i.e., at $\Delta\sigma$ below 5 MPa, are performed on WIPP salt with very high precision by IfG as a basis for the common improvement of the modeling by the partners. In this work package, the partners collaborate also with Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany)) (BGR) Hannover. BGR also performs lab creep tests with WIPP salt specimens, but in a higher temperature range than IfG, i.e., above 100°C. Additionally, BGR and SNL carry out microstructural analyses of unloaded and loaded specimens to identify the dominant deformation mechanisms in the range of small stresses.

Since it was a special topic at this workshop, recent results and the status of this work package are reported in the next chapter of these Proceedings.

WP2: Damage reduction

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

Currently, "healing" processes are not considered in the safety analysis for radioactive waste repositories, neither in the thermomechanical integrity analysis for the demonstration of the containment-providing rock zone (CRZ) which is only based on the evaluation of the dilatancy and minimum stress, nor in simulations of the tightness of geotechnical barriers which only consider the development of the excavation disturbed/damaged rock zone (EDZ, DRZ). Establishment of generally accepted “healing” approaches in the constitutive models may help to demonstrate more realistically the long-term performance of geological and technical barriers and, thereby, to enhance the confidence in the salt barrier robustness. Thus, reliable experimental data are of urgent need for developing improved healing approaches.

The laboratory tests of the influence of temperature and stress state on damage reduction in this work package are performed by TUC. Therefore, Kai Herchen of TUC presented the “healing” test program and current test results.

The dilatancy of a salt sample is measured for a quantification of damage during a test, because it is the main quantity in the damage and healing approaches in the constitutive models of the partners. In general, dilatancy measurements for damage reduction are a major challenge because the tests must be performed over a long test period at high pressures with very high resolution and stability. External influences such as fluctuations of the room temperature in the lab and the compressibility of the oil and test machine can have a large influence and must be considered.

For these reasons, four high-precision test machines at the TUC were developed further. In addition, optimized test procedures were developed.

In the first test series, all tests started at the same point in time and were carried out with the same loading history at constant temperature T = 35° C. After a reconsolidation phase with an isotropic stress state over 5 days, the tests were started by increasing the axial stress up to a deviatoric stress level of $\Delta\sigma$ = 27 MPa (σ_z = 30 MPa, $\sigma_x = \sigma_y$ = 3 MPa). After 11 days in this damage phase, the confining stress was increased to an almost isotropic stress state close to 30 MPa to reach the damage reduction process. In one test machine, a steel dummy was installed to measure the oil and plant compressibility. The other three tests were performed with salt samples from rock salt of the Asse mine. Two of the tests were terminated earlier to give an opportunity for a second independent dilatancy measurement method, such as immersion weighing, at intermediate stages. The test results of the three salt samples are illustrated in the top diagrams of Figure 2-1. An axial strain ε = 8.2 to 9.1 % and a maximum dilatancy ε_{vol} = 1.25 to 1.5 % were measured.

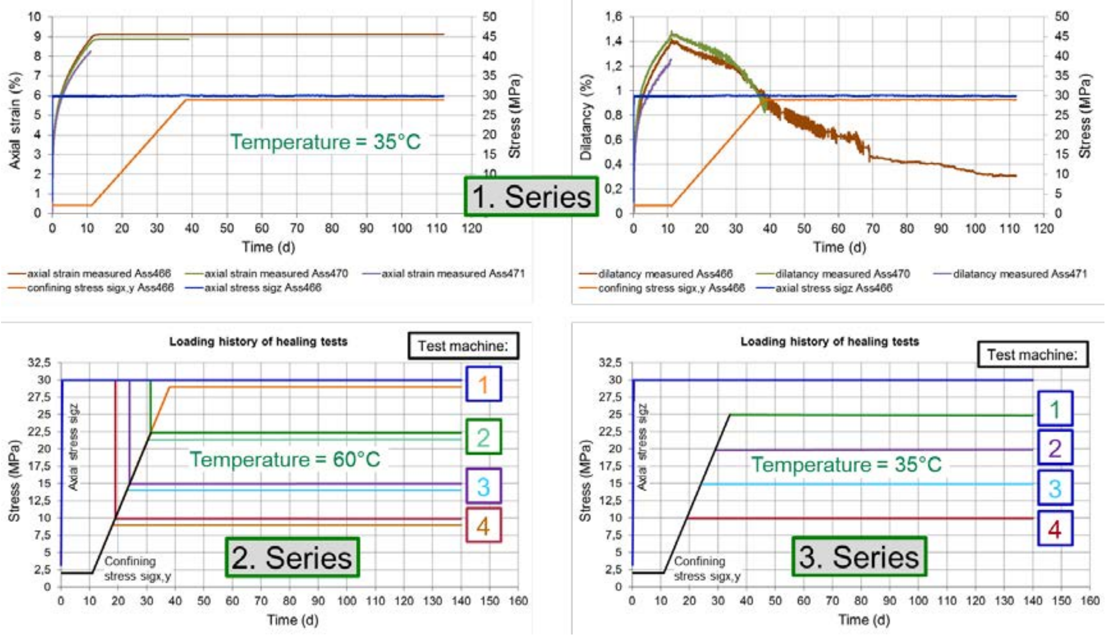


Figure 2-1. Top diagrams: Test results of a healing test. Bottom diagrams: Planned conditions of further healing tests with different stress states and temperatures.

Two further tests series are planned for the investigation of the healing behavior at different stresses and temperatures. Series 2, shown in Figure 2-1 bottom left, differs from the already performed test by a higher temperature of T = 60° C as well as lower isotropic healing levels. In test series 3, Figure 2-1 bottom right, healing is investigated at different deviatoric stress states.

In an additional newly developed test type, the load history is modified to identify at one specimen the damage-free creep behavior, the dilatancy boundary, the damage-induced creep behavior, the stress state where damage reduction starts, and the damage reduction behavior. This test is characterized by a constant differential stress but various axial and confining stresses. Based on the variation of the axial and confining stresses, at first only transient and stationary creep occurs, followed by damage-induced creep, i.e., creep with additional evolution of damage and dilatancy, and finally healing-induced creep. Figure 2-2 shows the loading history, measured dilatancy, ultrasonic wave velocity, and axial strain of a first test with Asse salt at temperature T = 30° C.

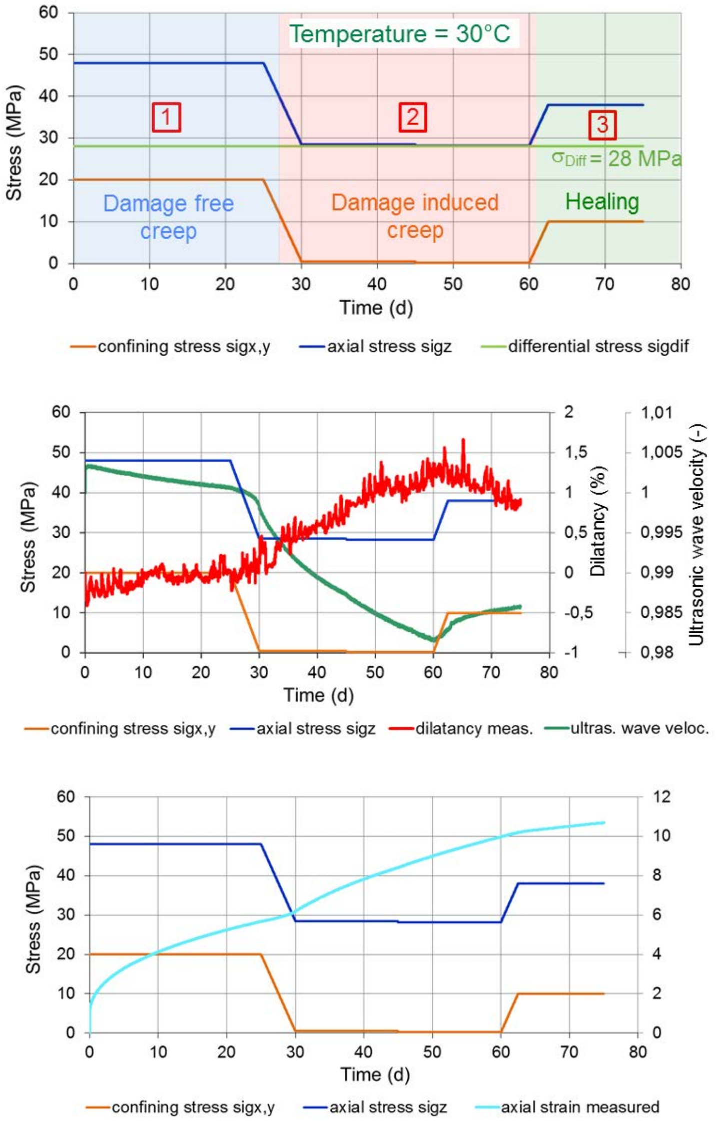


Figure 2-2. Loading history, measured dilatancy, relative ultrasonic wave velocity, and axial strain of a first test with Asse salt.

WP 3: Tensile stresses

Around underground openings in salt, tensile strength and tensile damage processes play dominant roles for the development of microcracks and progressive damage in the EDZ. Typical failure modes such as spalling are closely related to tensile damage (Figure 2-3). In addition to purely mechanical effects, i.e., due to rock convergence, tensile stresses may also be generated by thermal processes, e.g., due to temperature changes in a heat-generating radioactive waste repository or due to a temperature drop in a gas cavern if highly compressed gases are squeezed out.

In WEIMOS the impact of tensile stresses in the near and far-field of a repository is addressed by the following approaches:

- Comparison of how tensile stresses are treated in the various material laws
- Benchmark calculations of lab tests and field constellations
- Evaluation of the relevance of tensile stresses

The presented example of the recalculation of a Brazilian test demonstrates the capability of the constitutive models used (Figure 2-3). They can describe not only the characteristics of a visco-plastic material behavior, i.e., the three creep phases in combination with the strength and dilatancy behavior, but also tensile effects. However, while modeling results are plausible, additional systematic laboratory studies are required to overcome existing deficits regarding reliable modeling of tensile strength and failure as a function of damage (Günther et al., 2015).

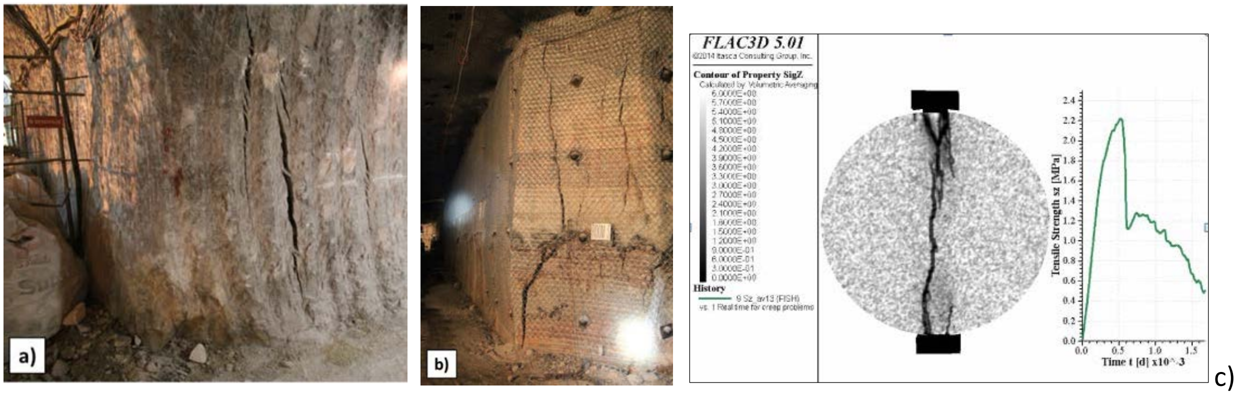


Figure 2-3. Tensile damage processes in salt. Observations a) in the Asse mine, and b) at the WIPP site; c) numerical simulation of a Brazilian test with the Günther/Salzer model.

WP 4: Layer boundaries, interfaces

The influence of layer boundaries, interfaces, clay seams or stringers, and contact surfaces on the convergence of underground openings became already visible during the simulations of Rooms D and B from WIPP in the previous Joint Project III. Here, some deviations of the simulation results from *in situ* measured data were explained with the influence of local sliding between rock salt and clay seams on the horizontal convergence, and with the influence of a separation between rock salt and an anhydrite layer above the room ceiling on the vertical convergence. Both phenomena were not considered in the calculations in Joint Project III because of the lack of experimental data.

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

In this work package, direct shear tests on several samples with clay seams, salt/anhydrite contact surfaces, or salt/polyhalite contact surfaces will be performed for SNL by RESPEC Inc. in their laboratory in Rapid City, SD. A test plan was elaborated by Steve Sobolik and Benjamin Reedlunn (SNL), and Stuart Buchholz (RESPEC) and presented at this workshop by Steve Sobolik. The drilling of cores in a mine close to WIPP (same salt formation, smaller depth) was completed in the fall of 2017. Test specimens have been prepared, but actual testing has not initiated as of this writing. Several excellent samples with a clay seam, halite/anhydrite interface, and halite/polyhalite interface were obtained. The tests were planned to begin in October 2017, but funding issues with the US Department of Energy (DOE) have delayed these tests until early 2018. The shear tests will be conducted at different normal loads and two different shearing rates. They will provide valuable data for a more realistic modeling of these phenomena.

Furthermore, Sandia has proposed *in situ* testing for a direct investigation of these processes underground. These tests would help to confirm the significance and transferability of the lab test results to *in situ* situations.

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

WP 5: Virtual Demonstrator

In this work package, a complex 3-D model will be calculated 1) with the existing material models, and 2) with the improved tools after the studies in WPs 1 to 4. The partners have chosen a main drift with a sealing system as an example, see Figure 2-4 left. A vertical cut through this structure resembles the 2-D plane strain model of Room D from Joint Project III. Therefore, this 2-D model was used as a basis for the Virtual Demonstrator.

Currently, test simulations are performed by all partners to e.g., adjust the 3-D discretization, reduce numerical issues, and find appropriate locations for the evaluation and comparison of simulation results. At first the open drift is calculated for 30 years after the assumed excavation, then the sealing system is introduced, and the subsequent phase is calculated for another 70 years. The plug is modeled in a simplified manner since the focus is not on the behavior of the sealing element. Besides the anhydrite and polyhalite layers, it is planned to introduce an additional interface (clay seam) that crosses the drift wall in order to study all the phenomena from WP 4.

With the final model, also the long-term evolution of stresses and strains and reduction of damage and dilatancy behind the plug will be studied.

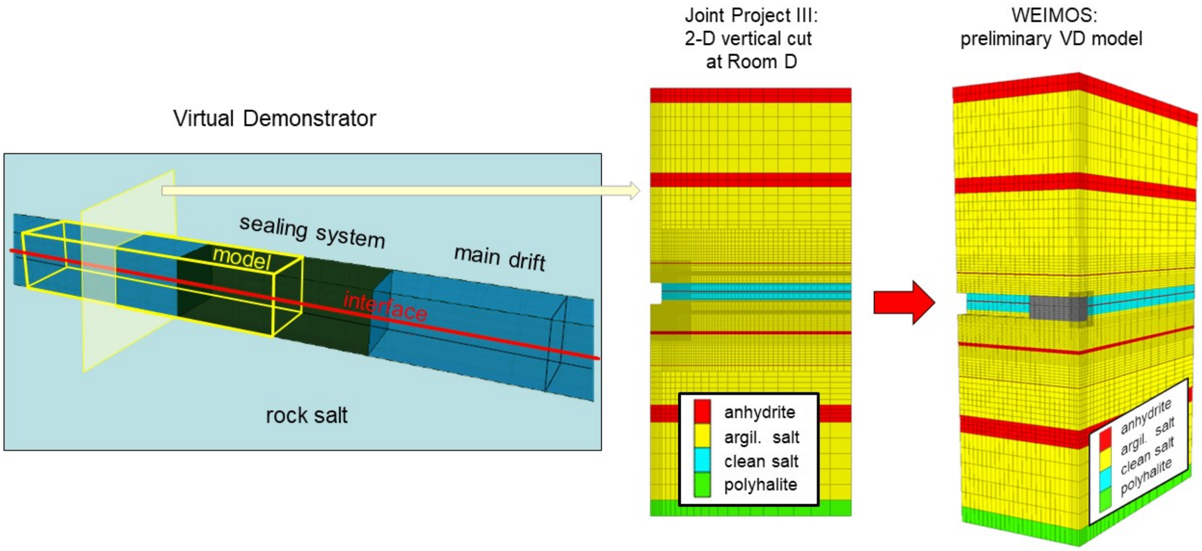


Figure 2-4. As a Virtual Demonstrator, a main drift with a sealing system was chosen. For reasons of symmetry, only half of the plug and a part of the residual drift is modeled. A vertical cut resembles the 2-D model of Room D calculated in Joint Project III, therefore it served as basis for the preliminary model of the Virtual Demonstrator in WEIMOS.

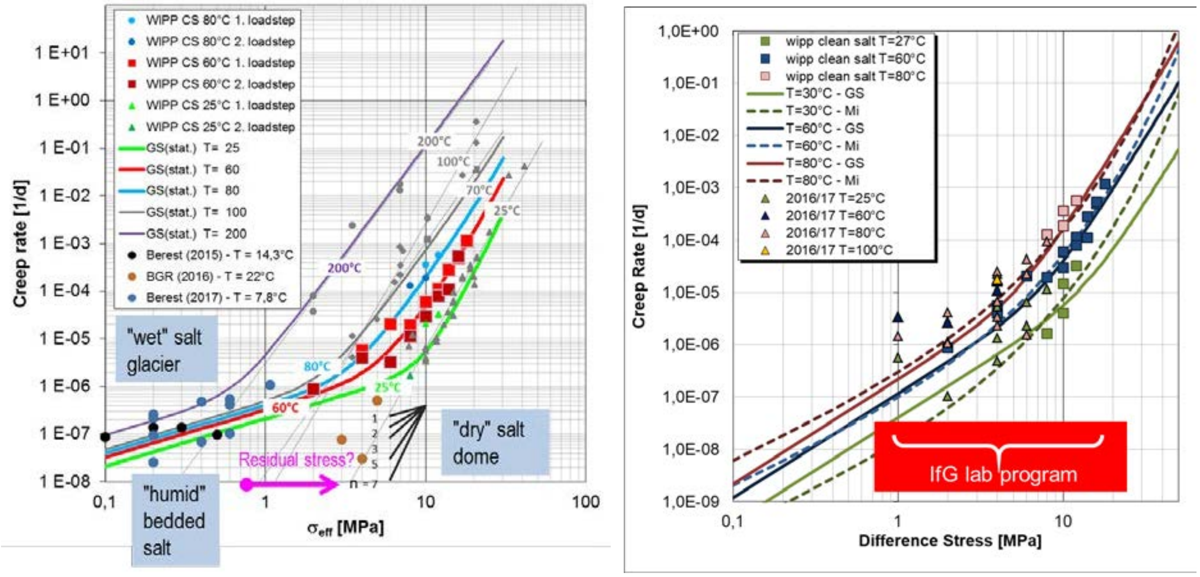
3 CREEP AT LOW DEVIATORIC STRESS

Testing salt under conditions of low deviatoric stress is a subset of investigations that comprise the architecture of the WEIMOS project, as discussed in Chapter 2. Owing to intense interest shown by the salt repository community in creep of salt at low stresses, the US/German workshop leadership extended an invitation to Professor Pierre Bérest, who along with a group of colleagues from the Solution Mining Research Institute, has executed some clever low-deviatoric creep tests with control of temperature and stress to tight specifications (SMRI Research Report RR2017-1, available at SMRI)

A fundamental principle for reliable extrapolation of creep behavior of natural salt over long periods of time and at low deformation rates using constitutive equations can only be carried out based on well-derived experimental data bases coupled with an understanding of acting deformation mechanisms. Despite decades of research on salt deformation, its behavior under low deviatoric stresses remains vague because establishment of significant creep deformation at such conditions presents an experimental challenge (e.g., Hardin et al., 2014).

Figure 3-1 provides steady-state creep rates determined for several types of salt at various temperatures and stress levels. In earlier laboratory testing (say, from 1970s through 1990s), differences between axial and confining stresses commonly ranged from 5 to 15 MPa, while confining stresses were sufficiently large to suppress dilatancy. Typically, the relationship between steady-state creep rate was a function of the deviatoric stress raised to a power ranging from 3 to 6 under such conditions. This can be generally appreciated from data plotted in Figure 3-1a, a synoptic view of lab test results on WIPP-salt in relation to findings from other authors [Bérest (2015, 2017: using different salt samples); BGR (unpublished data on Morsleben salt)] which also indicates deviation of this relationship as deviatoric stress decreases. In addition, isolines for the description of the strain rate-stress relationship at various temperatures resulting from curve fitting with the Günther-Salzer (GS-stat) material law are shown. The arrow labeled "Residual stress" indicates as an additional explanation of discrepancies between "dry" and “wet” salt the microscopically determined inherent stress level on domal salt samples which may possibly overlap the creep behavior due to hardening. Figure 3-1b presents an extended data base of WIPP salt (as of 09/2017) with tests a low deviatoric stresses ranging from approximately 1 to 10 MPa. In addition, curve fits using the Günther-Salzer (GS) or Minkley (Mi) material law are shown for various temperatures.

The data base obtained from *in situ* observations and laboratory tests on salt indicates that both dislocation (e.g., Carter & Hansen, 1983) and diffusional creep mechanisms (Urai & Spiers, 2007; Spiers et al., 1990) can be important in salt under long-term conditions. The implication of these different creep mechanisms on constitutive model development becomes visible from Figure 3-1a, showing experimental data sets for WIPP salt in relation to findings from other authors with different salt types in a log-log diagram. Current results from creep tests at low deviatoric stresses of $\Delta\sigma \leq 1$ MPa were presented by Bérest (2015; 2017) who performed uniaxial creep tests on various salt types using dead weight systems at underground test sites in salt mines. His findings demonstrate a shift in creep rates orders of magnitude higher than would be predicted by extrapolating from conventional tests at higher stresses, using a simple power law relationship. The stress response on salt creep is characterized by a change in slope. At deviatoric stress >5 MPa a stress exponent of 3 to 7 matches data, while the exponent is only 1 at deviatoric stress < 5 MPa.



a) b)

Figure 3-1. Steady-state creep behavior of salt. a) synoptic view of lab test results on WIPP-salt in relation to findings from other authors: Bérest (2015,2017); BGR (unpublished data); b) extended data base of WIPP salt (as of 09/2017) with tests a low deviatoric stresses: $\Delta\sigma = 1 - 10$ MPa.

The transition to low-deviatoric stress creep mechanisms appears to be temperature dependent, increasing at lower temperatures, as can be seen from the WIPP results. This observation is consistent with humidity-assisted creep at low stresses. However, recent tests at BGR performed with uniaxial test rigs on salt from the Morsleben dome show a behavior more consistent with a power law with an exponent of around 5, which is interpreted as dislocation creep. In contrast, the most recent investigations on WIPP salt in the framework of WEIMOS, performed as triaxial creep tests by IfG between $\Delta\sigma = 1$ and 10 MPa indicate also a creep mechanism change in deviatoric stress response, but the measured creep rates lie below the Bérest data (Figure 3-1b).

This collaborative research is an excellent example of investigations on several fronts approached in different manners toward solving a common dilemma. Experimental results at low deviatoric stresses are quite different than those projected or estimated based solely on experiments above 5 MPa. These matters clarify a future research agenda, exemplifying one of the great results of international collaboration. At least two aspects are important for future work:

1. Experimental differences between various groups need to be evaluated. Uniaxial tests are relatively easy to perform by implementing dead-weight systems, but suffer a disadvantage that test samples are not pre-consolidated. It is believed that the long transient creep phase and relatively higher creep rates reflect sub-structural reestablishment of the salt's natural architecture. This evolution can be mitigated by a triaxial test setup where samples can be pre-compacted under defined conditions. This advancement in experimental knowledge requires more sophisticated test procedures (Günther et al., 2014), and such tests require significant maintenance to ensure stable low-deviatoric stress conditions over long test periods. As an improvement of their usual creep test equipment, IfG constructed three new triaxial creep rigs, which are characterized by an improved strain measuring system capacitive Non-Contact Displacement Transducer with a resolution better than 1 nm) operating in a highly stabilized climate room.
2. Lithological differences exist between bedded and domal salt in water content and tectonic stresses during diagenesis and subsequent salt dome uplift. Because systematic investigations are missing, extensive microstructural investigations are underway, performed by SNL and BGR including sub-grain size piezometry for determining differential stresses (at paleo- and lab-conditions), precise determinations of water content, and its distribution.

Another means to investigate relevancy of the different creep behaviors involves finite-element simulations of a current salt dome uplift. Different constitutive relationships with application to natural cases were performed within the framework of the WEIMOS project. Figure 3-2 illustrates these models of salt dome formation by buoyancy of less-dense salt through a denser overburden. Usually a low and stable rate of rise is reached. Under such conditions continuing active uplift of the salt is due only to the remaining weight difference between the salt and the neighboring rocks. Using a simplified shape of a columnar salt diapir (with cap and adjacent rock conditions comparable to the simplified Gorleben site) in a 2D-geometry, rise of salt was estimated using two different strain rate / stress relationships corresponding to the experimental data base. A rise rate of the order of 0.03 mm per year is obtained when low stress-creep rates 3 orders of magnitude higher than extrapolated from a power-law fit at higher stresses are applied. This rate corresponds well to actual rise rates from the Gorleben salt dome (0.01 – 0.05 mm/a, after Zirngast, 1996), which tends to confirm accelerated creep rates at low-deviatoric stresses.

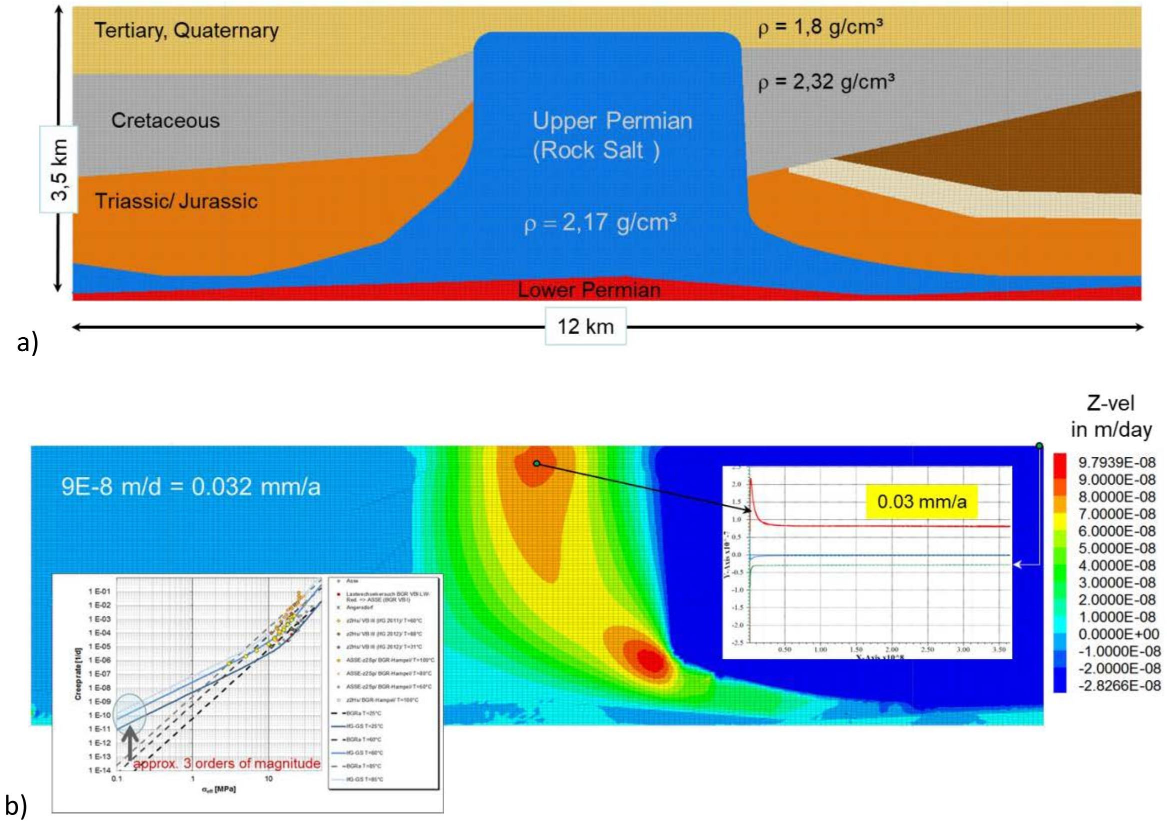


Figure 3-2. 2D Simulation of salt dome uplift. a) Generic geological model of a columnar salt diapir; b) Outcome of numerical simulation (Günther/Salzer model): velocity field of vertical uplift. The left inset illustrates the accelerated creep rate/Δσ-relationship and the right inset shows time-dependent change of vertical uplift for the respective history-point until equilibrium is reached.

Clearly, research of salt deformation under low-stress conditions is intriguing. As the example above illustrates, if the deformation rate at low-differential stress is higher than extrapolated from higher-stress creep results, overall response of large-scale salt grids will be accelerated. Extending the concept to WIPP Rooms B & D, a fundamental change in deformational behavior may account for underestimating room closure.

4 RECONSOLIDATION OF GRANULAR SALT

4.1 Overview

Reconsolidation of crushed salt has been a topic of interest for US/German collaborators for many years. A milestone report (Hansen et al., 2014) summarized reconsolidation principles and applications. The report represents collaboration among SNL, IfG, the Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) (Society for plant and reactor safety) and BGR. Reconsolidation remains a topic of active collaboration yet today, both for the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) Salt Club and US/German workshops because of the great potential it brings to operational-period drift closures and long-term seal systems.

As a case in point, the NEA Salt Club held their annual meeting a day in advance of the US/German workshop and featured a break-out session focused on crushed salt reconsolidation. Four related presentations were provided by technical staff from DBE TEC, RESPEC, IfG, and GRS. Discussion followed, and experts were queried as to the most important activities to advance the state of knowledge in repository-applicable R&D. Reconsolidation of crushed salt was also identified for an in-depth break-out session during the US/German workshop, providing further elaboration.

Furthermore, the Deutsche Arbeitsgemeinschaft für Endlagerforschung (German association for repository research) (DAEF) has been supporting research on granular salt reconsolidation, as introduced to US collaborators by Oliver Czaikowski at an exchange of salt technical understanding held at the BGR in March 2016. The DAEF represents leading German research organizations active in radioactive waste disposal research (http://www.endlagerforschung.de/). The aim of this association is to contribute to safe disposal of radioactive waste, to develop research, and to offer respective fact-based information.

On behalf of collaborators, Klaus Wieczorek presented an overview of the role of crushed salt backfill in a nuclear waste repository for decay heat transfer to the host rock and structural stabilization. After reconsolidation, this emplaced backfill provides a tight long-term barrier against brine transport, a capability that was more strongly emphasized in order to prove the confinement of radioactive waste inside a containment providing rock zone.

Under many circumstances, granular salt has been reconsolidated into an intact material, as shown in the micrographs in Figure 4-1. The key question remains: How and when will sufficiently low porosities/permeabilities be reached to achieve tightness? Therefore, systematic reduction of uncertainties is necessary for reliable repository dimensioning and additional R&D is highly desirable for further optimization. The break-out session allowed participants to suggest ideas for consideration in future studies, which are summarized further down in this chapter.

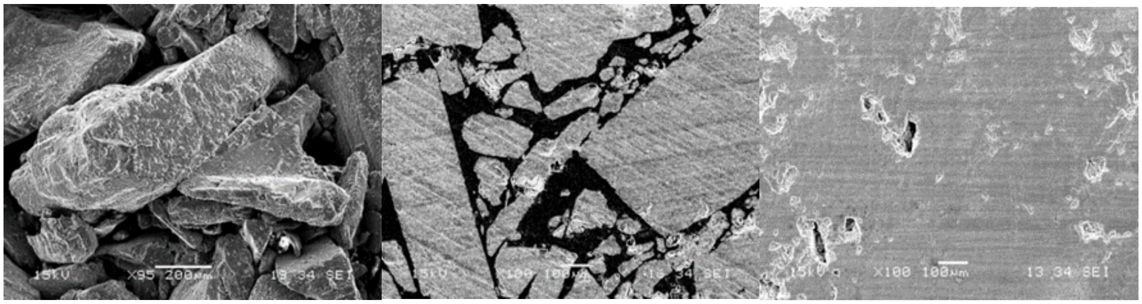


Figure 4-1. Evolution of damped crushed salt to intact material (from left to right).

Wieczorek led discussion of perceived open issues, which exist despite an extensive experimental database and availability of various material models. Several models have been applied to assess reconsolidation of granular salt. Modeling was not addressed in Hansen et al. (2014), and has been identified by Wieczorek as an important research area. He proposes validation and calibration among pre-selected existing models.

As part of the preliminary safety case for Gorleben, adequate performance of reconsolidating crushed salt was demonstrated, even assuming pessimistic conditions for reconsolidation. Nonetheless, uncertainties remain, which if addressed, could result in a more resilient design. It is felt necessary, therefore, to document the current state of research in crushed salt compaction, to identify gaps in knowledge, and thereby offer recommendations concerning a research agenda and subsequent proposal. Perceived shortcomings exist in the database and model validation, especially under conditions of low residual porosity where salt's barrier functionality begins. To address these issues, a research program is under consideration, including associate partnerships with American colleagues at SNL and RESPEC. In part, work going forward will bridge between what we know about granular salt reconsolidation, how it is modeled, and performance expectations when placed in an underground repository. Further understanding of micromechanical processes is paramount for evaluating modeling approaches. Nuances of this research include comparison of heretofore domal salt environments to potential disposal in flat-lying (bedded) salt formations.

The ultimate application for reconsolidated salt is to provide barriers to transport in a repository, so a natural complementary idea is to create conditions for crushed salt backfill to achieve high performance as early as possible. That means, build the barrier to high density upon construction by applying knowledge gained in our collaborations.

US/German collaboration should continue inquiry into behavior of reconsolidating salt to the extent possible. Analogues are highly useful, though initial and boundary conditions are usually not well known. Additional emphasis on acquiring salt consolidated *in situ* after backfilling would add to any studies of this nature.

Salt reconsolidation modeling

Several material constitutive models have been developed over time, as summarized by Wieczorek in the US/German workshop. One initial undertaking might rightfully compare various models. For example, WIPP researchers have developed models for their use, including Callahan (2011), as comparable models were forthcoming from European initiatives (Zhang, Hein, Olivella/Gens and Heemann). Reconsolidation models present similar technical challenges as found in development of constitutive models for intact salt. Many formulations are available, but it is unclear which one most correctly represents and predicts behavior. To further clarify these issues, comparative calculations might be conducted to expand upon those conducted by Project REPOPERM 2 (Kröhn et al., 2017). To facilitate model comparison a uniform material parameter set would need to be established.

Model comparisons might first evaluate similarities and differences by a calculating a simple benchmark example. Parameters could then be calibrated and adjusted. An example benchmark has already been documented (Kröhn et al., 2017). Comparison with new, specifically defined laboratory tests would reveal predictive capability.

Test specimens for completion of experimental database

Creation of test specimens was discussed at length. Permeability changes of greatest interest occur at porosities of significantly less than 10%. Nominally uncompacted granular material, such as disaggregated salt, possesses porosity around 35%. Therefore, a consistent and scientifically defensible procedure by which to create test samples preconditioned to 10% or less would be of great advantage to facilitate a suite of tests at low porosity. The challenge would be to create precompacted starting material in a relatively short time that represents *in situ* barrier salt that has been consolidated by room closure. An investigation into short-term production of special conditioned test specimens with low porosity and natural grain substructural conditions will be needed.

A successful pre-test phase would save months or years compared to traditional consolidation testing by oedometer or triaxial compression. Historically, testing of this type in Germany used domal salt, while future testing would include salt from flat-lying formations as well. A biaxial preconsolidation technique has been proposed where a conventional triaxial cell is arranged and axial displacement is static. Deformation would be applied in the radial direction, essentially creating a modified extension test. Targeted precompaction levels would be porosity of approximately 10%. The resulting mass would need to be characterized hydrologically and microstructurally.

Microstructural observations

Consolidation of granular salt has been widely studied, and microstructural observations using optical and scanning electron microscopes provide direct insight into deformation mechanisms during consolidation. Moisture effects are well known, and samples with nominal available moisture (say 1 weight percent) exhibit pressure solution processes with tight grain boundaries and areas of occluded fluid pore spaces. Recrystallization has been rarely observed in rock salt consolidation experiments. Figure 4-2a shows scanning electron microscope micrographs of occluded fluid pores on a fresh face of a broken reconsolidated sample. During reconsolidation, permeability becomes very low at porosities <3.0%, as brine becomes occluded along boundaries and within interfaces. The scanning electron microscope image is unvented WIPP run-of-mine consolidated salt at 250˚C.

Figure 4.2b is an etched thin section capturing recrystallization among grains with extensive polygonization (subgrains). The sample was vented WIPP run-of-mine salt consolidated at 250°C. Samples consolidated without additional moisture exhibit mainly cataclastic and plastic deformation. Experimental research will be required to develop short-term samples for further consolidation.

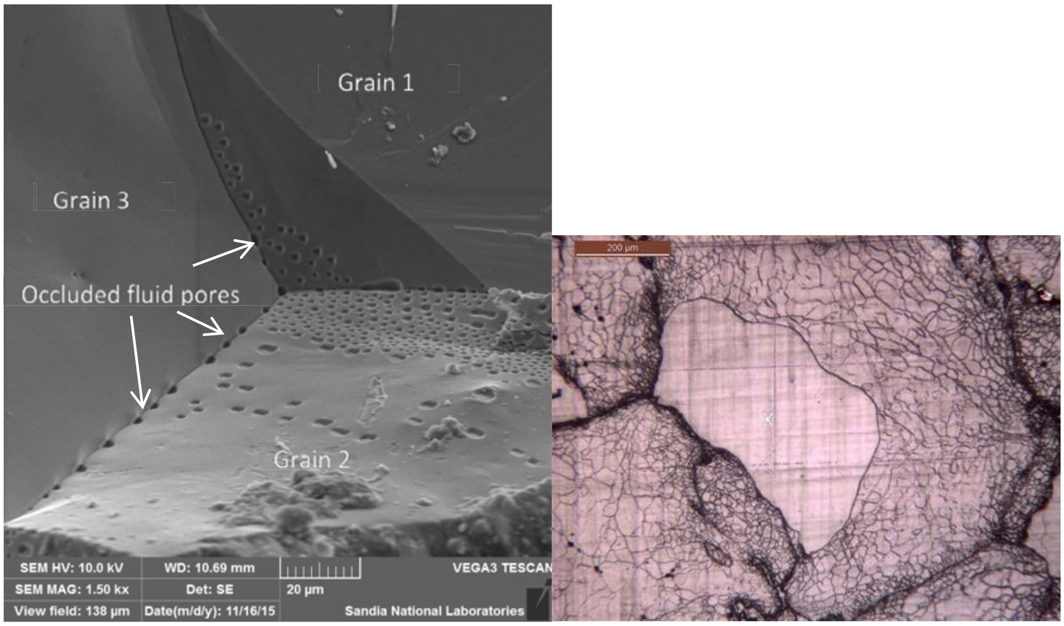


Figure 4-2. a. Occluded pore structure of reconsolidated salt (Stormont et al., 2017). b. Recrystallization.

Dynamic precompaction

In past studies for the WIPP shaft seal system, Sandia prepared samples in the lab and on a large-scale (40 cubic meters) using dynamic compaction, and then further consolidated the compacted material by hydrostatic compression. Dynamic compaction can create samples with 10% porosity, but simultaneously creates fine powder, and is not necessarily representative of slow closure under *in situ* conditions. Perhaps comparison between samples created by dynamic compaction and those created by hydrostatic compression could be done in the following sequence:

1. Document porosity,
2. Characterize resulting substructure,
3. Run identical consolidation tests,
4. Evaluate porosity and permeability,
5. Characterize the new consolidated substructure.

If moisture is available, it is possible response between dynamically compacted and triaxially compressed pre-conditioned samples would be the same.

Additives

Construction techniques capable of emplacing granular salt seals, perhaps with additives, to near final performance conditions greatly reduce the need for extrapolation via modeling. Permeability reduces more readily and at higher porosity with clay additives—a point that needs to be carried forward, as well. Placement of granular salt in a horizontal drift presents more challenge than compaction in a shaft, but perhaps initial placement properties could be engineered to high-performance conditions by mixing crushed salt with bentonite.

Pore pressure effects

The idea of pore pressure effects in reconsolidating salt remains enigmatic. Salt is unlike sandstone or granular material of hard particles because salt is highly deformable. An astute investigation could include vented and unvented samples. Venting should minimize creation of pore pressure, while unvented samples would seem to compel pore pressure to build up. It may be found that unvented samples will become impermeable, just like vented samples. It would be an interesting and relatively easy suite of tests.

4.2 Summary

Repository performance assessment applications involve long time periods and in some cases the properties of reconsolidating salt are needed many years after placement (well beyond existing laboratory data), requiring modeling and extrapolating engineering performance. Performance uncertainty can be lessened by deepening mechanistic understanding through continued research and additional validation garnered from industry practice and analogues. Laboratory results and natural and anthropogenic analogues support the proposition that granular salt can be reconsolidated to the point where it has mechanical and transport properties approaching or equivalent to natural, undisturbed salt.

Ongoing US/German Workshops on Salt Repository Research, Design and Operation include salt reconsolidation as a special focus area. The breakout session led by Wieczorek, Müller-Hoeppe and Hansen updated information on salt reconsolidation research. As noted, key questions involve how, when, and to what degree properties of reconsolidating granular salt approach or attain those of the native salt formation. Supporting data reveal predisposition for granular salt to reconsolidate in natural environments as well as under conditions involved with slurry injection and *in situ* construction techniques that may be applied in nuclear waste repositories. Reconsolidation of granular rock salt is expected to continue as a focus for future US/German workshops. Several suggestions were put forward, including resolving test-dependent parameter variations, advanced porosity measurements during tests, creation of consistent samples to avoid long time periods involved with testing, micromechanical processes and studies, complexity of mineral and brine composition, intermediate-scale operational period test, and evaluation of how uncertainty affects performance assessment. Reconsolidation clearly has many possible future priorities, and the topic itself remains highly important. Somehow, the immediate efforts will need to be streamlined in terms of what can be done in the framework of US/German collaboration.

5 KOSINA

5.1 Introduction

In July 2013, a site selection act for a repository for heat generating radioactive waste and spent nuclear fuel (SNF) in Germany was issued and amended in May 2017 (StandAG, 2017). This act directs the selection process for a repository site in Germany that best ensures the repository safety for a demonstration period of one million years. This requires the existence of generic repository concepts as well as suitable safety and safety demonstration concepts for all potential host rocks in Germany. In Germany, a reference concept for the disposal of heat-generating radioactive waste and SNF in salt domes was developed in the early 1980s. Comparable investigations for a repository in clay or crystalline host rock formations were launched in the early 2000s. Up to now, flat-bedded salt formations were not considered in Germany for the disposal of radioactive materials. For this reason, the R&D project KOSINA was launched and funded by BMWi represented by the Project Management Agency Karlsruhe in summer 2015. KOSINA is a German acronym for “Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept.”

5.1.1 Objectives and Work Program

The main objective of the project KOSINA – a joint undertaking of BGR, DBE TECHNOLOGY, GRS and IfG - is to develop a generic technical (site-independent) concept of a repository for heat-generating waste and SNF based on generic geologic models for flat-bedded salt formations in Germany. This program includes development of a safety concept and safety demonstration for such a repository type. To achieve the aforementioned objectives, the work program of the KOSINA project is divided into eight work packages which are strongly linked to each other and must be worked on iteratively:

WP1: Compilation of basic data and requirements

WP2: Derivation of generic geologic models and corresponding material parameters

WP3: Development of a safety and safety demonstration concept

WP4: Demonstration of geologic integrity

WP5: Development of repository concepts

WP6: Analysis of radiological consequences

WP7: Assessment of operational safety

WP8: Synthesis report

5.1.2 Generic Geological Models

As an initial work step of KOSINA, BGR and IfG evaluated the geologic conditions of bedded salt formations in Germany, mainly based on the results of the previous BGR-project “BASAL,” with respect to the minimum requirements for a HAW repository: e.g., depth, thickness, lateral extension after StandAG (2017) and AkEnd (2002). The latter are only fulfilled by some regional occurrences of saliferous formations of the Zechstein (Upper Permian) and the Malm (Upper Jurassic). Two structural types were distinguished as generic, referred to as model type A “flat-bedded salt” and model type B “salt pillow” (Figure 5-1).

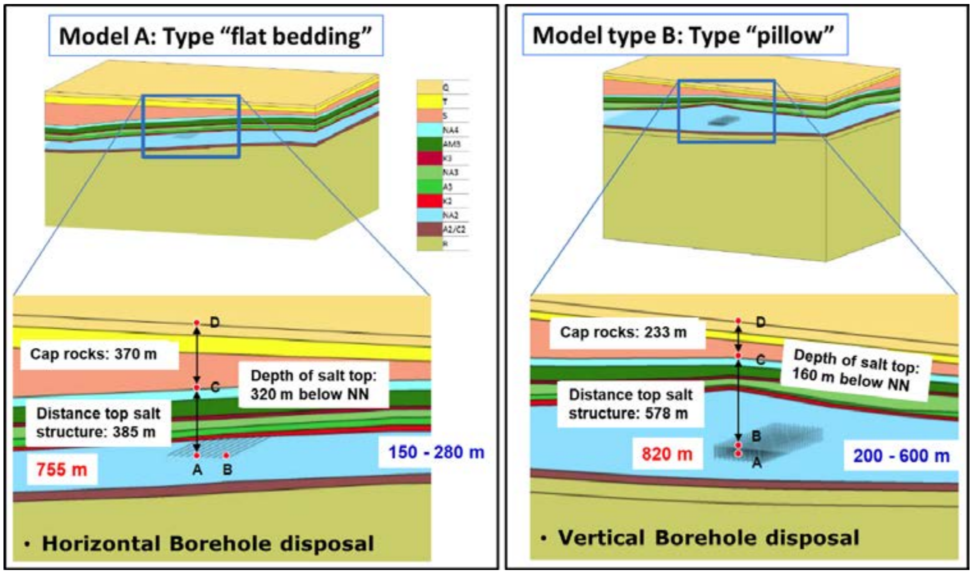


Figure 5-1. Generic sites (3D-models) of bedded salt formations with detail sections showing examples of repository design used for integrity analysis: left) model type A "flat-bedded salt," right) model type B "salt pillow."

Based on regional geological data, BGR developed generic geological profiles consisting of 18 stratigraphic units for both models, selecting the Staßfurt-Hauptsalz (z2HS) as an emplacement horizon. After construction of realistic generic 3D-models for both structures a sufficient salt thickness and lateral extension was confirmed (Kühnlenz, 2016). The "salt pillow" type has the advantage of a significant salt thickness increase due to density-induced lateral salt movement and local uplift. In contrast to salt diapirs, more or less concordant bedded salt layers were preserved and no piercing of the structure through the overlying sediments has occurred. In addition, as prerequisite for modeling, a comprehensive data base of thermal-hydrological-mechanical parameters of bedded salt formations, under considerations of the existing knowledge for domal salt, was compiled (Liu et al., 2017).

5.2 Repository Design

5.2.1 Design Fundamentals and Requirements

The design of a deep geologic repository relies on detailed information about the types and amounts of radioactive waste and on the knowledge about the geology at the site as well as on national regulations, ordinances, and design requirements. All these data must be compiled before the repository development process can be started. Then, the possible distribution patterns of the waste packages in the repository facility are determined by means of thermal calculations in order to not exceed given design temperatures in the host rock. Finally, shafts, drifts, and emplacement areas can be designed, considering the best practice of the mining industry as well as the special needs for such a repository as defined in specific regulations and in the safety case. The inventories as well as the predicted amounts of SNF are summarized in the German national waste management program (NaPro) (Nationales Entsorgungsprogramm, 2015). In Germany, a total of 10,500 metric tons of heavy metal of SNF is expected. The distribution of SNF from test and prototype reactors and from research reactors is available as well (VSG, 2011b) and has been updated in the course of the KOSINA project by adding the SNF of the research reactors Rossendorf and Mainz. In total, 540 waste packages of different types must be considered. Until 2005, reprocessing of SNF from German nuclear power plants was carried out in France and the United Kingdom. The corresponding waste packages comprise vitrified fission products, feed sludge, vitrified flushing water or compacted claddings and structural parts, amounting to approximately 8000 packages. Within the KOSINA project, disassembling of the SNF elements of the nuclear power plants was considered, as in previous repository concepts. Thus, structural parts with less heat production capacity will be placed into separate waste packages. In total, 2620 small-size waste packages must be considered. Other waste with negligible heat production was not considered in the KOSINA project.

The generic geologic models, necessary as fundamental data for the repository designs were developed by BGR and IfG. The regulatory framework for the design of a repository for heat-generating radioactive waste mainly consists of the safety requirements issued by Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety of Germany (BMU) in 2010 as well as of the atomic energy act, the mining act, and the radiation protection ordinance.

A few quantitative requirements regarding the technical design of the repository facility were fixed prior to the start of the design work. These requirements consist of minimum distances of the mine openings, to the surrounding salt formations, and of the emplacement areas to the position of the shafts. Thus, in the safety concept, the following minimum distances were fixed:

- 150 m to the top of the salt formation,
- 50 m to the top and to the bottom of the rock salt formation (emplacement level),
- 500 m lateral safety pillar (to exclude impacts of perhaps existing salt incline, considering the dipping of layers) and
- 300 m distance of the emplacement areas to the shafts.

These determinations enable a positioning of the repository facility in the generic geologic models. Accordingly, the depth of the repository facility in the geologic environment can be determined. The depth is 700 m below sea level for the disposal concepts in the geologic type “flat-bedded salt” and 830 m and 725 m below sea level for the type “salt pillow,” depending on the selected emplacement option.

In the course of the KOSINA project, two different emplacement options were investigated for each of the two geologic models. For the type “flat-bedded salt,” the drift disposal concepts for POLLUX® casks for heat-generating waste as well as for waste packages with spent fuel from research and prototype reactors was selected and the disposal concept of emplacing all types of waste packaged in small waste canisters of the type BSK-H into lined horizontal boreholes. For the geologic model type “salt pillow,” the emplacement concept of disposing all types of waste packed in small waste packages of the type BSK-V into lined deep vertical boreholes was selected. The second disposal concept consists of disposing all the waste by means of Transport and Storage Casks (TSCs) into short horizontal boreholes. Details concerning the description of the waste packages and the corresponding amounts of waste packages per emplacement option can be found in the KOSINA interim report (Bertrams et al., 2015). As an example, the repository design for the Transport- and Storage Casks is described in the following chapters.

5.2.2 Thermal Design Calculations

It was agreed within the KOSINA project to perform the thermal design calculations with a maximum design temperature of 200° C, which is in accordance with the regulations of the safety requirements of BMU as of 2010 (BMU, 2010). This decision provides the possibility to compare the design calculation results with those of previous studies; e.g., the preliminary safety assessment for the Gorleben site. Based on thermal and thermomechanical simulations, the minimum distances between waste packages and emplacement drifts were calculated. The calculations rely on the technique of an elementary cell model. In this case, symmetry conditions will be considered. This method allows modeling only one quarter of a waste package surrounded by backfill material and host rock. The use of adiabatic boundary conditions allows the consideration of the areas of the repository not modeled by reflection of the temperature gradient at the model borders. In this case, the model represents the case of an infinitely extended repository with an unlimited number of waste packages. The calculated temperatures in such models are most conservative and ensure meeting the temperature criterion. The technical design of a repository for heat-generating waste and SNF requires the consideration of thermal parameters. The determination of the depth of the repository, the existing temperature, and the basic stress condition at that level can be determined. The thermal material features of the geologic structures are considered in the calculations as well. The heat capacity of the heat-generating waste was determined according to the burn-off calculations in previous studies (VSG, 2011a). For the disposal of TSCs in small horizontal boreholes, the design point for the calculations is the contact point between waste package and the surrounding host rock salt. Thermal calculations were carried out for the spent fuel elements from pressurized water reactors and for waste packages with vitrified fission products from reprocessing, thus covering all waste types with lower heat production, like spent fuel elements from boiling water reactors and reactors of Russian type. The results of the thermal design calculations are shown in Figure 5-2, exemplarily for the pressurized water reactor spent fuel elements.

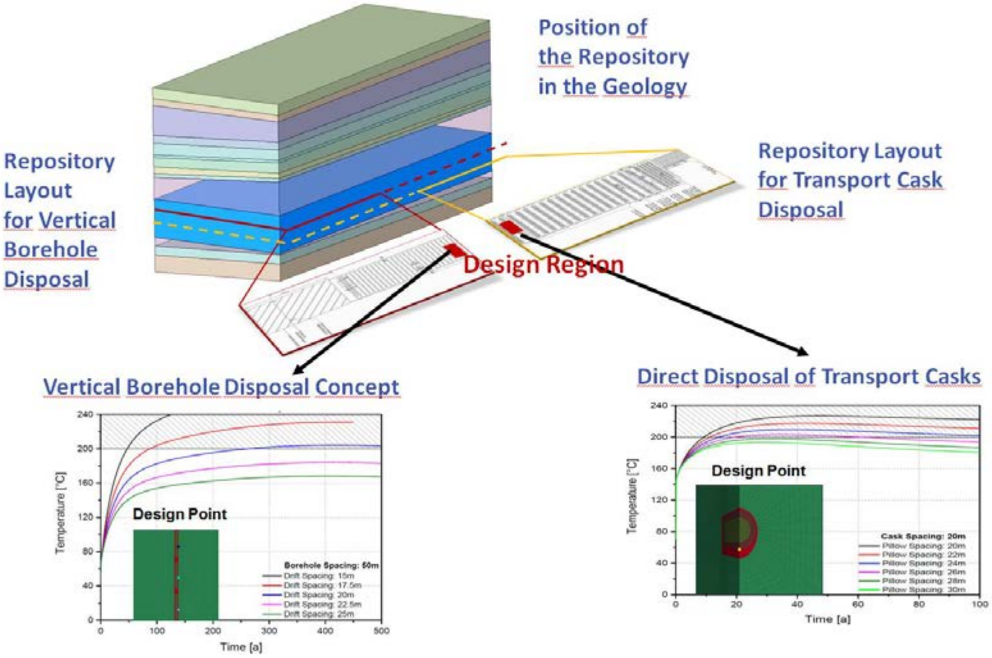


Figure 5-2: Results of thermal design calculations for emplacement of Transport Casks (TSCs) loaded with spent fuel elements (right).

5.2.3 Layout of the Repository

The requirements that must be considered when designing the repository facility include the depth of the emplacement level, the type of waste package transport and emplacement technique. The dimensioning of the mine openings in case of TSCs emplacement is mainly related to requirements occurring from the dimensions of transport and emplacement device. The corresponding safety distances in the mine openings are determined in the accident prevention regulations. A decisive mine layout criterion is the minimum width of host rock pillars between two emplacement drifts. The width of the emplacement fields is limited to 400 m to avoid additional mining requirements from the mining authority. The curve radius in a mine depends on the transportation technique. For rail-bound transport the radius is 25 m and for wheeled transport only 10 m. The length of the horizontal borehole will generally be limited to 100 m because of the application of dry drilling method in salt environment, but for one single TSC per borehole only a length of approximately 13 m was calculated considering the length of the cask as well as the length for a borehole seal.

The waste generally has to be shielded during transportation on surface, through the shaft to the underground and in the mine, up to the emplacement location. In case of TSCs the shielding is provided by the waste package itself. The transport of the TSC from the conditioning plant on surface through the shaft (in an upright position) to the emplacement field in the repository mine will be done via rail. The emplacement technique consists of a transport wagon with a rotatable upper-carriage as well as of a pushing device on top of the wagon. A conceptual design was performed on behalf of the German Nuclear Industry for the direct disposal of TSCs (Jussofie et al., 2016). Figure 5-3 shows the TSC emplacement scheme.

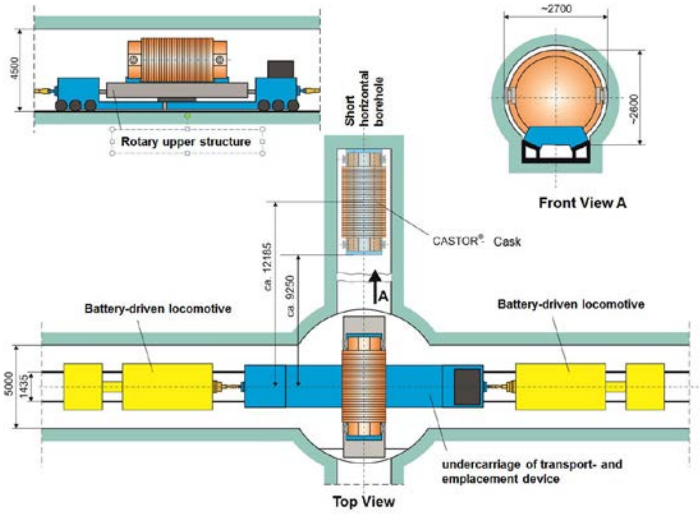


Figure 5-3: Emplacement scheme for the TSC-disposal concept: Step 1 - The TSC will be transported rail bound to the emplacement position in front of a horizontal emplacement borehole and turned by means of a rotary structure: Step 2 - The TSC will be pushed into the borehole by means of a pushing system fixed on the rotary upper structure.

The design of the emplacement field was done per the calculated thermal minimum distances between the emplacement boreholes and between the waste packages. Figure 5-4 shows a TSC-Type CASTOR® V/19 and a design of an appropriate emplacement field for TSCs.

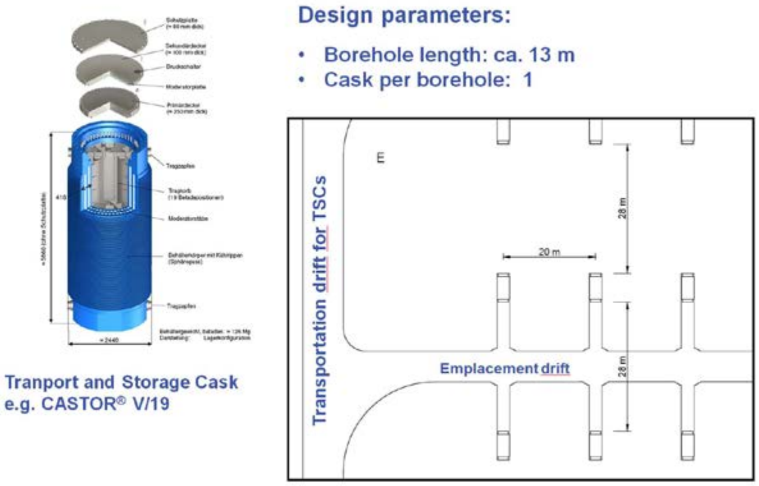


Figure 5-4: Plan view of an emplacement field for the TSC-disposal concept considering the calculated distances between TSCs and boreholes.

5.3 Integrity Analysis

Because the integrity of the geological barrier is crucial for protection from damage caused by ionizing radiation during the post-operational phase, extensive 2D and 3D thermo-mechanical calculations for both models were carried out by BGR and IfG, all looking at two different waste emplacement concepts: emplacement in drifts and in boreholes, as developed by DBE TECHNOLOGY. Two different geomechanical model approaches were applied for the description of deformation and damage processes: the well-known BGR-concept with modifications for the different creep capable salt rocks and the elasto-visco-plastic material law of Minkley.

Both, model concepts and numerical tools are verified and proven, which facilitates reciprocal supplement or proof of the results. Whereas BGR uses mainly the JIFE-code for investigation of large 3D models, focusing on the far field (the heat source is distributed over the emplacement area), IfG utilizes the UDEC code, whereas the emplacement geometry (e.g., canisters, crushed salt backfill) is explicitly modeled, additionally allowing it to describe the interactions between convergence and backfill (crushed salt consolidation state as input parameter for the consequence and radiological analysis of GRS Braunschweig).

Simulating the thermal impact and its time-dependent change the calculated stresses are used for evaluating the barrier integrity on the basis of the generally accepted dilatancy criterion and the fluid pressure criterion. Exemplarily, results are presented in Figure 5-5 for drift disposal in a salt pillow (model B) which demonstrates the temperature field induced reduction of horizontal stresses predominantly at the salt structure top (around the Aller formation), which is only temporarily whereby an unaffected salt barrier >400 m remains.

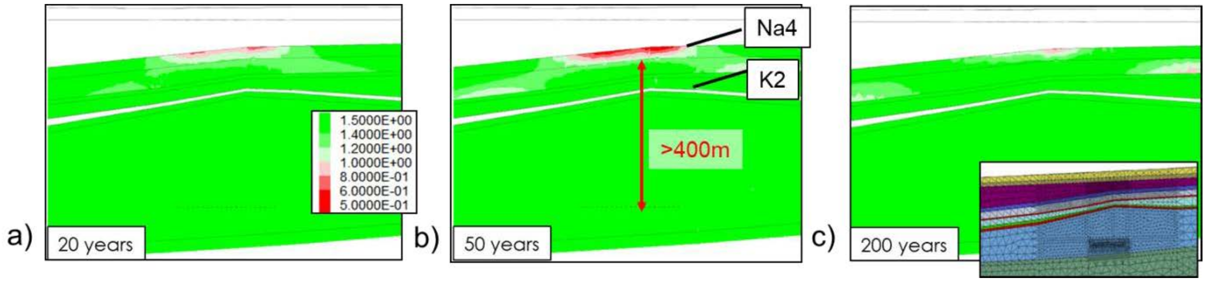


Figure 5-5. Evaluation of the fluid pressure criterion for different time steps after the start of drift emplacement for model B "pillow" (2D-modeling by IfG): Criterion violation ($\eta_F < 1$) in the pink to red zone.

The preliminary conclusions of the integrity analysis are

- Temporary violations of the minimum stress and dilatancy criterions occur at the top of the salt formation, according to the temperature impact but a sufficient thick salt barrier remains;
- Vertical bore hole emplacement shows higher effects than horizontal emplacement;
- Because of its higher salt-thickness the type B "pillow" has advantages over type A "flat-bedded salt." This is a function of the thickness of the salt formation, and not necessarily of the type of formation.

5.4 Radiological Consequences Analysis

The German site selection act for a repository for vitrified HLW and SNF demands the consideration of all kinds of suitable host rock formations for deep geological disposal. One of the eligible and presently investigated host rock formations is bedded rock salt. Within the framework of the national R&D project

KOSINA (conceptual design, safety concept and safety demonstration for a generic repository in bedded salt in Germany) the scientific bases for the geological characterization, safety concept, design, and safety assessment of a repository for HLW and SNF in bedded salt formations are being provided.

The current specifications governing the final disposal of HLW and SNF in Germany are defined by the Safety Requirements of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. In the context of the safety concept and the safety demonstration, the following three safety principles of the Safety Requirements should be stressed:

- The radioactive and other pollutants in the waste must be concentrated and contained in the CRZ, and thus kept away from the biosphere for as long as possible.
- Final disposal must ensure that in the long term, any release of radioactive substances from the final repository only negligibly increases the risks associated with natural radiation exposure.
- The final repository shall be constructed and operated in such a way that no intervention or maintenance work is required during the post-closure phase to ensure the reliable long-term containment of the radioactive waste in the containment providing rock zone.

Therefore, the key elements of the KOSINA safety concept and safety demonstration are the isolation and the containment of the radioactive waste in a deep geological repository. Isolation is mainly provided by the depth of the repository. Containment is provided by the CRZ and the integrity of the CRZ in the long-term. For those areas of the CRZ which are penetrated due to the construction of the repository, an adequate technical sealing system must be provided. If it is possible to prove safety in accordance with the Safety Requirements by a simplified radiological statement, thus relying only on the containment capacity of the host rock plus geotechnical barriers, near-surface processes are not considered to be safety relevant.

The German Safety Requirements state that a simplified radiological long-term assessment without modeling the dispersion of substances in the overburden and adjoining rock is permissible if the radioactive substances released from the CRZ do not exceed a certain maximum which is considered negligible. This ensures that only very small amounts of contaminants may be released. Radiological safety indicators shall be calculated using an established generic exposure model under certain assumptions. To implement the specifications in the Safety Requirements for a radiological indicator the RGI (Radiologischer Geringfügigkeits-Index (index of marginal radiological impact)) was applied.

In the KOSINA project the numerical simulations for the long-term performance assessment of the repositories were conducted with the tool RepoTREND (Transport and REtention of Non-decaying and Decaying contaminants in final REPOsitory), developed by GRS since 2007. The integrated software package provides functionalities for simulating the release of contaminants and their transport through the repository (near-field model), release and transport of radionuclides in the overburden (far-field model) as well as the estimation of the radiological consequences for man and environment (biosphere model), as illustrated in Figure 5-6.

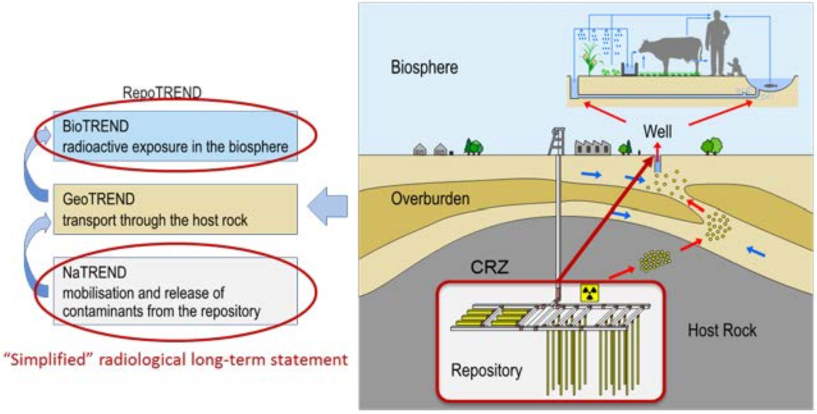


Figure 5-6. Features of RepoTREND model and applications to simplified radiological long-term statement.

Mobilization, retardation and advective-diffusive transport of contaminants as well as creep closure of mine openings were considered. Important parameter uncertainties (particularly regarding compaction of crushed salt and diffusion processes) were handled by parameter variations. Preliminary test cases enabled stepwise and iterative optimization of the repository design. To obtain information on the robustness of the system "what-if" cases were also included in the performance assessment.

The simulation period amounts to 10 million years, which is more than the required demonstration period of 1 million years. The modeled repository structure includes shaft seals 100 m long, sealing of the access drifts with wetted crushed salt and concrete barriers, an infrastructure area that is backfilled with highly porous gravel, and dry crushed salt backfill in emplacement areas and all remaining mine openings. A failure of all geotechnical seal (concrete) after 50,000 years is presumed, eventually resulting in continuous brine intrusion and radionuclide mobilization.

The modeling results of the radiological safety indicator RGI over time for the base case scenario of drift disposal are shown in Figure 5-7. The calculations show that inflowing brine slowly reaches the disposal areas after the designed functional time of the shaft and drift seals (50,000 years) eventually leading to a release of nuclides from the CRZ. The calculations yield an RGI of a mere 10^{-6} after 1 million years for radionuclide release in the liquid phase. Even after the full simulation period of 10 million years the RGI increases to only about $3 \cdot 10^{-3}$, which is still much below RGI of 1, where a safe containment of the radionuclides within the CRZ is demonstrated.

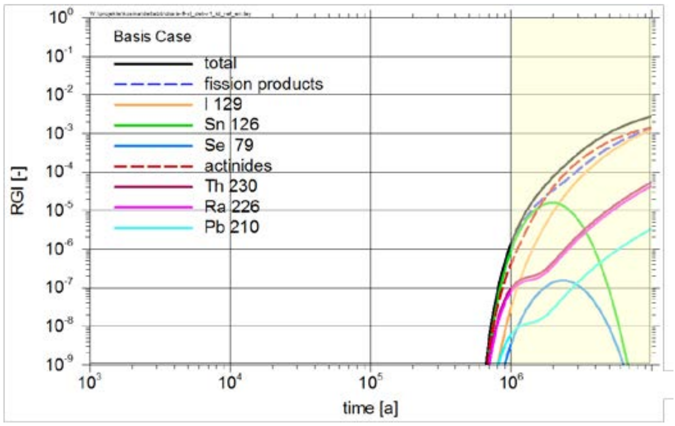


Figure 5-7. Radiological consequences (RGI) for base case scenario of drift disposal concept.

Supplementary to the analysis of base case scenarios extensive case studies were performed. These model calculations included preliminary test cases, where design parameters were tested in advance of the final repository layout, parameter variations for sensitivity studies, as well as “what-if” cases, in order to gain better understanding about the particular processes affecting the modeled repository system.

In summary, it can be stated that the consequence analysis for the base case scenarios, the investigated test cases, and “what-if” cases regarding a radionuclide release in the liquid phase cover a wide range of possible system evolutions and parameter distributions and are based on very detailed and profound process knowledge. All calculations show RGI values several orders of magnitude below the criteria set out in the Safety Requirements.

The results of the R&D project KOSINA provide evidence that a safe HLW-repository in a bedded salt formation with a suitable geological structure is feasible and its long-term safety can be demonstrated according to the state of the art in science and technology. This statement depends, however, on several generic assumptions which will have to be confirmed by comprehensive site-specific investigations. In spring 2018 the KOSINA-project will conclude and a synthesis report and technical appendices will be published.

6 OPERATIONAL SAFETY

6.1 WIPP

The Waste Isolation Pilot Plant had two events occur in February 2014 that will forever change the way the facility is operated and maintained.

On Wednesday, February 5, 2014, at approximately 10:45 Mountain Standard Time, an underground mine fire involving an EIMCO Salt Haul Truck (74-U-006B) occurred. There were 86 workers underground in the facility when the fire happened. All workers were evacuated, while six workers were transported to the Carlsbad Medical Center for treatment for smoke inhalation and an additional seven workers were treated on-site (US DOE, 2015).

An accident investigation board (AIB) was appointed to investigate the fire incident and was led by Ted Wyka. In his summary of the fire incident, Wyka presented the following as some of the contributing causes of the fire (Wyka, 2014):

- Nuclear Facility vs. Mine Culture: Difference in expectations between waste handling and non-waste handling vehicles
- Operability and recognition of impaired critical safety equipment
- Ineffective training and drilling
- Unreasonable expectations and uncertain capabilities of the Facility Shift Manager to manage all aspects of an emergency or abnormal event
- Maintenance, Emergency Management/Preparedness Programs and (nuclear waste partnership (NWP) contractor assurance system and Carlsbad Field Office (CBFO) oversight were evaluated as ineffective.
- Inadequate DOE Headquarters oversight

On Friday, February 14, 2014, there was a second incident in the underground, which resulted in release of americium and plutonium from one or more transuranic waste containers into the mine and the environment. The release was detected by an underground continuous air monitor and then directed through high-efficiency particulate air (HEPA) filter banks located in the surface exhaust building. However, a measurable portion bypassed the HEPA filters through leaks in two ventilation system dampers and was discharged directly to the environment from an exhaust duct. No personnel were determined to have received external contamination; however, 21 individuals were identified through bioassay to have initially tested positive for low level amounts of internal contamination as of March 28, 2014. Trace amounts of americium and plutonium were detected off-site (US DOE, 2015).

An AIB was appointed to investigate the radiological release event, also led by Ted Wyka. The summary of this AIB was captured in two reports which are both summarized in US DOE (2015):

The Radiological Event AIB identified the systemic root cause as the Los Alamos Field Office and National Transuranic Program/CBFO failure to ensure that Los Alamos National Laboratory (LANL) had adequately developed and implemented repackaging and treatment procedures that incorporated suitable hazard controls and included a rigorous review and approval process. The Los Alamos Field Office and CBFO did not ensure the adequate flow down of the Resource Conservation and Recovery Act and other upper tier requirements, including the WIPP Hazardous Waste Facility Permit, Attachment C, Waste Analysis Plan, WIPP Waste Acceptance Criteria, and the LANL Hazardous Waste Facility Permit requirements into operating procedures at LANL.

6.1.1 Focus of Recovery

Following the events, remedial action focused on recovery of the facility with an added emphasis on safety culture. The WIPP Recovery Plan, Revision 0 (September 30, 2014) produced by the DOE highlighted recovery actions that were to take place, with safety as the number one priority.

As pointed out by the AIB findings (US DOE, 2015), the nuclear safety documentation and safety management programs needed revisions and revitalization. DOE has numerous nuclear facilities around the country that have expertise with nuclear safety documentation and safety management programs, those facilities were called upon to aid WIPP in the effort to correct AIB findings. DOE and the WIPP Management and Operating contractor NWP spent considerable resources to improve the safety management programs and nuclear safety documentation.

The recovery plan (US DOE, 2014) pointed to improvements and changes at the facility that would be necessary to return to operations. The facility was in a very different operational capacity than it was prior to the events. During the events, underground ventilation shifted from unfiltered to filtered mode, reducing air flow from approximately 425,000 to 60,000 cubic feet per minute. Restricted ventilation was immediately identified as an area that required attention because air flow governs how many different operations could occur in the underground. Management decided that filtered ventilation needed to be increased, as the repository was to remain in filtration mode following the radiological event. Two projects were identified to produce additional ventilation. One was termed the interim ventilation system (IVS) which would add fan and filter banks to the ventilation system allowing for an increase in filtered air. The IVS was necessary to return to waste emplacement operations. An additional system, the supplemental ventilation system, was developed to produce ventilation required to return to mining in the WIPP underground. The IVS is now operating at the site and the supplemental ventilation system is going through readiness reviews to begin operating. These systems were neither designed nor intended to provide a long-term solution to WIPP ventilation needs. Two capital asset projects were proposed and started to produce a long-term solution. The different ventilation plans are explained in the recovery plan (US DOE, 2014).

In addition to limited ventilation, WIPP underground access was constrained due to concerns of radioactive contamination. These two limitations controlled the amount of work that could be performed. Mine stability operations (bolting of the host rock) were not performed for almost 9 months following the events. Before the events, rock bolting was a daily operation because salt continues to deform into excavations.

Overall, the WIPP site had numerous processes, procedures, documents, equipment, and systems that needed significant work to address shortcomings that led to the events (US DOE, 2014).

6.1.2 Ground Control Issues

As noted, ground control is continuous at WIPP. The WIPP site is different than production mines with similar host rock in that much of the underground was mined with the intention of being open and maintained for an extended period. Ground control activities and measures are taken to maintain open areas to allow work to be performed in a safe configuration. Following the events, routine ground control activities were not possible for almost 9 months. Thus, the condition of the underground deteriorated. Prior to the events, ground control at WIPP could be classified as "in maintenance mode" or "caught up." Following the extended lapse of ground control activities, much of the WIPP underground was beyond routine maintenance and was in "catch up" mode.

The recovery plan (US DOE, 2014) points to the importance of mine stability and identifies a plan to recover a stable configuration. Problems with the recovery plan included limited ventilation, ongoing issues in the underground (e.g., hoist outage, volatile organic compounds concerns, radiological contamination), lessened ground control activities efficiency. Bolting now must proceed in a perceived contaminated environment, requiring new training, new procedures, and additional personnel.

Reduced ground control efficiency led to additional prohibited areas due to mine stability concerns. The longer prohibited areas remained inaccessible, the more structural instability developed. Degradation was manifested by rock fall in September, October, and November of 2016 (Figure 6-1, Figure 6-2, and Figure 6-3).

Figure 6-1. Roof fall in WIPP Panel 4 access drift (WIPP Update Oct 3, 2016).

Figure 6-2. Roof fall in WIPP Panel 3 access drift (WIPP Update Oct 5, 2016).

Figure 6-3. Roof fall in WIPP Panel 7 Room 4 (WIPP Update Nov 4, 2016).

Following the first two roof falls, a controlled withdrawal from the south end of the WIPP underground was implemented in October 2016 (WIPP Update Oct 14, 2016). Lack of ground control efficiency resulted in loss of disposal area. Following these roof falls, DOE and NWP declared ground control the number-one priority moving forward into resumption of operations.

6.1.3 Resumption of Operations

As ground control operations remained the number-one priority, there was also a concentrated effort toward resolving all findings from the AIB reports with the goal of resuming operations. In the fall of 2016 two independent, different readiness activities were performed to evaluated if WIPP was prepared to resume operations.

In October 2016, a Contractor Operational Readiness Review (CORR) was performed by an independent group (WIPP Update Dec 23, 2016). The CORR encompassed all aspects of the restart of the contact-handled waste emplacement operations at WIPP and provided DOE and CBFO with an independent assessment of NWP’s readiness to commence contact-handled waste emplacement operations. The CORR report identified several pre-start and post-start findings but concluded that waste emplacement operations could proceed safely once the pre-start findings were resolved and all prerequisites were completed. The full CORR report is available at http://www.wipp.energy.gov/Special/WIPP_CORR_Final_Report.pdf.

Additionally, the DOE Operational Readiness Review (DORR) performed another independent evaluation of the WIPP site to determine if it was capable of safely resuming waste emplacement operations (WIPP Update Dec 23, 2016). The DORR team concluded that upon satisfactory closure of the pre-start findings and approval of corrective action plans for the post-start findings, WIPP can safely restart waste emplacement in accordance with DOE standards. The full DORR report is available at http://www.wipp.energy.gov/Special/WIPP_DORR_Final_Report.pdf.

On December 23, 2016, DOE authorized NWP to resume waste emplacement operations. This decision confirmed that all pre-start corrective actions identified in the two operational readiness reviews had been completed and properly validated and other required actions were completed (WIPP Update Dec 23, 2016). Waste emplacement activities resumed in January 2017, shortly after this approval.

WIPP received its first waste shipment since the February 2014 events on April 10, 2017 (WIPP Update April 10, 2017). This shipment represented WIPP returning to limited operations of both emplacement and waste receipt. Due to the limited ventilation, ground control issues, and contamination, shipment rates are not expected to approach pre-event rates until the two capital asset projects (the permanent ventilation projects) are completed.

6.1.4 Path Forward

The WIPP has a plan and path forward to resuming full operations. The plan forward for emplacements and mining activities illustrated in Figure 6-4 was laid out in the Town Hall meeting on March 16, 2017, http://www.wipp.energy.gov/wipprecovery/Presentations/Town_Hall_Slides_03_16_17.pdf.

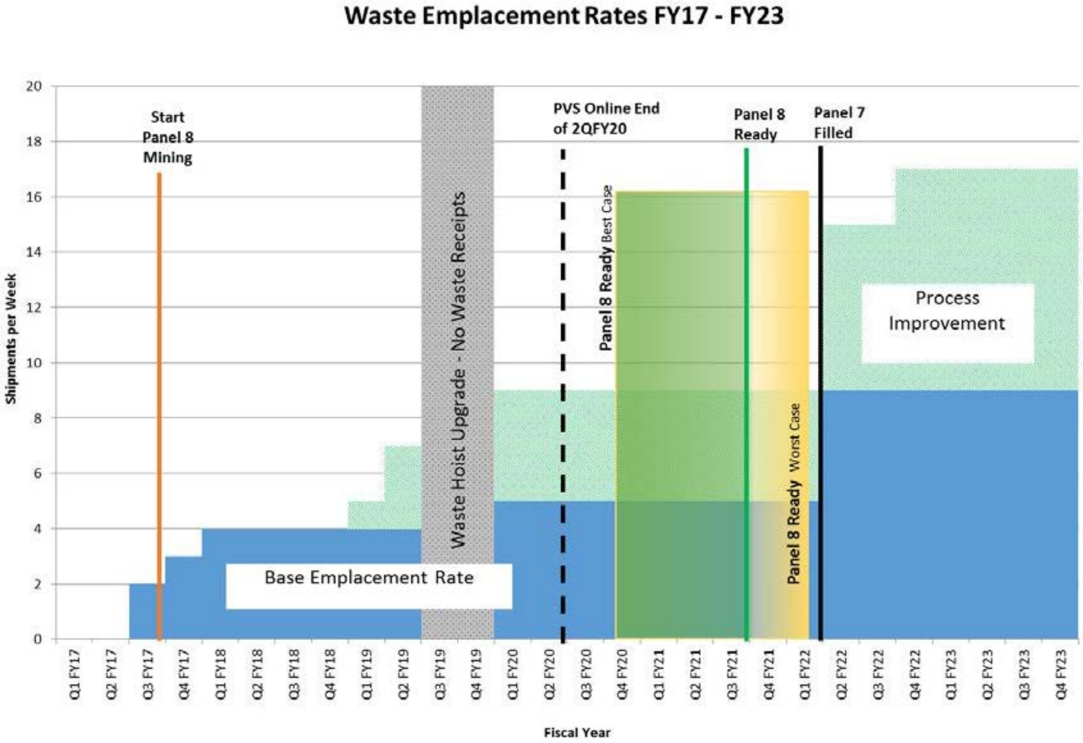


Figure 6-4. WIPP Mining and Emplacement Model.

The two capital asset projects' schedules were identified at the Town Hall meeting on September 28, 2017 (Figure 6-4), http://www.wipp.energy.gov/wipprecovery/Presentations/Town_Hall_Slides_09_28_17.pdf.

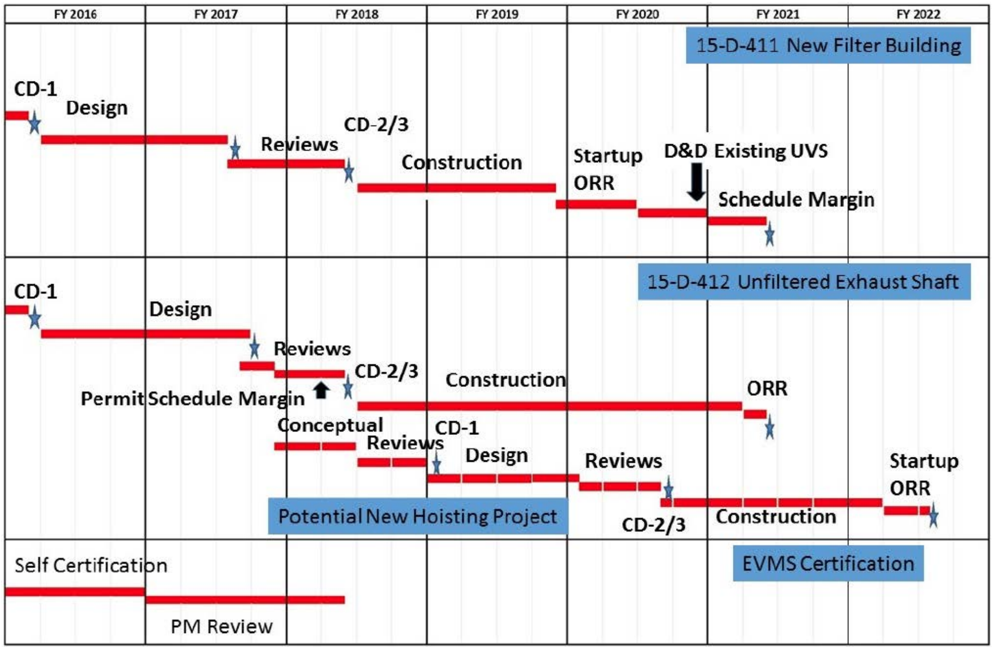


Figure 6-5 New Underground Filtration System/Shaft.

As can be seen by these two figures, WIPP is expected to resume full operations in fiscal year 2022 (FY22), 8 years after the events in 2014.

6.1.5 Summary

The path to limited operations at WIPP has been successful, notwithstanding many learning opportunities along the way. As pointed out in the AIB reports, there were many operational deficiencies precipitating the events, some of which developed over the operational period of the facility. A growing dichotomy of culture evolved between nuclear facility practice and conventional mining. The focus of operations as well as contractor incentives were on rate of waste emplacements/shipments processed per year. This led to production focus that often-overlooked operational maintenance of critical safety equipment. The training and oversight programs were found to be lacking as well.

The WIPP site enjoyed over a decade of incident free, productive operations. As was evident by the AIB reports, complacency in operations, facilities, and oversight increased over time. Following the events, DOE focused on nuclear safety and ground control was inadequate. Limited operations have now successfully resumed and continue to increase with gained efficiencies. A path to full operations has been identified with progress being made. WIPP operations expect to regain full functional capability, but will always have the reminder of lessons learned, which forever changed the way the facility is operated and maintained.

6.2 Interaction between Operational Safety and Long-Term Safety (Project BASEL)

The need to ensure operational safety including radiation protection during the operational phase will require specific measures that influence the design and operational planning of a deep geological disposal facility. Contrary to other nuclear or industrial facilities, the implementation of a repository must comply with additional requirements because post-closure safety must be guaranteed for hundreds of thousands of years. In a safety case, a comprehensive set of safety arguments must be compiled and the operator’s confidence in the operational and long-term safety of the disposal facility must be demonstrated and communicated. The documentation and communication of the different safety assessments for the operational and post-closure phases are fundamental tasks of the safety case, which should include the assessment and documentation of the interactions between operational safety and post-closure safety.

Fundamental objectives of the operational safety are the protection of personnel and the environment, with a focus on the operating personnel. Moreover, the operator must demonstrate that the state of the facility at the time of closure will be compatible with the legal requirements for long-term safety. For both, a comprehensive system analysis of the features, events, and processes (FEPs) during the operational phase is necessary.

In the German R&D project BASEL, a FEP catalogue for the operational phase was developed based on the national disposal concepts for clay and salt. The FEP catalogue contains analyses of the processes and events that affect the components (features) of the repository system in its entirety. It was used to identify and document a) hazards for the operational phase, b) the initial state of the repository’s post-closure phase, and c) the impacts of the FEP on and consequences for post-closure safety.

7 SPECIAL TOPICS

After the session on operational safety, there was a final session on special topics of interest to the Workshop attendees that included: a summary of the Actinide Brine Chemistry (ABC salt) meeting, ongoing collaborations between SNL and GRS on regional groundwater flow, and a German perspective regarding deep borehole disposal.

The first talk was given by Don Reed from LANL, in Carlsbad, New Mexico (co-author Marcus Altmaier from Karlsruhe Institute of Technology - Institute for Nuclear Waste Disposal (KIT-INE). It was a summary of the March 2017 ABC Salt (V) workshop in Ruidoso, New Mexico. Don presented results from each of the major sessions at ABC Salt, including a WIPP progress update, international actinide chemistry updates, microbial effects, corrosion and sorption, modeling and solubility studies, temperature effects, and the redox of actinide chemistry.

The second talk was jointly given by Anke Schneider (GRS) and Kristopher Kuhlman (SNL). This presented ongoing work to simulate basin-scale density-dependent groundwater flow in the non-salt sediments above the WIPP site. The presentation gave background material on the model that is being implemented (Corbet, 2000). Anke presented a summary of the capabilities of d^3f++, and progress that has been made implementing the WIPP case. Kris presented the capabilities of PFLOTRAN and the progress made by SNL re-implementing the problem. Both presenters agreed the comparison is difficult because the domain is a large area and the geologic units have extreme aspect ratios and permeability contrast. Even though both simulators have extensive parallel capabilities, the time steps required to simulate both a free surface and density dependent flow require make the long simulation time (24,000 years) difficult. The presenters agreed to work on simpler test cases in the coming year and work their way up to more complex and realistic cases.

The third and final talk was given by Tino Rosenzweig (TU-BAF) on the German perspective about deep borehole disposal. He briefly summarized recent research on the topic by SNL and SKB. The presentation outlined several engineering considerations considered to be challenges, including: storage and emplacement of waste packages in a liquid, confirmation of the impermeability of the casing and cement, waste package accident scenarios that require fishing, sealing of the borehole, and retrievability. Tino presented some preliminary results indicating a large number of boreholes (at both 44.5 cm and 91.4 cm diameter) would be needed to dispose of the entire German radioactive waste inventory. He also illustrated that the larger diameter borehole would require additional technology development.

8 CONCLUDING REMARKS

As can be appreciated from the content of these Proceedings, discovery and progress continue via sustained partnering of international colleagues. In addition to the summaries of individual chapters, presentations and abstracts (as provided) are also included in the Appendices. These Proceedings afford ready access to resources, references, data plots, computer output, photographs and summaries for persons interested in salt repository research, design, and operation. The science and technology developed in these collaborations pose enormous potential, because salt repositories can solve waste disposal issues in the long-term and at a large-scale.

The next US/German workshop will be hosted by the BGR in Hannover Germany in September 10-11, 2018 in the two days preceding SaltMechIX—the ninth conference on the mechanical behavior of salt (*https://www.saltmech.com)*. SaltMechIX is organized jointly by the BGR (Hannover), the IfG (Leipzig), and the TUC. These two salt-specific technical meetings are organized independently, but coordinating the US/German workshop on salt repository research, design and operation with SaltMechIX helps reduce time and travel costs. SaltMechIX publishes a traditional hard-cover book including reviewed papers from each contributor associated with the conference, and their preparations are well underway.

Topics to be considered for the next US/German workshop have also been identified, though details will be sorted out by workshop leadership. It is worth noting personnel changes that have been made to the US/German workshop leadership. In the past few years, Walter Steininger, Wilhelm Bollingerfehr and Frank Hansen have organized the sessions, solicited contributions, and invited certain persons for special contributions. In 2018, contents of the workshop will be organized by Wilhelm Bollingerfehr, Sean Dunagan (replacing Frank Hansen), Michael Bühler (replacing Walter Steininger), and Sandra Fahland on behalf of BGR.

Topics to be developed for the US/German workshop may be modified depending upon formal contributions to SaltMechIX, but certainly an update of the WEIMOS collaboration remains a central theme. Similarly, comparison of bedded, pillow, or dome salt formations is contemporary in the US and Germany; therefore, conclusions resulting from the project KOSINA could influence decisions made in the US. Several workshop participants advocated for a break-out session on geotechnical seals in salt. There are many sealing strategies vitally important to salt repositories, including ongoing work in reconsolidation, use of salt blocks, consideration of geotechnical stability, cement-based materials, construction methods, and operational and long-term performance.

To ensure continuity of the US/German workshop and production of the Proceedings, it was mutually decided that the host organization assume responsibility for producing the Proceedings. For 2018, colleagues at the BGR have accepted this responsibility. To assist in this compilation, we have conventionally asked subject matter experts to summarize specific technical issues that comprise chapters of the Proceedings. Chapter authorship is also organized near the close of each workshop. The 2018 Proceedings document would be a BGR report, in a manner appropriate to their procedures. In the subsequent year, presumably held in the US, the host would assume this responsibility. The international community provides several websites on which the Proceedings can be stored, such as BGR, NEA, SNL, RESPEC or other sites to be determined.

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APPENDIX A: AGENDA

Final Technical Agenda

8th US/German Workshop on Salt Repository Research, Design, and Operation, COVRA Premises

September 4 – Monday, NEA Salt Club Meeting same venue

September 5 - Tuesday

Day 1	8:00-08:30	**Registration**	
	08:30-08:45	**Kick off** and organizational details	F. Hansen, USA M. Bühler, PTKA W. Bollingerfehr, DBE TEC
	08:45-09:00	Welcome COVRA	E. Verhouf, COVRA
	09:00-09:15	Welcome BMWi	H. Wirth, BMWi
	09:15-09:30	Short Report on SC meeting	J. Mönig, GRS
	09:30-10:00	IAEA repository studies	A. Orrell, IAEA
	10:00-10:30	**Break** and ***<u>Group Photo</u>***	
	Developments in National Programs (chair: S. Mayer-IAEA)		
	10:30-11:00	Dutch Waste Management Strategy	E. Verhoef, COVRA
	11:00-11:30	Welcome DOE and Summary of US WM status	T. Gunter, DOE
	11:30-12:00	German Waste Management Strategy	T. von Berlepsch, DBE TEC
	Safety Case Issues (chair: W. Steininger, KIT)		
	12:00-12:30	Netherlands Safety Case experiences OPERA	N.N., NRG
	12:30 13:30	**Lunch**	
	13:30-14:00	PA Codes comparison: PFLOTRAN & RepoTrend	D. Becker, GRS, J. Frederick, SNL
	14:00-14:30	Uncertainties in SC	D. Becker, GRS,
	14:30-15:00	FEP-matrix and database	G. Freeze, D. Sevougian, SNL, J. Wolf, GRS
	15:00-17:00	*Tour of Flood Museum*	
	18:00	*Workshop Dinner at Restaurant Vierbanne*	

Final Technical Agenda

8th US/German Workshop on Salt Repository Research, Design, and Operation, COVRA Premises

September 6 – Wednesday

Day 2	**Geomechanical Issues (chair: M. Bühler; KIT)**		
	9:00-09:30	Invited Lecture: Salt Creep at Low Deviatoric Stress	P. Berest, France
	09:30-10:00	Current status of research in the Joint Project WEIMOS	A. Hampel, Hampel Consulting; T. Popp, IfG; K. Herchen, TU Clausthal
	10:00-10:30	Salt testing: Low deviatoric stress and shear	S. Buchholz, RESPEC
	10:30-11:00	New results of the KOSINA project	T. Popp, IfG, N.N., BGR, E. Matteo, SNL
	11:00-11:30	**Break**	
	Geomechanical Issues contd´(chair: F. Hansen)		
	11:30-12:00	New developments in KOSINA - Modelling	J. Kindlein, GRS
	12:00-12:30	Outcome of the Repoperm Project	K.-P. Kröhn, GRS
	12:30-13:30	**Lunch**	
	13:30-14:00	Reconsolidation of granular salt (DAEF report)	K. Wieczorek (GRS), BGR, DBE TEC, IfG, TU Cl
	14:00-15:00	**Breakout Session**	
		Reconsolidation of salt backfill material	K. Kuhlmann, SNL, T. Popp, IfG, K. Wieczorek, GRS, F. Hansen, USA, N. Müller-Hoeppe, DBE TEC
	15:00-15:30	**Break**	
	Repository Design and Operational Safety (chair: W. Bollingerfehr, DBE TEC)		
	15:30-16:00	Project BASEL (Interaction between OS and LTS)	J. Wolf, GRS
	16:30-17:00	Repository design in bedded salt (KOSINA)	W. Bollingerfehr, DBE TEC
	17:00	*Adjourn for the day –* *no scheduled group activity*	

Final Technical Agenda

8th US/German Workshop on Salt Repository Research, Design, and Operation, COVRA Premises

September 7 – Thursday

08:30	**Repository Design and Operational Safety (chair: W. Bollingerfehr, DBETEC)**		
	08:30–09:00	The regulator's perspective of DOE's 2014 certification application for WIPP"	K. Economy, EPA
	09:00-09:30	WIPP recovery and Operational Safety	S. Dunagan, SNL
	09:30-10:00	WIPP Future Advancements and Operational Safety	R. Whisenhunt, NWP
	10:00-10:30	Sandia's Salt Design Concept for HLW and DSNF	E. Matteo, SNL
	10:30-11:00	**Break**	
	Special Topics (chair: K. Kuhlman, Sandia)		
	11:00-11:30	Actinide and brine chemistry in salt repositories	D. Reed, LANL M. Altmaier, KIT/INE
	11:30-12:00	Groundwater Models of WIPP	A. Schneider, GRS, K. Kuhlman, SNL
	12:00-12:30	German VDB-project CREATIEF	T. Rosenzweig, TU BAF,
	12:30-12:45	Wrap up and outlook	Organizers
	12:45-14:00 14:00 – 16:00	**Lunch** ***Visit Storage Facility (optional)***	

APPENDIX B: WELCOME ADDRESSES:

Mr. Wirth

BMWi Address for 8th Annual Workshop September 5, 2017

Ladies and Gentlemen,

On behalf of the Federal Ministry for Economic Affairs and Energy (BMWi), I would like to welcome you to our eighth US-German Workshop on Salt Repository Research, Design, and Operation. It is a great pleasure to have the workshop in the Netherlands, and we appreciate it very much that our Dutch colleagues from COVRA agreed to hosting it here. Moreover, our Dutch colleagues are esteemed regular attendees of our workshops. We are very grateful as well for all the organizational efforts that went into preparing for this workshop.

As in previous years, the workshop has been jointly organized by Sandia National Laboratories, DBE-Technology and the Project Management Agency Karlsruhe. I would like to thank Ms. Marianne Cornet from COVRA in her capacity as the local organizer, Mr. Frank Hansen and Ms. Laura Connolly from the US, and Mr. Wilhelm Bollingerfehr, Mr. Walter Steininger and Mr. Michael Buehler from Germany for their hard work and dedication in preparing for this workshop.

Ladies and Gentlemen,

Our cooperation is based on a Memorandum of Understanding between the US Department of Energy (DOE) and the German BMWi. Moreover, it is based upon the people involved in this work, their commitment, and the close and excellent relationships – both on a personal and a scientific and technical level – that have evolved over the past few years. It is already a tradition to keep this workshop open to other interested countries as well. Our Dutch colleagues, in particular, have made many valuable contributions to our discussions and, this year, they have invited us to hold our workshop here in Middelburg. I would therefore like to extend a very special welcome to Mr. Ewoud Verhoef, the Deputy Director of COVRA. And I would also like to welcome Mr. Timothy Gunter from the Office of Nuclear Energy within the US Department of Energy. In addition, I would like to welcome Mr. Andrew Orrell and Mr. Stefan Mayer from the International Atomic Energy Agency (IAEA).

Ladies and Gentlemen,

The fact that this workshop is being attended by high-ranking representatives from the US, Germany and the Netherlands and as well those from the IAEA shows how important our bilateral research cooperation is to our countries. This cooperation is still considered topical, of high importance, and is greatly appreciated. Once again, this workshop is bringing together nearly sixty salt experts. They will be updating each other on the latest developments in their work. Our annual workshop is well-established and has become a showcase for US-German cooperation. The outcomes of the workshop discussions will certainly provide valuable input for new research activities.

Ladies and Gentlemen,

It might be of interest for you to learn about the changes and new developments that have taken place in Germany since the last workshop in Washington, and about how these changes are influencing our work. Since we met last year, the regulatory and organizational framework for future nuclear waste disposal in Germany has further evolved. Two independent bodies, the Commission for the Storage of High-Level Radioactive Waste (Repository

Commission) and the Commission to Review the Financing for the Phase-out of Nuclear Energy (KFK) concluded their work in 2016. Their recommendations were used in the process of drafting new regulations and putting in place new procedures. The Act Reorganizing Responsibility for Nuclear Waste Management (VkENOG), drafted under the leadership of the Federal Ministry for Economic Affairs and Energy, regulates the financing of nuclear disposal and the organizational and management structure as well. It entered into force on June 16, 2017. The Repository Site Selection Act (StandAG), drawn up under the leadership of the Federal Ministry for the Environment, defines the site selection procedure for a high-level waste repository and all the organizational procedures associated with this process. This law became effective on May 16, 2017.

Ladies and Gentlemen,

In adopting these new laws, Germany has taken an important step towards the safe disposal of nuclear waste. Moreover, Germany has now paved the way for starting the so-called unbiased selection of a suitable site for a repository for high-level radioactive waste. This will be done from scratch, starting with a blank map.

Through these two pieces of legislation, Germany has taken care of the financing for the entire disposal process, starting from the dismantling of nuclear power plants, through to final disposal.

Please allow me to give you a few more details about the content of the two pieces of legislation.

Under the Act Reorganizing Responsibility for Nuclear Waste Management (VkENOG), the various responsibilities for disposal have been assigned and the financing of the decommissioning and dismantling of nuclear power plants and the interim and final storage of nuclear waste secured. The Act will prevent any situation whereby costs would be shifted towards society, and avoid any undue economic burden being placed on operators as well. More specifically, this means that:

- Operators will continue to be responsible for managing and financing all activities linked to the decommissioning and dismantling of the plants and for competent packaging of radioactive waste. The companies have already made adequate provisions for this. If necessary, they will also have to foot the bill for any additional costs.
- The government is in charge of interim storage and final disposal. The funding required for this, a grand total of 24.1 billion euros, was provided by the operators and transferred into a dedicated fund on July 1, 2017.

The Repository Site Selection Act (StandAG) sets out the following requirements for the siting process:

- The waste is to be disposed of within the territory of Germany, in a deep geological repository in rock salt, clay stone or crystalline rock.
- The repository is to be sealed off permanently, but in a way that allows retrievability of the waste during the entire operational phase and, in case of unforeseen circumstances, the possibility of recovery at any time during a 500-year timespan following the sealing of the repository.
- A comparative procedure is to be used to select the site with the best safety for a compliance period of one million years.
- The site selection process is to be a participative, scientific, transparent, self-learning and self-reviewing procedure.
- There are detailed provisions concerning the organizational structure of those relevant bodies to guarantee that the general public can participate in the process at regional and national level.

Ladies and Gentlemen,

Another key point intensively discussed within both commissions was the structure of the responsible organizations. It was agreed that there will be a new supervisory authority, the Federal Office for the Safety of Nuclear Waste Management (Bundesamt für kerntechnische Entsorgungssicherheit, BfE), and a new operating firm, the implementing body, owned by the Federation, the Federal Final Disposal Company (Bundes-Gesellschaft für Endlagerung, BGE). The responsibilities for operating interim storage facilities have also been reassigned to the Federal Interim Storage Company (Gesellschaft für Zwischenlagerung, BGZ). These are the interim storage facilities Gorleben and Ahaus and the interim storage facilities at the nuclear power plant sites. The BGE and the BGZ are currently being established and will be subordinate to the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Both new organizations will draw on expertise that is already available. The Federal Final Disposal Company will be created by merging parts of DBE, the company Asse, and a part of the Federal Office for Radiation Protection. The Federal Interim Storage Company will be formed from former parts of the Nuclear Service Company (Gesellschaft für Nuklear-Service or GNS).

You will hear more about the procedure to be used in the site selection process and about the overall organizational structure from Mr. von Berlepsch, who will speak about the German Waste Management Strategy.

Ladies and Gentlemen,

So, what does this mean for our future joint research? First of all, it means that we will continue to rely on broad-based scientific support and international networks and expertise as we proceed with organizing the disposal of high-level waste. Still of high priority is the further development of the state-of-the-art research into disposal and building the scientific and technical basis for constructing and operating a final repository. This means that we need to continue to do work in these fields, build new skills, and train and educate the next generation of researchers. In the context of our workshop-related work, it means that we must continue to do research into rock salt, for instance address and resolve questions that are still open, and deal with issues regarding a repository in bedded salt. This is one of the fields where we can greatly benefit from our cooperation with the US, a country that has long-standing experience in rock salt, among other things, from its experience with operating the Waste Isolation Pilot Plant (WIPP).

Ladies and Gentlemen,

Discussions here in Middelburg also serve to foster technological and scientific development in the various areas covered in this workshop. Key issues are the safety case and geomechanics, which have been, and will continue to be topics of high importance. Another very important point is operational safety. We will hear more about that tomorrow. This is a highly complex issue that is becoming increasingly important in the context of those programs that will soon enter the licensing phase. The joint BASEL project will address this issue and we will hear a little about this project in the presentation from Mr. Jens Wolf. Moreover, we will need to continue the activities related to questions on sealing a final repository. Most of this work will continue to take place under the ELSA project. Let me use this opportunity to say a few words about the joint WEIMOS project, which is being conducted by American and German colleagues in close cooperation. The project comprises joint lab work and modeling by different programs. The results of the lab work are being used to develop models of materials and modeling techniques for a final repository in rock salt. For this purpose, Sandia National Laboratories has provided seventeen drill core samples from the WIPP. These samples have a combined length of approx. 10.5 meters and weigh 1.6 tons and are being used to study rock healing and creep under low deviatoric stresses. The tests are being conducted at Clausthal University of Technology, the Institute of Geomechanics Leipzig and the Federal Institute for Geosciences and Natural Resources (BGR). The scientists are also jointly working on work packages designed to provide new insights into tensile stress and on modeling work based on a virtual demonstrator. The presentation by Mr. Andres Hampel will show the latest results from the WEIMOS-project.

Ladies and Gentlemen,

We are convinced that the joint US-German research and development activities provide important and excellent contributions to better understanding the properties of rock salt. Furthermore, they help us to think about and discuss new issues of mutual interest. We are convinced that these results contribute very well to the objectives of the research concept of the Federal Ministry for Economic Affairs and Energy.

The United States continues to be our number-one international research partner on rock salt. We are also very happy that the Netherlands regularly take part in our discussions. This is very positive because, in the Netherlands, rock salt is also being considered as a possible host rock option. Moreover, in the Dutch scientific community, there is a good level of knowledge on salt available.

Personally, I am very much looking forward to learning more about the HABOG (Hoogradioactief Afval Behandeling- en Opslag Gebouw) Storage Facility during our guided tour, and to learning about the Dutch way of dealing with radioactive waste. Once again, let me thank our Dutch colleagues for preparing and hosting this workshop.

And as far as Germany is concerned, I can only confirm that we are more than willing to share our long-standing expertise on salt as we address the challenges ahead. Our cooperation allows all partners to benefit from synergies that will help them in their own programs. We can all benefit from the findings, both in scientific and economic terms, and continue our work based on what we have already achieved. This is what makes this cooperation so valuable for all of us.

Ladies and Gentlemen,

Let me stress that the German government continues to view rock salt as a potential host for radioactive waste and that there is further need for research in this field. It is therefore my hope that our successful cooperation will continue at just the same level of intensity.

I wish us all a successful event.

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS FROM 8TH WORKSHOP

	NAME	ORGANIZATION
1	Joachim Stahlmann	TU Braunschweig
2	Jonathan Kindlein,	GRS
3	Erika Neeft	COVRA
4	Till Popp	IfG
5	Stuart Buchholz	RESPEC
6	Andrew Orrell	IAEA
7	Stefan Mayer	IAEA
8	Uwe Düsterloh	TU Clausthal
9	Jay Santillan	EPA
10	Ed Matteo	SNL
11	Pierre Berest	École Polytechnique
12	Melissa Mills	SNL
13	Tim Gunter	DOE
14	Kathleen Economy	EPA
15	Erik Webb	SNL
16	Jennifer Frederick	SNL
17	Oliver Czaikowski	GRS
18	Thilo von Berlepsch	DBE Technology GmbH
19	Anke Schneider	GRS
20	Christoph Lüdeling	IfG-Leipzig
21	Janis Trone	SNL
22	Sean Dunagan	SNL
23	Sandra Fahland	BGR
24	Jens Wolf	GRS
25	KristopherK uhlman	SNL
26	Nina Müller-Hoeppe	DBE Technology GmbH
27	Klaus-Peter Kröhn	GRS
28	Tatjana Kühnlenz	BGR
29	Ewoud Verhoef	COVRA
30	Steve Sobolik	SNL
31	Michael Bühler	PTKA
32	David Fellhauer	KIT/INE
33	Dirk-Alexander Becker	GRS
34	Frank Hansen	RESPEC
35	Kai Herchen	TU Clausthal
36	Walter Steininger	KIT
37	Stephan Bödecker	LBEG Niedersachsen
38	Wilhelm Bollingerfehr	DBE Technology GmbH
39	Andreas Hampel	Hampel Cons.
40	Bettina Franke	LBEG Niedersachsen
41	Benjamin Reedlunn	SNL
42	Holger Wirth	BMWi
43	Yildirim Savas	Leibniz Uni Hannover
44	Geoffrey Freeze	SNL
45	Marcus Altmaier	KIT-INE
46	David Sevougian	SNL
47	Klaus Wieczorek	GRS
48	Phillip Vardon	TU Delft
49	Jörg Mönig	GRS
50	Jaques Grupa	NRG
51	Karl-Heinz Lux	TU Clausthal

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APPENDIX D: BIOS

Marcus Altmaier

Dr. Marcus Altmaier has studied chemistry and received a PhD in Radiochemistry from the University of Cologne. In 2000 he joined the Institute for Nuclear Waste Disposal (INE) in Karlsruhe, Germany. Since 2012 he is Head of Radiochemistry Division of INE at the Karlsruhe Institute of Technology (KIT).

Dr. Altmaier is an expert on aquatic chemistry and thermodynamics of actinides and long lived fission and activation products. Experimental research activities focus on actinide chemistry in aqueous media (radionuclide solubility, complex formation, ionic strength effects). Dr. Altmaier is involved in several Nuclear Energy Agency (of the Organisation for Economic Co-operation and Development) related activities and is a member of the German THEREDA project team. Dr. Altmaier has a strong interest in radioanalytical techniques, actinide and fission product chemistry and the study of radionuclide solubility phenomena in dilute to concentrated salt brine systems. Dr. Altmaier has been involved in several national and international projects, ranging from fundamental scientific research on actinide chemistry to applied work related to the final disposal of nuclear waste in deep underground facilities. He is the author of several peer reviewed publications and presented his work at numerous international scientific conferences.

Dirk-Alexander Becker

Pierre Bérest

Pierre Bérest is emeritus professor at Ecole Polytechnique, Palaiseau, France. He graduated from Ecole Polytechnique and Paris School of Mines. He is the author or coauthor of 200 papers (Journals and Conference Proceedings) in the field of Continuum Mechanics applied to underground works (Plasticity, viscoplasticity, buckling, thermomechanics, thermodynamics) applied to mines, tunnels, underground storage of gas, oil, CO2 and nuclear wastes disposal.

Stephan Bödecker

Wilhelm Bollingerfehr

Diplom-Bauingenieur (M.Sc.eq) –civil engineer

Prokurist

Head of Research and Development Department

DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine

After finishing the Technical University of Hannover in Germany as a civil engineer in 1985, he gained extensive experience in the field of repository design and development of engineered barriers. As project engineer and project manager he developed concepts for technical barriers for repositories in salt and managed the construction of prototype barriers. In addition, he was responsible for developing transport and emplacement systems and components for heat generating radioactive waste, industrial demonstration test included. Nowadays, as Prokurist and head of the Research and Development (R&D) department he is responsible for a staff of some 10 scientists and engineers all of them working in RD&D projects in the field of safe disposal of heat generating waste (reprocessing waste and spent fuel). His recent work was focusing on the development of a repository design and closure measures for a high-level radioactive waste (HLW) repository in salt formations in the context of a preliminary safety case. One new challenge he is faced with is an analysis of possibilities to retrieve emplaced waste packages and to develop technical solutions for retrieval processes for HLW-repositories in salt and clay formations.

Since autumn 2012 he has the honor to give lectures on Repository Techniques at the University of Braunschweig at the Institut für Grundbau und Bodenmechanik (Institute of Geotechnics) lead by Prof. Stahlmann.

Stuart A. Buchholz

Mr. Buchholz is the manager of the Materials Testing Laboratory for RESPEC Consulting and Services in Rapid City, South Dakota, USA. He holds B.S. and M.S. degrees in Geological and Mechanical Engineering from the South Dakota School of Mines and Technology. Mr. Buchholz started his professional career at Halliburton Energy Services where he worked as a wireline logging engineer in the Gulf of Mexico for 7 years. Mr. Buchholz has been a geomechanical consultant for RESPEC for the last 12 years and has extensive experience in analyzing salt caverns that are used for hydrocarbon and waste storage, dry mine excavations in bedded and domal salt formations, and dry- and solution-mined potash excavations.

Michael Bühler

Oliver Czaikowski

Sean Dunagan

Sean manages the Special Projects and Remote Site Support department at Sandia National Laboratories (SNL) in Carlsbad, New Mexico, USA. His department engages across a range of activities at the Waste Isolation Pilot Plant (WIPP) such as ground control, the National TRU Program, performance assessment code development, and repository configuration/design. Sean previously was the Department of Energy's Senior WIPP Recovery Manager, overseeing the WIPP site recovery to resume operations following the 2014 events. Additionally, Sean has extensive experience in WIPP performance assessment as an individual contributor and a manager. Sean's education includes a BS and MS degree in industrial engineering with a focus in operational research from Texas Tech University.

Uwe Düsterloh

Degree: PD Dr.- Ing. habil.
Institution: Clausthal University of Technology
Chair: chair for waste disposal technologies and geomechanics

1982- 1988 field of study: mining engineer
1989- 1993 PhD work – geomechanical investigations on the stability of salt caverns for waste disposal
2009 Habilitation - proof of stability and integrity of underground excavations in saliniferous formations with special regard to lab tests
1989 - 2012 chief engineer at Clausthal University of Technology

Kathleen Economy

Ms. Economy has been working on nuclear waste repository issues since 1992. She has held various roles in the preparation of performance assessments for both the WIPP and the Yucca Mountain Project. In 2010 she began her role as a WIPP regulator for the US Environmental Protection Agency. She has a master's degree in Hydrology from New Mexico Institute of Mining and Technology.

Sandra Fahland

Civil engineer degree (Dipl.-Ing.) in 1997 at the Technical University of Braunschweig, Germany and Ph.D. degree (Dr.-Ing.) in 2004 at the Technical University of Clausthal, Germany. Joined the Federal Institute for Geoscience and Natural Resources, Department 3 —Underground Space for Storage and Economic Use, in 2005 as a scientist of the Sub-Department — Geotechnical Safety Analyses — Scientific background: Rock mechanics - especially salt mechanics, thermomechanical numerical analysis of underground structures, radioactive waste disposal, field measurements.

David Felhauer

Bettina Franke

Jennifer M. Frederick

Jenn Frederick is a senior member of the technical staff at SNL in Albuquerque, New Mexico, USA. She is a computational geoscientist and a PFLOTRAN developer, an open source, massively parallel subsurface simulator for multiphase flow and reactive transport in porous media. Jenn specializes in geological fluid dynamics and software engineering, and applies these skills to develop software required to model performance assessment for deep geologic repositories. Jenn earned a B.S. in Bioengineering from the University of Illinois at Chicago, a M.S. in Mechanical Engineering from the University of California, Berkeley, and a Ph.D. in Earth & Planetary Science with an emphasis in Computational Science and Engineering from the University of California, Berkeley.

Geoff Freeze

Geoff Freeze is an Engineer/Hydrogeologist at SNL in Albuquerque, New Mexico, USA. Mr. Freeze has over 30 years of professional experience in radioactive waste disposal, probabilistic risk and safety analyses, groundwater modeling, and site characterization. He has supported radioactive waste disposal programs in the US (at both Yucca Mountain and WIPP) and internationally, including 4 years as the Yucca Mountain Project Lead for Features, Events, and Processes.

Mr. Freeze has authored over 40 journal articles and project reports, taught short courses in computer solutions to groundwater problems, and written chapters on “Decision Making” and “Solute Transport Modeling” for the McGraw-Hill Environmental Handbook. He holds an M.S. degree in Agricultural Engineering from Texas A&M University and a B.A.Sc. degree in Civil Engineering from the University of British Columbia.

Jaques Grupa

Tim Gunter

Tim Gunter, US Department of Energy (DOE), is a Nuclear Engineer (B.NE 1979, Georgia Institute of Technology) with over 35 years of professional experience in nuclear related fields. He is currently a Federal Program Manager for Spent Fuel and Waste Disposition in the DOE’s Office of Nuclear Energy, where he manages a multi-million-dollar R&D program for geologic disposal of SNF and high-level radioactive waste. His previous experience includes naval nuclear reactor plant systems testing and nuclear performance assessment at the Charleston Naval Shipyard; facility startup and engineering for the DOE Savannah River Site including initial start-up of the Defense Waste Processing Facility (the first operating high-level waste vitrification facility in the US). Subsequently, with the DOE Yucca Mountain Project Office, he was the supervisor of the Regulatory Compliance Branch and the DOE licensing lead for the pre-closure safety assessment. He assisted with the completion and submittal of the Yucca Mountain High-Level Waste Repository License Application to the Nuclear Regulatory Commission, and managed the technical input to over 300 licensing contentions. He is a current Member of the American Nuclear Society.

Jörg Hammer

Jörg Hammer studied geology (Diploma) at the Mining University Leningrad/Sankt Petersburg (1977 – 1982; M. Sc. in Geology). From 1982 to 1986 he worked as scientific assistant at the Technical University Bergakademie Freiberg, Department of Mineralogy, and wrote in 1986 his Ph.D. in Geology and Geochemistry ("Geochemistry of copper shale near Sangerhausen, Eastern Germany"). He then worked at the Department of Geochemistry, University Greifswald and finalized in 1995 his habilitation ("Geochemistry and petrogenesis of granitoids in Lusatia and Erzgebirge/Ore Mountains"). From 06/1996 to 06/2002, he worked as head of project in the Geological Survey of Mecklenburg-Vorpommern and investigated geochemistry and mineralogy of quarternary sediments in connection with landfill protection in northeast Germany. Since 07/2002, he works as a senior scientist and since 2008 as the head of the subdivision "Geological Exploration" at the Federal Institute for Geosciences and Natural Resources in Hannover.

Andreas Hampel

Dr. Hampel is a physicist. After his PhD work at the TU Braunschweig about deformation micro-processes in metals and alloys, he started in 1993 at the BGR Hannover his investigation of the thermo-mechanical behavior of rock salt and the development of the Composite Dilatancy Model. In 1998 he began to work as an independent scientific consultant, since 2004 he has been the coordinator of a Joint Project series on the comparison of constitutive models for rock salt.

Frank Hansen

Since the 1970's Frank Hansen actively engaged national and international nuclear waste repository science, engineering, research, development, and demonstration. Frank began his career in 1974 at RESPEC, where he started their thermomechanical testing laboratory. His career included research in rock mechanics essential to licensing WIPP and Yucca Mountain. He has collaborated extensively internationally, including founding this modern series of US/German workshops. Frank retired as a Senior Scientist from Sandia in February 2017. He is now engaged as a Professional Associate with RESPEC, which facilitates continued involvement with international salt repository research. He is a registered professional engineer in New Mexico and South Dakota and an ASCE Fellow.

Jaap Hart

Kai Herchen

Jonathan Kindlein

Jonathan Kindlein is a scientist at Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) GmbH (GRS) Braunschweig. He's got a Diploma in Civil Engineering (emphasis Structural Mechanics) from Bauhaus-University Weimar and a Ph.D. in Civil Engineering (emphasis Reactive Transport Modeling) from Technical University Braunschweig. Jonathan has been engaged in safety assessments of RAW final repositories for more than ten years, for four years at GRS in several projects concerning process analyses and long-term safety analyses for repository systems in salt.

Klaus-Peter Kröhn

Klaus-Peter Kröhn is a senior scientist at the branch of the GRS GmbH in Braunschweig. He got a degree in civil engineering at Hannover University where he also got his PhD. His expertise covers (a) development of model concepts, formulation of mathematical models and writing of simulation codes, (b) modeling groundwater flow and solute transport, CO2 migration in deep geological formations, and bentonite re-saturation, and (c) planning, execution and evaluation of experiments concerning bentonite re-saturation, compaction of crushed salt and two-phase flow.

Kristopher Kuhlman

Kristopher Kuhlman is technical staff at SNL in Albuquerque, New Mexico, USA. His research interests include ultra-low-permeability rocks and geologic disposal of radioactive waste in mined repositories and boreholes. Kris worked for Sandia at WIPP in Carlsbad, New Mexico before working on deep borehole disposal. He now is focused on modeling, laboratory testing, and field testing related to generic salt repositories. Kris got a BS in Geological Engineering from Colorado School of Mines and a PhD in Hydrology from University of Arizona.

Tatjana Kühnlenz

Christoph Lüdeling

Karl-Heinz Lux

Edward Matteo

Ed Matteo is technical staff at SNL in Albuquerque, New Mexico, USA. Ed's research interests include fluid-mineral interfaces and reactive transport in porous media, esp. chemical durability/reactivity of cementitious materials and clay minerals. For the last few years, he has worked on engineered barrier system design and repository design for DOE-NE's *Used Fuel Disposition and Spent Fuel and Waste Science and Technology* Campaigns. Ed has a PhD in Chemical Engineering from Princeton University and a BS in Chemical Engineering from the University of New Mexico.

Stefan Mayer

Melissa Mills

Melissa Mills is a member of the technical staff at SNL, and has been involved in several experimental research initiatives in the Nuclear Waste Research and Disposal Organization at SNL for the last 6 years. Contributed projects include thermal and chemical effects on clay minerals for engineered barriers, iodide interaction with clay minerals, compacted clay pellet percolation and diffusion studies, as well as microscopic analysis of geomaterials. She holds a Master's in Civil Engineering from the University of New Mexico and was a Nuclear Energy-University Program Fellow, with research focused on the characterization of consolidated granular salt, investigating deformation mechanisms, pore structure, and substructures by microscopic examination.

Jörg Mönig

Jörg Mönig has a degree in Physical Chemistry from the Technical University of Berlin. For 30 years, he is conducting research in the field of radioactive waste disposal. In this time, he contributed to many R&D projects with experimental investigations in the laboratory and *in situ* as well as with theoretical and numerical studies. He has participated to the safety analyses both for the closure of the Morsleben Mine and of the Asse Mine. From 2004 to 2012 he led the Department Long-term Safety Analyses of GRS. Since 2013 Jörg Mönig is Head of the Repository Safety Research Division of GRS in Braunschweig, Germany.

Nina Müller-Hoeppe

Erika Neeft

Dr. Neeft is the technical coordinator of the Dutch research program into geological disposal of radioactive waste at the waste management organization COVRA (Central Organisation for Radioactive Waste (Centrale Organisatie Voor Radioactief Afval, Dutch nuclear waste processing and storage company). She holds a MSc degree in Earth Sciences from Utrecht University and a PhD in reactor physics (transmutation of nuclear waste) from Delft University of Technology.

S. Andrew Orrell

Mr. Andrew Orrell is the Section Head for Waste and Environmental Safety at the International Atomic Energy Agency where he is responsible for the development and promulgation of internationally accepted standards, requirements and guides for the safe management of radioactive waste and spent fuel, decommissioning, remediation and environmental monitoring. In addition, Mr. Orrell oversees the planning and execution of support to the International Atomic Energy Agency (IAEA) Member States for the implementation of the IAEA Safety Standards, and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

Prior to joining the IAEA, Mr. Orrell was the Director of Nuclear Energy Programs for SNL, where he was responsible for laboratory development initiatives involving all facets of the nuclear fuel cycle. He provided executive leadership for Sandia’s Lead Laboratory for Repository Systems program, managing the completion of the post-closure performance assessment and safety case for a license to construct the nation's first geologic repository for high-level nuclear waste at Yucca Mountain. Prior to working on Yucca Mountain, he managed site characterization programs for a deep geologic repository for transuranic waste at WIPP, and developed transportation optimizations for the National Transuranic Waste Management program.

With over 25 years of professional experience in nuclear fuel cycle and radioactive waste management for the U.S. and several international programs, Mr. Orrell is versed in the complex interdependencies between nuclear energy development, waste management, decommissioning, remediation and disposal. Mr. Orrell routinely advises government and industry leaders on the technical and policy implications for radioactive waste management, including repository development and licensing, national policy development and regulation, site characterization and safety case development, storage, transportation, and the securing of public confidence.

Teresa Orellana-Perez

Till Popp

Dr. Till Popp is a mineralogist working since 1986 in the field of hydro-mechanical rock investigations at a lab or field scale. Since 2003 he is appointed at the IfG, Leipzig as project manager, mostly responsible for research projects aiming on disposal of radioactive and toxic waste in salt and argillaceous clay formations.

Donn Reed

Benjamin Reedlunn

Benjamin Reedlunn has a master’s degree in material science and a doctorate in mechanical engineering from the University of Michigan. In 2012, he joined Sandia to study the thermomechanical behavior of structural metal alloys. More recently, as Sandia’s representative in Joint Project WEIMOS, he has been investigating constitutive models for salt and performing simulations of geomechanical experiments at WIPP.

Anke Richter

Tino Rosenzweig

Tino Rosenzweig is a Research Assistant at the Technical University Bergakademie in Freiberg, Germany, Institute of Mining and Special Civil Engineering. His research is in the field of Hydro-consolidation, Soil Liquefaction, and Deep Borehole Disposal of High-level Radioactive Waste. Dr. Rosenzweig has a PhD (Dr.-Ing.) with a major in Geotechnical Engineering; a Master of Science Degree and a Bachelor of Science Degree with majors in Industrial Engineering and Management – all from the Technical University Bergakademie Freiberg.

Jay Santillan

Yildirim Savas

Anke Schneider

S. David Sevougian

Dr. S. David Sevougian is a principal member of the technical staff at SNL with over 30 years of experience in earth sciences, including geologic repository sciences, hydrogeology, geophysics, decision analysis, and petroleum engineering. He has an AB degree in physics from Cornell University and a PhD in petroleum engineering from The University of Texas at Austin. He is a member of the American Nuclear Society and the Society of Petroleum Engineers. Recently he has been working on the safety case and safety assessment methodology for evaluating a generic deep geologic repository for commercially generated SNF, as well as a possible separate geologic repository for nuclear wastes generated from national defense activities. He is researching concepts related to several types of host rocks, including granite, argillite, and bedded salt.

Steven Sobolik

Steven Sobolik is a Principal Member of the Technical Staff at SNL in Albuquerque, New Mexico, USA. He is a mechanical engineer by degree, obtaining his Bachelor’s and Master’s degrees from Texas A&M University. He began his career at Sandia in 1984, performing high-velocity impact tests at the Sandia rocket sled track. Since 1995 he has specialized in computational and experimental geomechanics, applied to radioactive waste repository projects such as the Yucca Mountain Project and WIPP; underground oil storage caverns in salt formations for the US Strategic Petroleum Reserve; CO2 sequestration, wellbore integrity, and other underground storage and geomechanical projects. He has authored or co-authored numerous papers on the mechanics of salt as they relate to the storage of oil, gas, and radioactive waste, and is a frequent presenter at international conferences on rock and salt mechanics. He is a member of the American Society of Mechanical Engineers, the American Rock Mechanics Association, the American Geophysical Union, and the Solution Mining Research Institute.

Joachim Stahlmann

Joachim Stahlmann has been working as head of the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität Braunschweig since October 2002. Since the early 1990s he has been active in the field of salt mechanics and underground disposal. He has worked on the construction of the shafts at the Gorleben exploration site and has developed the decommissioning concept and sealing structures in the radioactive waste repository Morsleben, particularly the stability and integrity, as well as the functionality of flow barriers and shaft seals. He was a member of the Consulting Group Asse for the Asse mine until 2007.

Walter Steininger

Walter Steininger is a physicist (University of Stuttgart). He made his doctoral thesis at the Max-Planck-Institute for Material Research, Material Science, and worked as a project scientist at the Staatliche Materialprüfungsanstalt, University of Stuttgart, in the field of radiation embrittlement of RPV steels. Since 1991 he is working as a program manager at the Project Management Agency Karlsruhe, Water Technology and Waste Management at the Karlsruhe Institute of Technology, managing, behalf of ministries respective RD&D programs related to high-level radwaste disposal.

Janis Trone

Philip Vardon

Ewoud Verhoef

Holger Völzke

Dr. Völzke is a mechanical engineer and has 24 years of experience in the area of spent fuel and radioactive waste management with the Federal Institute für Materials Research and Testing. There he is head of Division 3.4 “Safety of Storage Containers” and responsible for safety evaluation, experimental and numerical design testing, research projects, and advising authorities, industry and the public. Dr. Völzke is member of the German Nuclear Waste Management Commission - Committee on Waste Conditioning, Transport and Interim Storage, consultant for the IAEA and managing collaboration with several international partners.

Thilo von Berlepsch

Erik Webb

Erik manages the Geoscience Research & Applications Group, the core of Sandia’s geoscience capability with six departments centered around Geotechnology and Engineering, Geophysics, Atmospheric Sciences, Geomechanics, Geochemistry, and Geothermal Research. These departments engage across atmospheric monitoring and modeling, climate programs, fossil energy, geoengineering, nuclear repository programs, detection of underground structures, basic science of geological materials, geothermal energy, and geological elements of treaty verification and nuclear weapons programs for multiple federal agencies, foreign governments and in partnership with universities and commercial companies.

Rodney Whisenhunt

Klaus Wieczorek

Degree in geophysics at the University of Münster 1984, since 1985 in repository research, since 1995 with GRS Repository Safety Research Division in Braunschweig. Various projects on rock salt, clay, and crystalline rock, including *in situ* testing and thermal-hydrological-mechanical model simulation. Head of geotechnical section of the GRS department of process analyses.

Holger Wirth

Jens Wolf

Jens Wolf is a scientist at GRS GmbH. He holds a Diploma in Geology/Hydrogeology and a Ph.D. in Civil Engineering (Hydraulic and Environmental Systems). For eleven years, he has been engaged at GRS in several projects concerning long-term safety analyses for repository systems in salt, clay and crystalline host rocks.

Ralf Wolters

APPENDIX E: ABSTRACTS

FEP Catalogue, Database, and Knowledge Archive

Geoff Freeze*, S. David Sevougian*, Michael Gross**, Kris Kuhlman*,
Jens Wolf***, and Dieter Buhmann***

*Sandia National Laboratories (SNL)
**Nuclear Regulatory and Support Services (NRSS)
***Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH

8th US/German Workshop on
Salt Repository Research, Design, and Operation
Middelburg, The Netherlands
September 6-8, 2017

ABSTRACT

This presentation describes the ongoing development and application of a matrix-based approach for feature, event, and process (FEP) analysis to support the characterization and post-closure performance assessment modeling of deep geologic repositories for SNF and high-level radioactive waste.

The new organizational structure is built around a two-dimensional FEP classification matrix and is based on the concept that a FEP is typically a process (e.g., thermal, hydrologic, chemical, mechanical, biologic, radiologic) or event (e.g., seismic, igneous, human intrusion) acting upon or within a feature or component (e.g., waste form, waste package, host rock). The two-dimensional structure of the FEP matrix makes it easier to identify groups of related FEPs and thereby better inform characterization needs and performance assessment models.

The FEP matrix approach is currently being applied to develop a comprehensive set of FEPs for a generic salt repository, as part of a joint collaboration between the U.S. and German repository research programs. The goal of the collaboration is to populate an international FEP database for salt repositories. However, the current FEP matrix is applicable to any host rock, including repositories located in crystalline and/or argillaceous formations. Recent efforts have focused on a more systematic identification and organization of individual FEPs within a given process/event category.

For example, new thermal-hydrologic FEPs are generally organized by the nature of the driving force. This includes flow processes arising from fluid pressure differences, from capillary processes, and from gravity- and density-driven processes. Each individual FEP is then further subdivided into “Associated Processes,” which represent more detailed phenomena that need to be considered (i.e., screened) when constructing a PA model for repository system performance.

In addition to the development of a complete list of FEPs and Associated Processes, an on-line electronic database (www.saltfep.org) has been developed. The salt FEP Database is organized around the new FEP matrix structure, and is being developed by GRS to facilitate FEP identification, documentation, analysis, and screening. The salt FEP Database will also support a salt knowledge archive, with relevant documents linked to individual FEPs.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525. This work is supported by DOE Office of Nuclear Energy, Office of Spent Fuel and Waste Science and Technology. SAND2017-9305C.

Very Slow Creep Tests on Salt Samples

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8th US/German Workshop on
Salt Repository Research, Design, and Operation

Middelburg, The Netherlands

September 6-8, 2017

ABSTRACT

Four 2-year-long multistage creep tests have been performed on creep testing devices set in the Altaussee Mine in Austria to take advantage of the very stable temperature (and humidity) conditions in this salt mine. This cooperative testing program was supported by the Solution Mining Research Institute. Loading steps were planned to be 0.2, 0.4 and 0.6 MPa (The actual applied loads were slightly different) — much smaller than the loads usually applied during creep tests, which are in the range 5-15 MPa. Five salt samples were used: two from the Avery Island salt mine in Louisiana, two from the Gorleben salt mine in Germany, and a sample cored at Hauterives, France.

Main findings (Figure 1) are as follows:

1. During these low-stress creep tests, transient creep is long (6 to 10 months).
2. Steady-state strain rates when stresses are low are much faster (by 7-8 orders of magnitude) than what can be extrapolated from high-stress tests.
3. Even if tests results are scattered, the exponent of the power law in the low-stress domain seems to be close to $n=1$ (instead of $n=5$ in the high-stress domain in the case of the Gorleben and Avery Island salts).

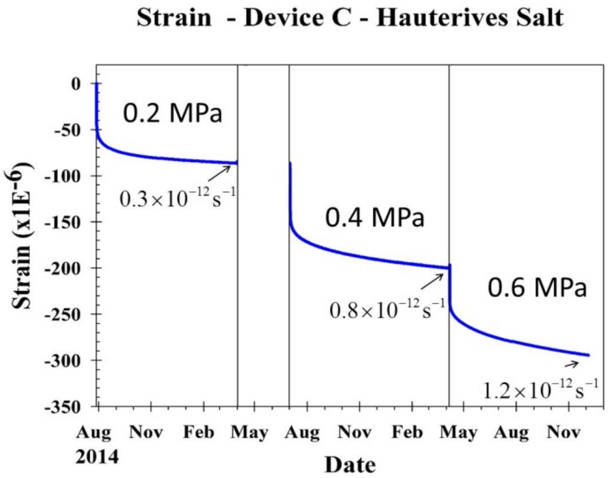

Figure 1. A three-stage, two-year long creep test on a Hauterives salt sample.

Testing Shear Strength and Deformation along Discontinuities in Salt

Steven R. Sobolik

Sandia National Laboratories, Albuquerque, NM, USA

Stuart Buchholz

RESPEC, Rapid City, SD, USA

ABSTRACT

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

This presentation discusses the initiation of laboratory experiments designed to measure the mechanical behavior of a bedding interface or clay seam as it is sheared. The series of laboratory direct shear tests reported in this paper will be performed on several samples of materials typical of WIPP emplacement drifts. The test series will include tests with machined blocks of halite and other materials such as anhydrite, clay, or polyhalite. These tests will be conducted at several normal and shear loads up to expected *in situ* pre-mining stress conditions, and at multiple shear velocities to scope for potential velocity-dependence of shear stress evolution. At the time of the presentation, the test plan has been written, and locations for extracting core with clay seams and halite contacts with anhydrite and polyhalite have been identified, with coring to begin in September 2017.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Radiological Consequences Analysis for a HLW Repository in Bedded Salt in Germany – Project KOSINA

J. Kindlein

GRS GmbH

8th US/German Workshop on
Salt Repository Research, Design, and Operation

Middelburg, The Netherlands

September 6-8, 2017

ABSTRACT

Within the framework of the German research and development project KOSINA (conceptual design, safety concept and safety demonstration concept for a generic repository in bedded salt in Germany) the scientific basis for the geological characterization, safety concept, design and safety assessment of a repository for high-level radioactive waste and spent nuclear fuel in bedded salt formations is being provided. In this presentation, some research findings regarding the safety demonstration and radiological consequences analysis will be presented in detail.

The safety concept for a repository in bedded salt describes in a verbal, argument-based way how the natural conditions, processes and technical measures at large yield a status of safety. Fundamental principle of the safety concept is the concentration and containment of the radioactive and other pollutants in the waste in the containment providing rock zone, which ensures isolation from the biosphere. The safety demonstration concept describes i.e., how nuclide release scenarios are evaluated by appropriate radiological safety indicators.

The radiological consequences analysis performed at GRS within the KOSINA project primarily consists of the calculation of the radiological safety indicator for different test cases and scenarios for the various repository design and waste emplacement options. Here, the modeling results of the disposal concept ‘drift disposal’ are being presented in detail by means of computational flow and transport modeling of the repository mine (near field) and assessment of the radiological consequences (biosphere model). The used software package RepoTREND will shortly be introduced, the modeling concept and employed radiological indicators explained. Major modeling results will be presented and drawn conclusions discussed.

Outcome of the REPOPERM Project

Klaus-Peter Kröhn

GRS GmbH

8th US/German Workshop on
Salt Repository Research, Design, and Operation

Middelburg, The Netherlands

September 6-8, 2017

ABSTRACT

The REPOPERM-project was concerned with the mechanical and hydraulic behavior of compacting crushed salt backfill at low porosities. This specific topic was extensively investigated by means of experimental as well as theoretical work.

Phase 1 of the project started out to answer the question if there is a threshold porosity at which all flow channels are completely shut off even before compaction is actually completed. It turned out, though, that such a threshold porosity would lie in a range where measurement of the porosity is of inherently untolerable uncertainty.

Phase 2 thus concentrated on the reliable prediction of crushed salt behavior under repository conditions. Of particular interest were mechanical and hydraulic data for compaction of wet material. Out of a large variety of experiments the long-term uniaxial compaction test on samples with different initial moisture content and the measurement of two-phase flow parameters for different degrees of compaction should be mentioned here explicitly. On the theoretical side the transferability of a calibrated material model was investigated, based on three different experiments. Finally, the first true thermo-hydro-mechanically coupled model with realistic parameters was successfully set up and run.

All in all, the REPOPERM-project has advanced the knowledge about compaction of crushed salt considerably. This includes, however, the awareness of knowledge that has not been acquired, yet. Some conclusions could thus be drawn from the findings of the project ending with a list of recommendations for further work.

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

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C. Lerch, N. Müller-Hoeppe (DBE TECHNOLOGY),
C. Lüdeling, T. Popp (IfG), U. Düsterloh, R. Wolters (TUC)

8th US/German Workshop on
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Middelburg, The Netherlands

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ABSTRACT

Crushed salt is the preferred candidate material for backfill measures and for realization of long-term seals in potential repositories for high-level radioactive waste in rock salt formations. With respect to repository design, analysis and performance assessment, solid knowledge of the thermal, mechanical, and fluid transport properties of crushed salt is required.

Over time the crushed salt will be consolidated by convergence of the host rock. The key questions are how, when, and to what degree the properties of reconsolidating crushed salt approach or attain those of the native salt formation.

The main objective of the Deutsche Gesellschaft für Endlagerforschung (German Association for Repository Research) (DAEF) initiative was to develop a strategy for reliable prediction of crushed salt properties under repository conditions based on identified shortcomings. Hence, this paper comprises two aspects:

1. An assessment of
   - the current understanding of the mechanisms and influencing parameters of crushed salt reconsolidation and their hydraulic impact,
   - the existing experimental data base, and
   - available constitutive models for numerical simulations.
2. Recommendations for completion of the experimental data base and the further development and validation of constitutive models.

The phenomenology and current process understanding of crushed salt reconsolidation is discussed in detail by Hansen et al., (2014). Therefore, this topic has been addressed only briefly in this paper.

Experimental data on crushed salt consolidation available today comprise results of oedometer tests and triaxial (Kármán type and true triaxial) tests. Experiments have been carried out at ambient and elevated temperatures, some with addition of brine or bentonite. However, they were usually not designed to enable validation of constitutive models. They show shortcomings in one or several of these fields:

- Precise knowledge of stress state (oedometer tests)
- Test conduction (complicated loading/unloading patterns)
- Porosity range (most tests reach only medium porosities)
- Accuracy of porosity measurement at high consolidation

- Sample pre-treatment
- Systematic parameter variations (lack of controlled series varying one parameter)

Besides the consolidation process itself, the hydraulic impact is important. Measurements of permeability at low porosities are a challenge, e.g., due to nonstationary flow conditions and two-phase flow phenomena in wetted specimens.

Several constitutive models, from purely empirical to microstructurally inspired, exist and are implemented. However, the models are at best partially validated, especially considering the low porosity range, and consistent parameter sets for larger sets of experiments on specific crushed salt varieties have not been derived.

Based on this evaluation of the currents status, we propose the following strategy for future work:

- Completion of the experimental database: Definition and execution of systematic laboratory procedures, including
    - reproducible sample preparation (e.g., concerning grain size, moisture, precompaction),
    - experimental procedures (e.g., time, temperature and stress state),
    - high-precision data sets (e.g., porosity, permeability), and
    - controlled lab test series.

- Validation of constitutive models:
    - Definition of a set of benchmark test series,
    - comparison of models against the tests, and
    - modification or extension of the models (e.g., by including additional processes or internal variables) where necessary.

- As a result, reliability of constitutive models should be demonstrated by reproducing a large set of lab tests under different conditions.

Future progress could undoubtedly profit from international cooperation, drawing on the DAEF institutions as well as the knowledge, experience and facilities present at partners around the world.

Interaction between Operational Safety and Long-Term Safety (Project BASEL)

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[2] DBE TECHNOLOGY GmbH

8th US/German Workshop on
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Middelburg, The Netherlands

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ABSTRACT

The need to ensure operational safety including radiation protection during the operational phase will require specific measures that influence the design and operational planning of a deep geological disposal facility. Contrary to other nuclear or industrial facilities, the implementation of a repository has to comply with additional requirements because post-closure safety must be guaranteed for hundreds of thousands of years. In a safety case, a comprehensive set of safety arguments must be compiled and the operator's confidence in the operational and long-term safety of the disposal facility must be demonstrated and communicated. The documentation and communication of the different safety assessments for the operational and post-closure phases are fundamental tasks of the safety case, which should include the assessment and documentation of the interactions between operational safety and post-closure safety.

Fundamental objectives of the operational safety are the protection of men and the environment with particular focus on the operating personnel. Moreover, the operator must demonstrate that the state of the facility at the time of closure will be compatible with the legal requirements for long-term safety. For both, a comprehensive system analysis of the features, events, and processes (FEP) during the operational phase is necessary.

In the German research and development project BASEL, a FEP catalogue for the operational phase was developed based on the national disposal concepts for clay and salt. The FEP catalogue contains analyses of the processes and events that affect the components (features) of the repository system in its entirety. It was used to identify and document a) hazards for the operational phase, b) the initial state of the repository's post-closure phase, and c) the impacts of the FEP on and consequences for post-closure safety.

Current research on deep borehole disposal of spent nuclear fuel and high-level radioactive waste - considerations within a German research project

Tino Rosenzweig

8th US/German Workshop on
Salt Repository Research, Design, and Operation
Middelburg, The Netherlands
September 6-8, 2017

ABSTRACT

What is deep borehole disposal about? The concept consists of drilling a borehole into crystalline basement rock to a depth of about 5000 m. From these 5000 m, at least the lower 2000 m have to be in crystalline basement rock. The lower 2000 m will be the later waste disposal zone for the emplacement of the waste canisters containing used nuclear fuel or vitrified radioactive waste from reprocessing, while the upper 3000 m will be the sealing zone. The overburden consists of layers of salt and/or clay to be able to identify a containment providing rock zone. The sealing zone reaches from 3000 m depth to the surface.

The deep borehole disposal option seems to have many advantages in relation to a mining-disposal. One is the great distance between the waste canisters and the biosphere. It is several times deeper than typical mined repositories, resulting in a longer sealing zone up to 3000 m and a very long transport path for potential radionuclide release. The host rock should have a low permeability as well as high saline and reducing conditions. Due to the great distance to the surface, it is possible to have several different overlaying layers like clay and salt.

The deep borehole disposal concept has many severe challenges to deal with. One example is drilling a borehole with a large diameter (adjusted to the size of the waste canister) to a depth of 5000 m. This is not common in the drilling industry, since the oil and gas industry usually tries to drill with the smallest possible diameter. Another crucial point is the final disposal of the waste canisters in a fluid. In other concepts, especially in mined repository concepts the most important objective is to dispose waste canisters in dry host rock and to avoid any contact with fluids. However, in the deep borehole disposal concept a fluid is necessary to keep the borehole stable. It is impossible to pump the slurry out of the casing to create a dry borehole. Another challenge is the impermeability of the casing and the cementation. It is also harder or nearly impossible to solve problems when accidents occur in a deep borehole. There exist technologies in the oil and gas industry when for example equipment gets lost or a drill string tears. Then you can use fishing technologies, which are common in the drilling industry, but if this does not work, there are spare solutions for such kind of accident management. Two other challenges are the qualified sealing of a fluid filled borehole and the retrievability of emplaced waste canisters. How will you place for instance bentonite in a fluid filled borehole and control the density of the bentonite? Or how will you bring down asphalt for instance up to 1500 m? In summary, there are a lot of challenges, which need to be solved and tested especially. These tests need to be carried out not only in a small scale but also *in situ*.

The aim of a German research project (Acronym: CREATIEF), funded by BMWi, is to identify the most sensitive aspects of the deep borehole disposal option with regard to safety and technical feasibility. For example, the drilling technology up to 5000 m, the emplacement of the waste canisters, the disposal of the waste canisters in a fluid filled borehole, ensuring the possibility of waste canister retrieval and the sealing of the fluid filled borehole. It is necessary to identify what materials can be used and by which technology the chosen materials can be brought down in the borehole. Another aim of the research project is to develop a concept for the disposal in terms of a waste canister design based on the known waste inventory of Germany. The size and number of the waste canisters needs to be calculated and the resulting number of boreholes accordingly. Finally, an evaluation of the deep borehole disposal option will be performed by showing the chances and the risks of this disposal option in Germany.

In a first step, the waste inventory in Germany was compiled. This is known because the last nuclear power plant will be shut down by the end of the year 2022. Thus, in Germany, the waste consists of SNF, of vitrified waste from reprocessing, of structural components of SNF disassembling and of spent fuel of prototype and research reactors. The amount of each waste type is known as well.

To create a concept, especially a drilling concept a geological profile is needed. Therefore, a simplified generic geologic profile was designed, which represents realistic geologic situations in Germany. The crystalline rock should reach from a depth of 5000 m up to about 2500 m and the overburden should consist of salt and clay with a large horizontal expansion to benefit from their positive properties and to be able to identify a containment providing rock zone. These are the necessary requirements for a safe repository. Due to the fact that the drilling technology and the diameter of the casing have a huge influence on the size of the waste canister, it was necessary to develop a drilling concept first prior to the design of a waste canister. Two variants were considered. On the one hand, todays conventional drilling diameters in oil and gas exploration were investigated. The result of these considerations was, that 44.5 cm or 17 ½ inch should be the final borehole diameter in a depth of 5000 m in the crystalline rock that could be realistically achieved. On the other hand, the necessary diameter for a reasonable and practical canister was considered. On basis of these considerations, the diameter of the borehole was assessed. Nevertheless, the diameter should stay in an area that still seems achievable with further drilling research. A borehole diameter of about 90 cm seems to be practical and achievable. For the two variants, the idea was to show the effect of a bigger diameter of the waste canister on the number of boreholes. For a borehole with a diameter of 44.5 cm, which equals 17 ½ inch, there exists a drill bit which is able to drill into crystalline hard rock. When the final borehole diameter equals 17 ½ inch you need much bigger drill bits in the upper regions. Additionally, up to four casings are necessary depending on geology, but the maximum casing diameter according to the API-Standard is 30 inch. So, depending on the geology it might be possible that even a start-shaft is needed. For the bigger final borehole diameter of 90 cm, further research is not only needed for the depth of 5000 m but also for the even bigger diameters of the casings and drill bits above.

The state of the art in drilling engineering shows small borehole diameters are feasible only so that the borehole can only take up a small canister. The inner diameter of this canister would be much smaller than the one, where further research in the drilling technology is necessary. The greatest disadvantage of the smaller borehole is that only SNF can be disposed of. In the larger borehole, it could be possible to dispose of all waste forms, even existing canisters with vitrified waste, the structural components of SNF and the SNF of prototype and research reactors. Thus, all forms of the HLW in Germany would fit into the large diameter borehole. The number of boreholes that are needed to get the radioactive waste disposed was calculated accordingly. With today's available drilling technology, about 400 to 500 boreholes are required. Considering it would be possible to realize a borehole diameter of about 90 cm in a depth of 5000 m only about 31 boreholes are necessary. A small number of boreholes would be very advantageous to accept the deep borehole option as an alternative to a mined repository.

The deep borehole disposal option has some very difficult and big challenges to deal with and will require R&D work in several areas. According to the current state of the art in drilling technology, it is impossible to create a repository with a realistic number of deep boreholes, which could take all the HLW in Germany. The main reason is standard equipment from oil and gas industry is not suited for repositories of HLW. There are still many unsolved problems that might never be solved; particularly the issue of retrievability, which is mandatory in Germany.

APPENDIX F: PRESENTATIONS

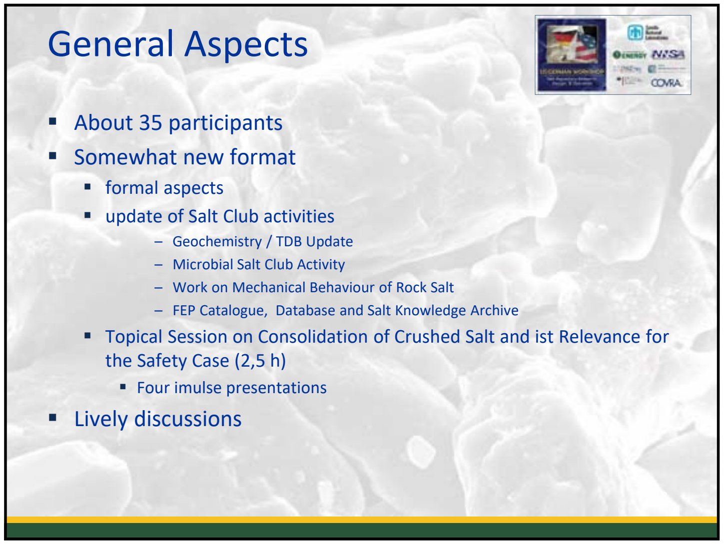
Short Report on Salt Club Meeting

Jörg Mönig
GRS

Middelburg, The Netherlands
September 5-7, 2017

Election of Chairperson & Steering Group

- Chair: Jörg Mönig
- Steering Group
  - Germany: Wilhelm Bollingerfehr, Michael Bühler
  - The Netherlands: Jacques Grupa, Erika Neeft
  - Poland: Andrzej Chwas
  - USA: Sean Dunagan, Tim Gunter



General Aspects

- About 35 participants
- Somewhat new format
  - formal aspects
  - update of Salt Club activities
    - Geochemistry / TDB Update
    - Microbial Salt Club Activity
    - Work on Mechanical Behaviour of Rock Salt
    - FEP Catalogue, Database and Salt Knowledge Archive
  - Topical Session on Consolidation of Crushed Salt and ist Relevance for the Safety Case (2,5 h)
    - Four imulse presentations
- Lively discussions

Outlook

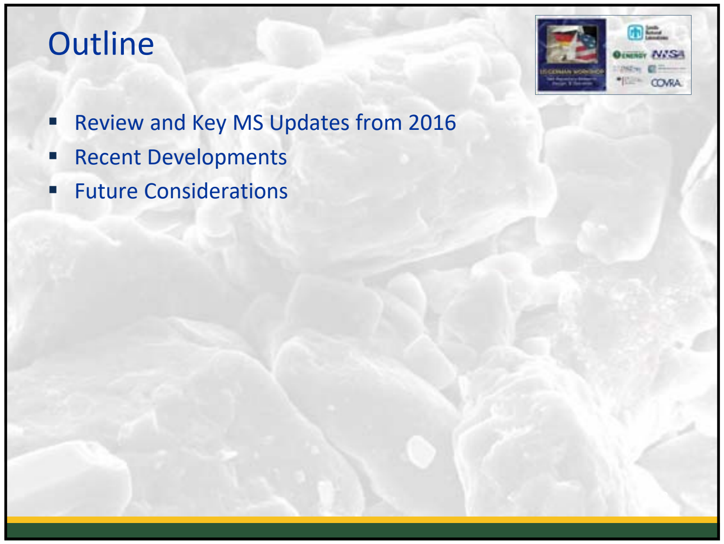
- Invitation to UK (RWM, BGS) to join Salt Club
- Encouragement to Poland for a more active/visible membership

- Steering Group Meeting (Videoconference) Next spring
- SC-8 Meeting: Sept. 07, 2018 near Hannover

8th US/German Workshop on Salt Repository Research, Design, and Operation

Andrew Orrell / Stefan Mayer
IAEA

Middelburg, The Netherlands
September 5-7, 2017

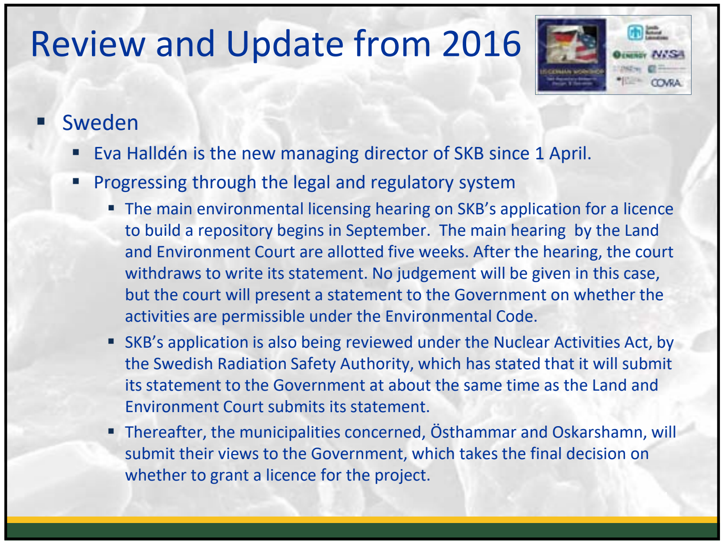


Outline

- Review and Key MS Updates from 2016
- Recent Developments
- Future Considerations

Review and Update from 2016

- Finland
  - In 2000, Olkiluoto was selected as the site for final disposal. The repository construction licence application was submitted in 2012. Construction licence was granted in November 2015 and the operation licence application will be submitted in 2020. The final disposal is scheduled to start in 2020's. According to current plans the repository would be sealed by 2120's.
  - *(June 2016) Fennovoima submitted an EIA program regarding a final disposal facility of its spent nuclear fuel to Finnish authorities, and signed a service agreement with Posiva Solutions Oy (a marketing division of Posiva Oy) to enable Posiva's expertise to be utilized in Fennovoima's final disposal of spent nuclear fuel.* "The agreement between Posiva Solutions and Fennovoima does not …include disposal of Fennovoima's used nuclear fuel in Onkalo."



Review and Update from 2016

- Sweden
  - Eva Halldén is the new managing director of SKB since 1 April.
  - Progressing through the legal and regulatory system
    - The main environmental licensing hearing on SKB's application for a licence to build a repository begins in September. The main hearing by the Land and Environment Court are allotted five weeks. After the hearing, the court withdraws to write its statement. No judgement will be given in this case, but the court will present a statement to the Government on whether the activities are permissible under the Environmental Code.
    - SKB's application is also being reviewed under the Nuclear Activities Act, by the Swedish Radiation Safety Authority, which has stated that it will submit its statement to the Government at about the same time as the Land and Environment Court submits its statement.
    - Thereafter, the municipalities concerned, Östhammar and Oskarshamn, will submit their views to the Government, which takes the final decision on whether to grant a licence for the project.

Review and Update from 2016

- France
  - ANDRA expects to apply for a construction and operating licence for CIGEO in 2018, with construction due to start 2020.
  - In February, a local court annulled the transfer of a forest from the local municipality to ANDRA, which could impact implementation of the CIGEO facility. Other protests have occurred.
  - November IAEA Peer Review of the CIGEO Safety Option Dossier that lays out chosen objectives, concepts and principles for ensuring operational and long-term safety.

https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx

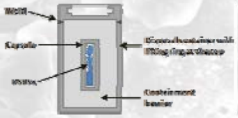
    - IRT observation: The decision to introduce an industrial pilot phase and prepare a Safety Options Dossier is commendable. It confirms the responsiveness of Andra to public consultation and is a good example of taking account of the public's concerns in the Cigéo development programme.

Review and Update from 2016

- Germany
  - Covered later today.
- USA
  - More later today (US) and Thursday (WIPP)
  - Pivot back toward Yucca Mountain: Trump administration has included a budget request for $120m to restart the repository program, stalled since 2010.
    - Shelving the DBFT and the Defense Repository projects.
- South Australia
  - Public acceptance challenge

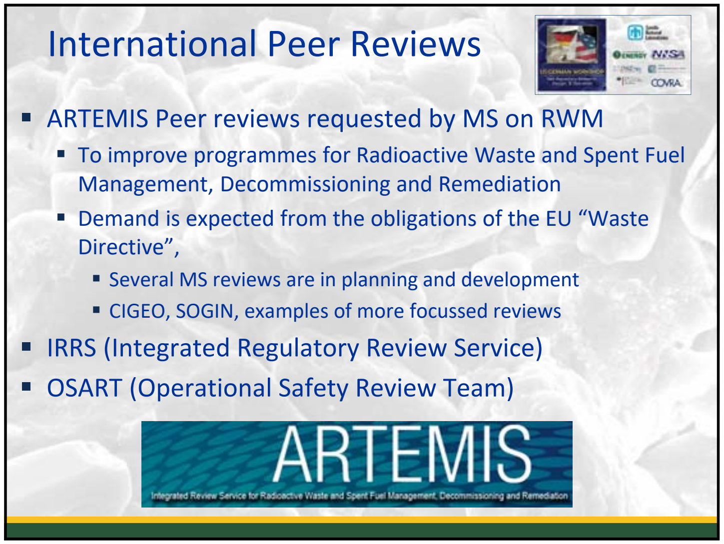
Recent Developments

- IAEA Continues Numerous Projects Supporting Disposal
  - Compendium of URF RD&D
    - *NWTRB: Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: Update;* A Report to Congress and the Secretary of Energy, February 2016
  - Joint Convention Extraordinary and Review Meeting
  - Shallow Borehole for DSRS (salt?)
  - Stakeholder Involvement and Communication
  - Safety Standards revision and development
  - Cost Estimation guidance
  - Site Investigation Planning
  - Uranium Legacy Site Remediation (Central Asia and EBRD)
  - International Conference on the Safety of Radioactive Waste Management (Nov 2016)
    - http://www-pub.iaea.org/iaeameetings/50807/International-Conference-on-the-Safety-of-Radioactive-Waste-Management
  - URF Network
    - https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx



Example Projects

- HIDRA
  - Human Intrusion in the Context of Disposal of Radioactive Waste
- GEOSAF-II
  - Demonstration of the Operational and Long-Term Safety of Geological Disposal Facilities for Radioactive Waste
- PRISMA
  - Practical Illustration and Use of the Safety Case Concept in the Management of Near-Surface Disposal Application
- MODARIA II
  - Modelling and Data for Radiological Impact Assessments
- TBD
  - Step-wise Approach to Licensing for Regulator and Operator
- URF Network
  - Fostering knowledge sharing and multilateral use of underground research facilities



International Peer Reviews

- ARTEMIS Peer reviews requested by MS on RWM
    - To improve programmes for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation
    - Demand is expected from the obligations of the EU “Waste Directive”,
        - Several MS reviews are in planning and development
        - CIGEO, SOGIN, examples of more focussed reviews
- IRRS (Integrated Regulatory Review Service)
- OSART (Operational Safety Review Team)

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

Future Considerations

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

60 Years
IAEA Atoms for Peace and Development

Thank you!

RADIOACTIVE WASTE STRATEGY IN THE NETHERLANDS

Ewoud Verhoef

COVRA

US-German Workshop 2017, Nieuwdorp

RADIOACTIVE WASTE

- 2 nuclear power plants
  1 operating (500 MWE)
  1 shut down(GKN 1997)
- 2 research centers
- U-enrichment plant
- Mo-production

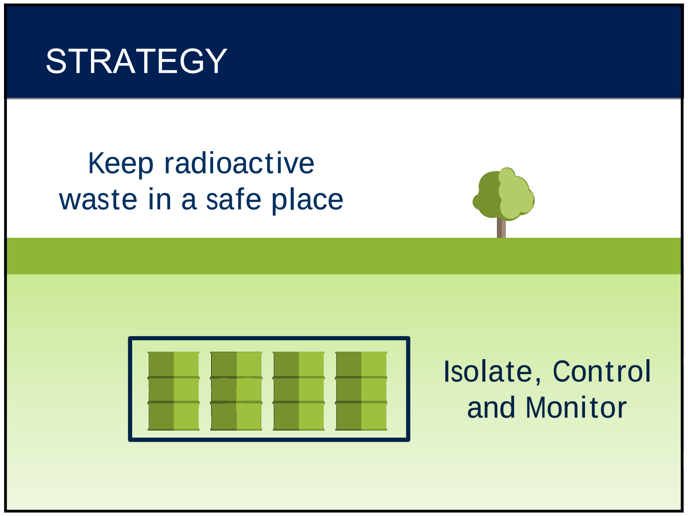
- industry
- medicine
- research

COVRA NV

RADIOACTIVE WASTE

- HLW: 100 m^3
- LILW: 11.000 m^3
- NORM: 20.000 m^3

COVRA NV



STRATEGY

Keep radioactive waste in a safe place

Isolate, Control and Monitor

SOLUTIONS FOR THE NETHERLANDS

- small amount of waste
- high ground water table
- high population density
- high environmental awareness
- advanced spatial planning

no shallow disposal, only geological disposal

COVRA NV

POLICY

- **all waste managed and owned by COVRA**
- **all waste at one industrial site**
- **at least 100 years storage, in buildings**
- **disposal after 100 years either in national or international context (dual track)**
- **research**

stable policy since 1984

COVRA

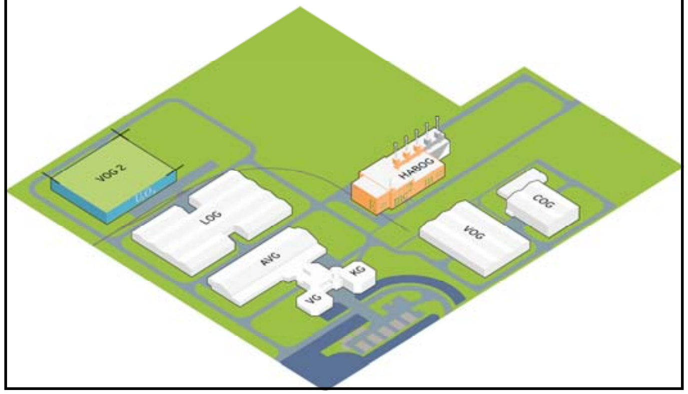
- **Established 1982**

→ Nieuwdorp 1992

- **State-owned enterprise 2002**
- **60 people**
- **20 million turnover**

Only statutory task: care for Dutch RW to protect people & the environment

SITE

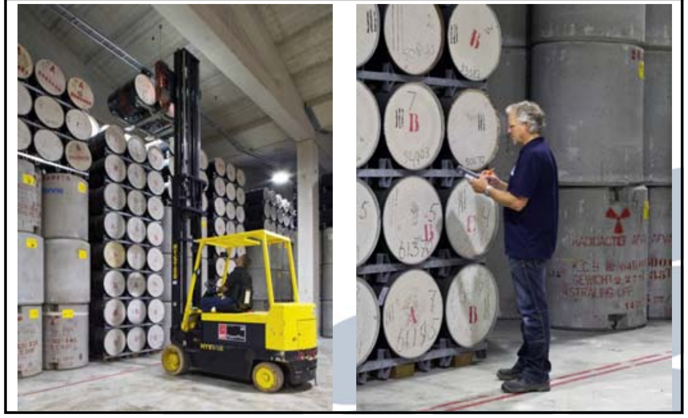


LMLW

- **Defence in depth**
- **proven technology**
- **simple, robust storage buildings**
- **minimal equipment**

- **stable product**
- **small units**
- **repairable**

LMLW



HLW storage: HABOG

HLW storage

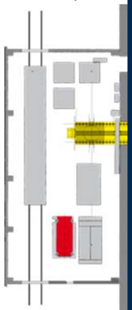
All events ≤ 10^{-6} covered

- **earthquakes VI½ Mercali**
- **plane crash (F16-A Falcon fighter)**
- **flooding +10 m NAP**
- **lpg gas cloud explosion**
- **severe winds 125 m/s**

HLW

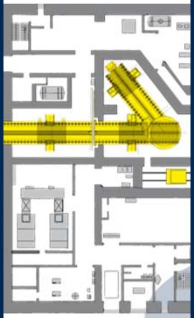
HABOG LAYOUT

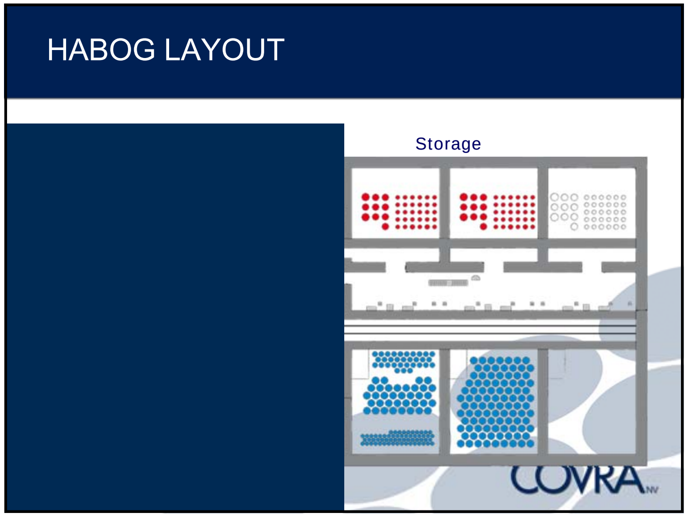
Reception



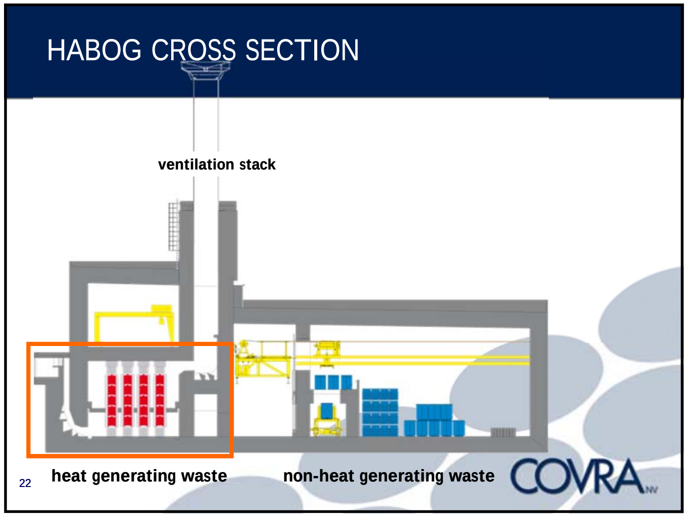
HABOG LAYOUT

Treatment

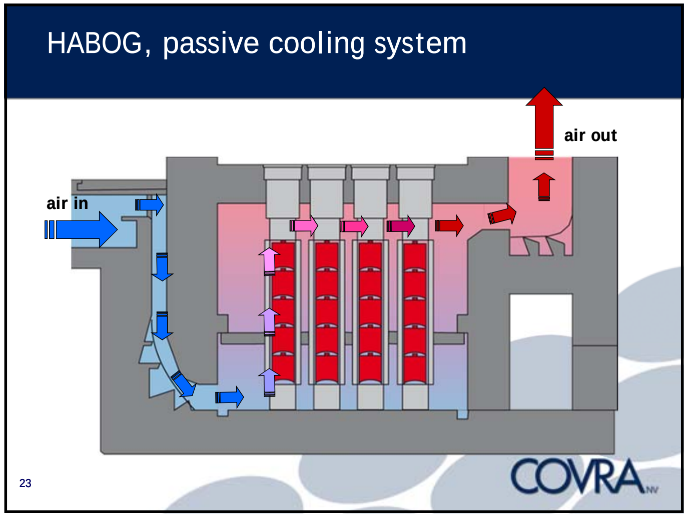




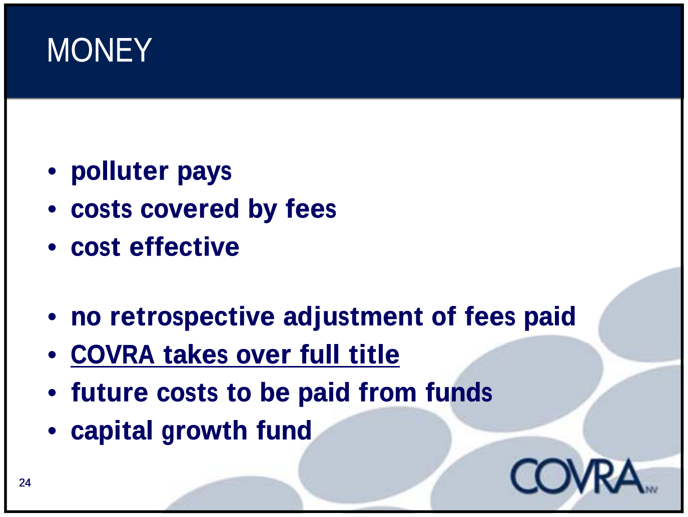
HABOG LAYOUT



HABOG CROSS SECTION



HABOG, passive cooling system

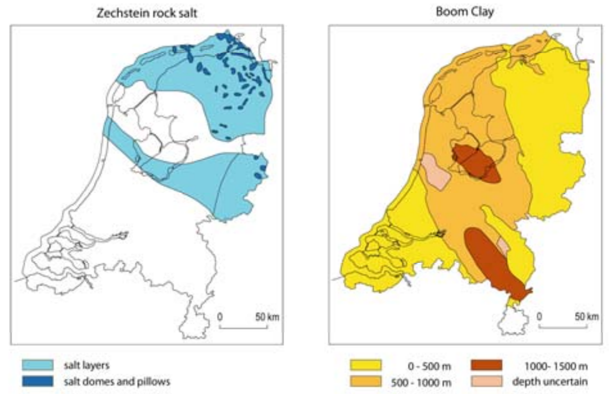


MONEY

- **polluter pays**
- **costs covered by fees**
- **cost effective**

- **no retrospective adjustment of fees paid**
- **COVRA takes over full title**
- **future costs to be paid from funds**
- **capital growth fund**

RESEARCH



OPERA

Research Programme Disposal Radioactive Waste

- 2009:
  - Start preparation third programme
  - Coordinated by COVRA
  - € 10 million – 7 years
  - financed by government & industry
- 2011: start programme
- 2017: First Safety Case

OPERA

COVRA NV

CONFIDENCE

STORAGE FOR MORE THAN 100 YEARS?

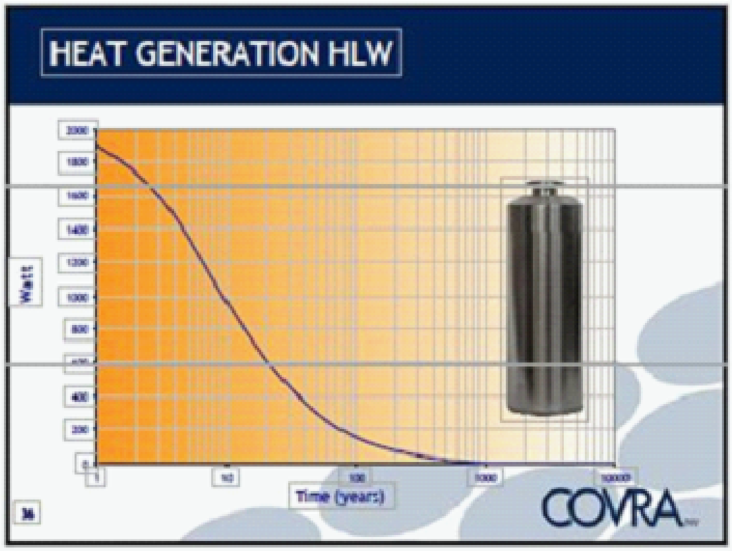
MUSEUM DEPOT

MUSEUM DEPOT

MARIE CURIE

COMMUNICATION

- **HABOG is a Work of Art:**
  METAMORPHOSIS
  (William Verstraeten)
- **Show on the outside what is happening inside**
- **Look through the 1.70 m concrete walls to the outside**



HEAT GENERATION HLW

2003

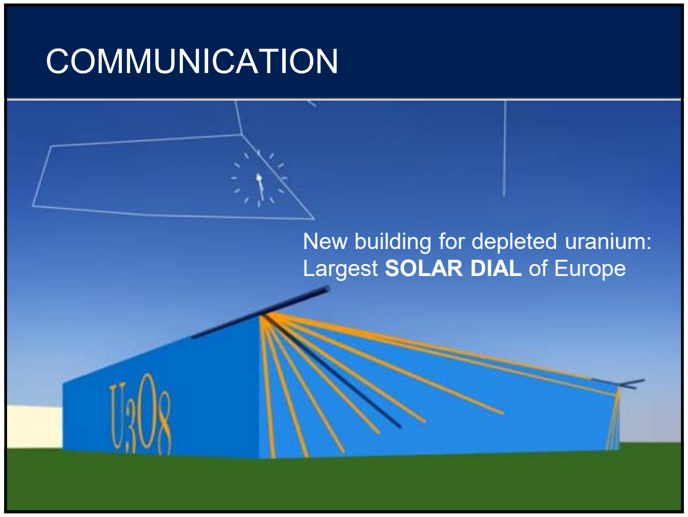
2023

2043

2063

2083

2103



COMMUNICATION

New building for depleted uranium:
Largest **SOLAR DIAL** of Europe

HRH Prinsess Beatrix will open the building September 13 2017
Open day for the public

German Waste Management Strategy

US / German Workshop on
Salt Repository Research, Design, an Operation

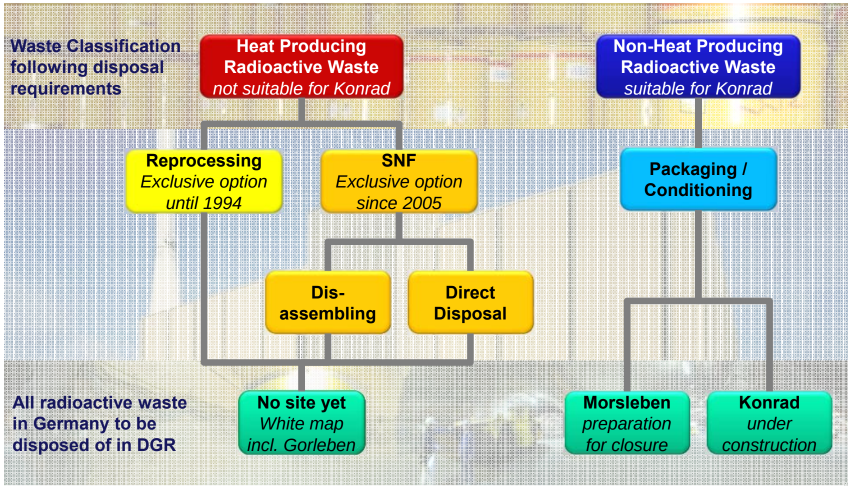
Dr. Thilo v. Berlepsch
DBE TECHNOLOGY GmbH
September 5th, 2017

Content

- **Introduction**
  - Overview on Radioactive Waste Streams in Germany
- **Political Background**
  - Commissions and Acts
- **Site Selection for a HLW repository**
  - Involved Organisations

Introduction

Radioactive Waste Classification and Disposal Routes



Waste Classification following disposal requirements

Heat Producing Radioactive Waste
not suitable for Konrad

Non-Heat Producing Radioactive Waste
suitable for Konrad

Reprocessing
Exclusive option until 1994

SNF
Exclusive option since 2005

Packaging / Conditioning

Dis-assembling

Direct Disposal

All radioactive waste in Germany to be disposed of in DGR

No site yet
White map incl. Gorleben

Morsleben
preparation for closure

Konrad
under construction

History of Radwaste Programme

1963	• Agreement to dispose of radwaste in DGR, preferably in salt
1967	• Start of research in the research mine of Asse salt mine
1971	• Begin of disposal in Morsleben (ERAM)
1975	• Start of evaluation of the Konrad iron ore mine
1979	• "Entsorgungsnachweis" requirement for NPP operation
1979	• Begin of exploration in Gorleben salt mine
1981	• Begin of construction of Gorleben interim storage facility
1995	• 1st SNF storage in Gorleben interim storage facility
1999	• 1st licence application for on-site interim storage (Emsland)
2000	• 1st Gorleben moratorium (for 10 years)
2002	• 1st SNF storage in on-site interim storage (Emsland)
2011	• New radioactive waste disposal facility road-map
2012	• 2nd Gorleben moratorium

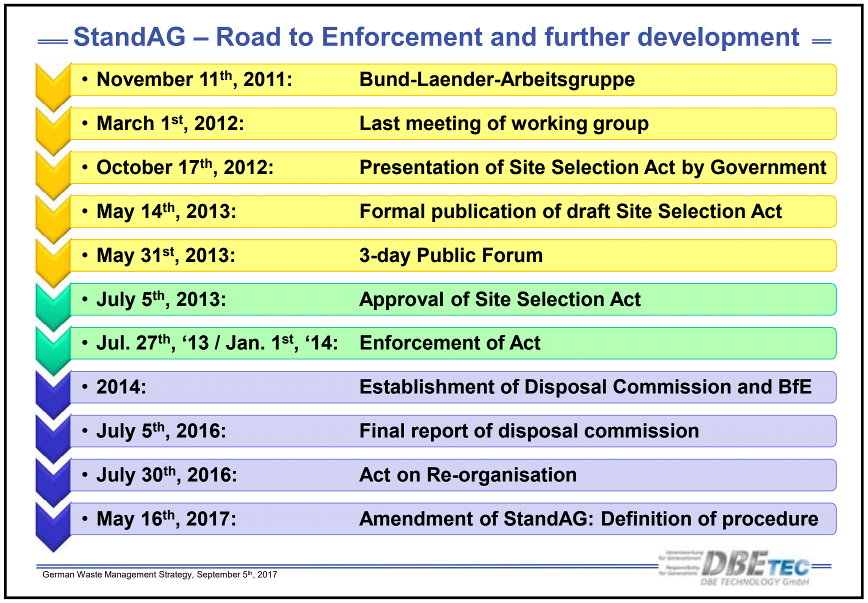
Overview on German Disposal Projects

- So far operated by Asse GmbH
  - Asse mine used only as URL since 1978, currently under decommissioning
- So far operated by DBE:
  - Gorleben: Heat-generating waste, underground survey started in the 1990's, on hold
  - Konrad: Non heat-generating waste, under construction
  - Morsleben: Operational Waste (1980's until 1998), planning for decommissioning

Political Background

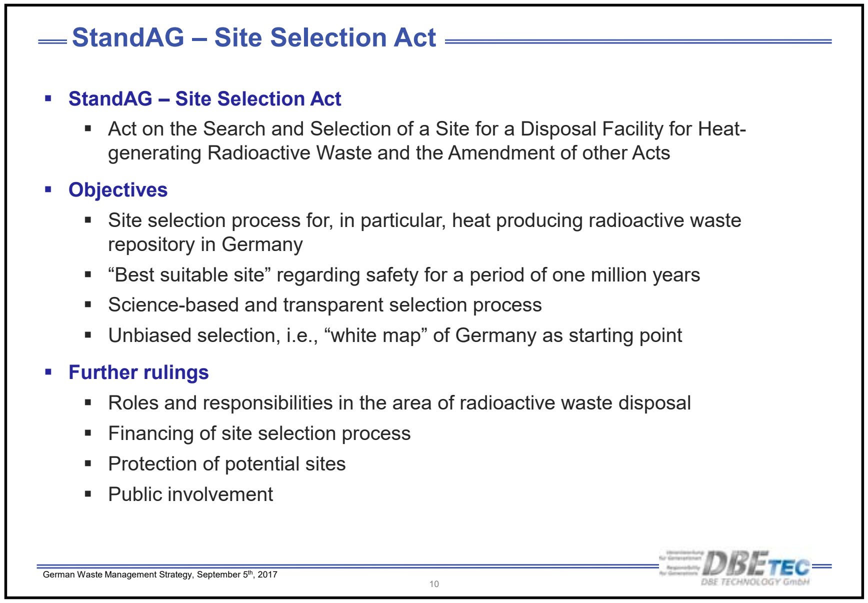
KfK: Financial Viability of Nuclear Phase-out

- **October 14th, 2015: Implementation of Commission by Federal Government**
  - Review the financial viability of the nuclear phase-out in Germany
  - Representatives of politics, science, churches, workers unions, NGOs (no industry representatives)
- **December 16th, 2016: Approval of Act by Federal Government to transfer Commission's recommendations into Federal Law**
  - Mandatory transfer of money from Utilities into public fund for transportation, storage and disposal (17.2 bn €)
  - Voluntary transfer of risk premium (35,5 %: 6.1 bn €) into public fund releasing Utilities from any later liabilities
  - Enactment pending until EC decides positively on state aid assumption
- **State owned organisation for storage to be founded**
  - Transfer of storage facilities into one new state owned organisation
  - Heat producing waste: 2019 / Non heat producing waste: 2020
  - GNS already transferred centralised storage facilities into separate organisations (still owned by GNS)



StandAG – Road to Enforcement and further development

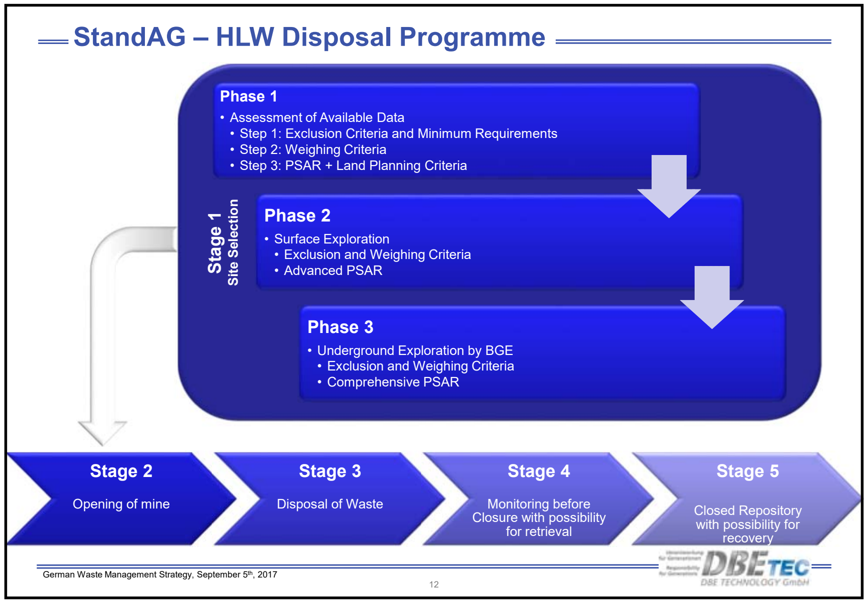
• November 11th, 2011:	Bund-Laender-Arbeitsgruppe
• March 1st, 2012:	Last meeting of working group
• October 17th, 2012:	Presentation of Site Selection Act by Government
• May 14th, 2013:	Formal publication of draft Site Selection Act
• May 31st, 2013:	3-day Public Forum
• July 5th, 2013:	Approval of Site Selection Act
• Jul. 27th, ‘13 / Jan. 1st, ‘14:	Enforcement of Act
• 2014:	Establishment of Disposal Commission and BfE
• July 5th, 2016:	Final report of disposal commission
• July 30th, 2016:	Act on Re-organisation
• May 16th, 2017:	Amendment of StandAG: Definition of procedure



StandAG – Site Selection Act

- **StandAG – Site Selection Act**
  - Act on the Search and Selection of a Site for a Disposal Facility for Heat-generating Radioactive Waste and the Amendment of other Acts
- **Objectives**
  - Site selection process for, in particular, heat producing radioactive waste repository in Germany
  - “Best suitable site” regarding safety for a period of one million years
  - Science-based and transparent selection process
  - Unbiased selection, i.e., “white map” of Germany as starting point
- **Further rulings**
  - Roles and responsibilities in the area of radioactive waste disposal
  - Financing of site selection process
  - Protection of potential sites
  - Public involvement

Site Selection



StandAG – HLW Disposal Programme

Stage 1
Site Selection

Phase 1
- Assessment of Available Data
  - Step 1: Exclusion Criteria and Minimum Requirements
  - Step 2: Weighing Criteria
  - Step 3: PSAR + Land Planning Criteria

Phase 2
- Surface Exploration
  - Exclusion and Weighing Criteria
  - Advanced PSAR

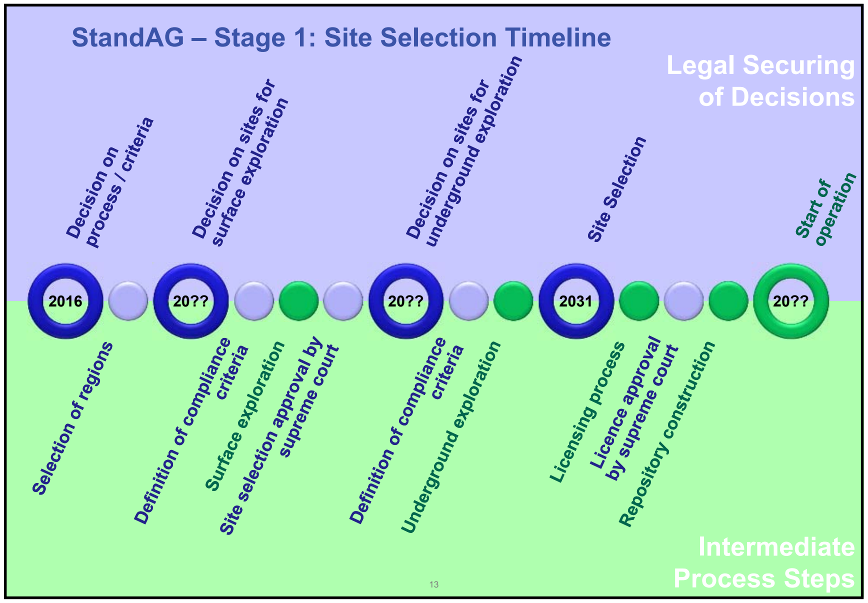
Phase 3
- Underground Exploration by BGE
  - Exclusion and Weighing Criteria
  - Comprehensive PSAR

Stage 2
Opening of mine

Stage 3
Disposal of Waste

Stage 4
Monitoring before Closure with possibility for retrieval

Stage 5
Closed Repository with possibility for recovery



StandAG – Stage 1: Site Selection Timeline

Legal Securing of Decisions

- 2016
- 20?? – Decision on process / criteria
- 20?? – Decision on sites for surface exploration
- 20?? – Decision on sites for underground exploration
- 2031 – Site Selection
- 20?? – Start of operation

Selection of regions

Definition of compliance criteria

Surface exploration

Site selection approval by supreme court

Definition of compliance criteria

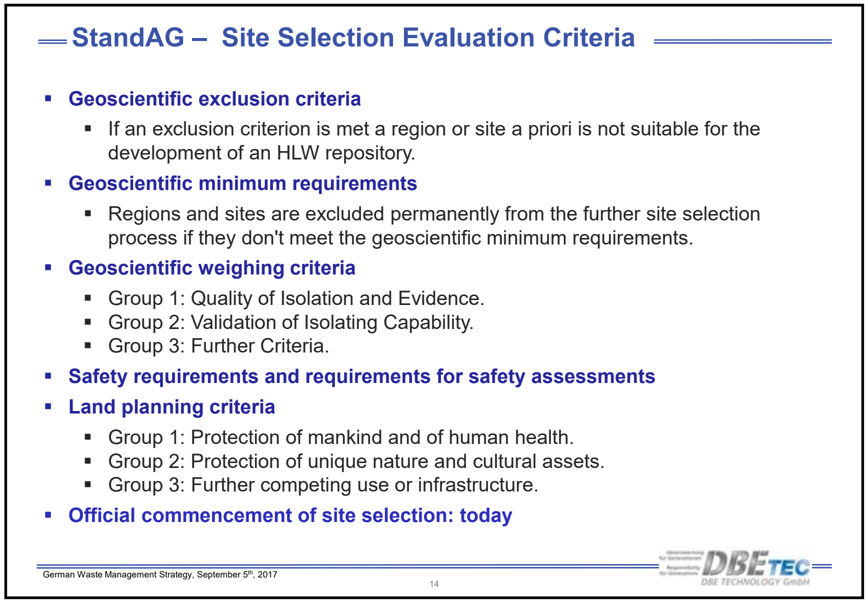
Underground exploration

Licensing process

Licence approval by supreme court

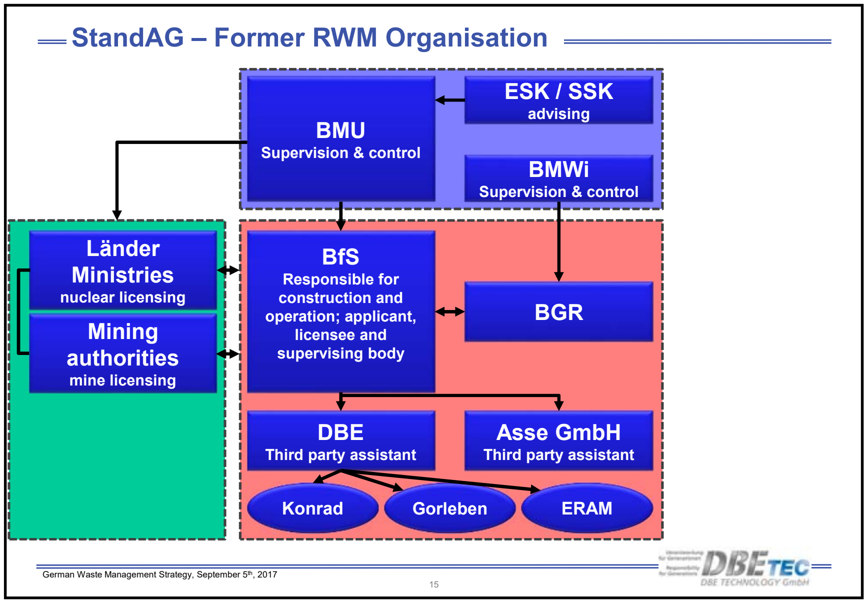
Repository construction

Intermediate Process Steps



StandAG – Site Selection Evaluation Criteria

- **Geoscientific exclusion criteria**
  - If an exclusion criterion is met a region or site a priori is not suitable for the development of an HLW repository.
- **Geoscientific minimum requirements**
  - Regions and sites are excluded permanently from the further site selection process if they don't meet the geoscientific minimum requirements.
- **Geoscientific weighing criteria**
  - Group 1: Quality of Isolation and Evidence.
  - Group 2: Validation of Isolating Capability.
  - Group 3: Further Criteria.
- **Safety requirements and requirements for safety assessments**
- **Land planning criteria**
  - Group 1: Protection of mankind and of human health.
  - Group 2: Protection of unique nature and cultural assets.
  - Group 3: Further competing use or infrastructure.
- **Official commencement of site selection: today**



StandAG – Former RWM Organisation

BMU
Supervision & control

ESK / SSK
advising

BMWi
Supervision & control

Länder Ministries
nuclear licensing

Mining authorities
mine licensing

BfS
Responsible for construction and operation; applicant, licensee and supervising body

BGR

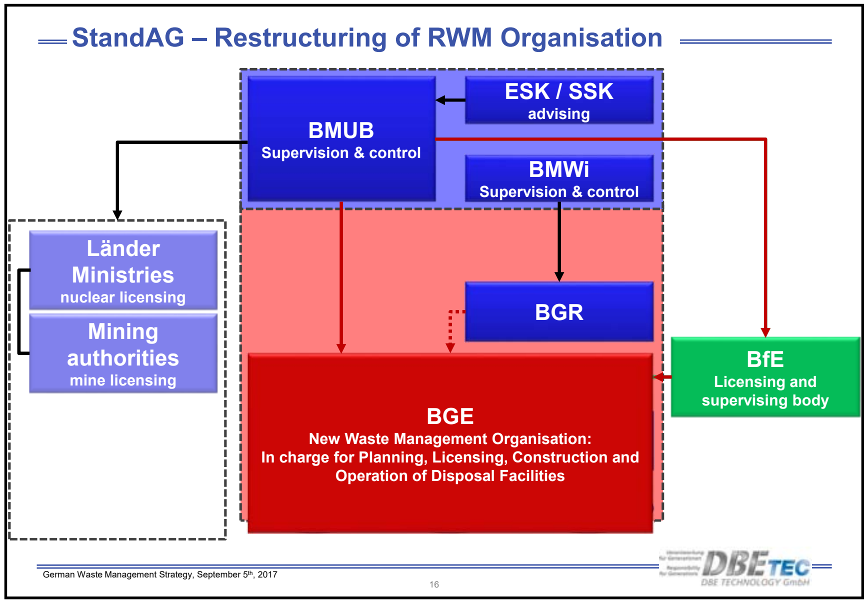
DBE
Third party assistant

Asse GmbH
Third party assistant

Konrad

Gorleben

ERAM



StandAG – Restructuring of RWM Organisation

BMUB
Supervision & control

ESK / SSK
advising

BMWi
Supervision & control

Länder Ministries
nuclear licensing

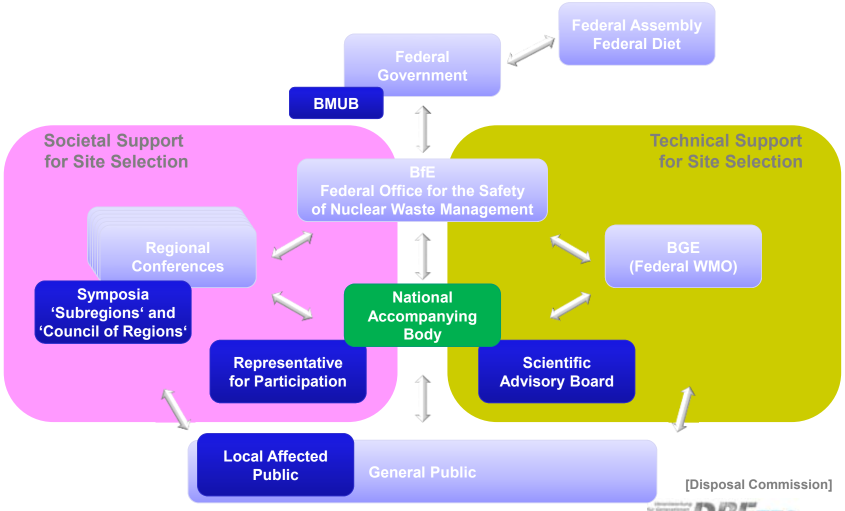
Mining authorities
mine licensing

BGR

BfE
Licensing and supervising body

BGE
New Waste Management Organisation:
In charge for Planning, Licensing, Construction and Operation of Disposal Facilities

StandAG – Involved Bodies in Site Selection



Federal Assembly
Federal Diet

Federal Government

BMUB

Societal Support for Site Selection

Technical Support for Site Selection

BfE
Federal Office for the Safety of Nuclear Waste Management

Regional Conferences

BGE
(Federal WMO)

Symposia ‘Subregions‘ and ‘Council of Regions‘

National Accompanying Body

Representative for Participation

Scientific Advisory Board

Local Affected Public

General Public

[Disposal Commission]

StandAG – Implementation of new organisations: BfE

BfE: **Bundesamt für Entsorgungssicherheit**
Federal Office for the Safety of Nuclear Waste Management

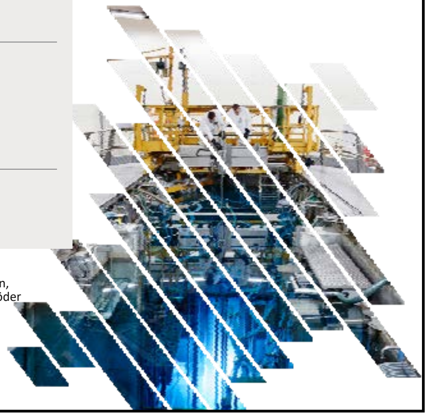
- **Foundation date**: September 1st, 2014
- **Tasks**
    - Regulation of site selection and the co-ordination of public participation,
    - Nuclear licences for interim storage facilities and transports of nuclear fuels,
    - Procedures under mining, water and nuclear law relating to disposal,
    - Issues related to the safety of nuclear waste management, and
    - Task-related research in these areas.
- **Staffing**:
    - Transfer of relevant staff from BfS (mainly the former „EÜ“ – Endlagerüberwachung: disposal supervision) into BfE in April 2016

StandAG – Implementation of new organisations: BGE

BGE: **Bundesgesellschaft für Endlagerung**
Federal Organisation for Disposal

- **July, 2016: Foundation date**
- **Tasks**
    - Planning, construction and operation of radioactive waste repositories,
    - Implementation of the site selection procedure for a HLW repository:
        - development and implementation of exploration programmes,
        - development of safety assessments,
        - proposals for regions and sites
    - April 25th, 2017: Transfer of operational tasks for Asse, Gorleben, Konrad and Morsleben to BGE
- **Staffing**
    - April 25th, 2017: Transfer of relevant staff from BfS
    - June: Transfer of DBE’s shares to the State
    - End 2017: Merger of Asse GmbH and DBE to BGE

SAFETY CASE EXPERIENCES IN THE NETHERLANDS



Jacques Grupa, Jaap Hart , Hans Meeussen, Ecaterinca Rosca-Bocancea, Thomas Schröder (NRG-RIA)

Ton Wildenborg (TNO)

Dirk-Alexander Becker, Dieter Buhmann, Jens Wolf (GRS Braunschweig)

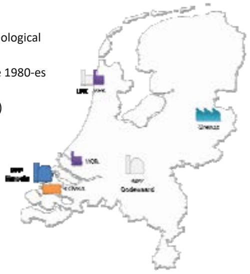
Eef Weetjens, Joan Govaerts (SCK·CEN)

Contents

- Dutch nuclear profile
- Research Program
- PA model - Safety Assessment
- Results of test calulcations
- Conclusion

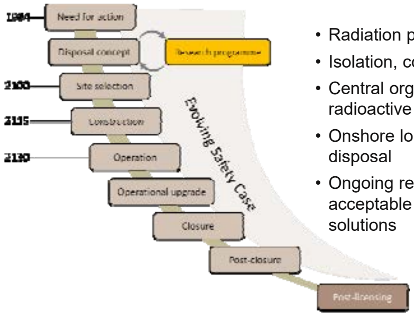
Introduction

- The Netherlands has a small nuclear profile
- Almost all radioactive waste fractions are foreseen for geological disposal
- A decision for long-term interim storage goes back to the 1980-es
- Policy on „isolate, control & monitor“ (ICM, 1984) and requirement for retrievability of radioactive waste (1993)
- Multinational disposal solutions are under consideration



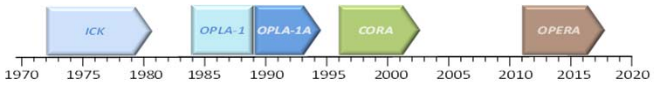
Dutch RW Management

Netherlands has adopted the strategy of **long-term interim storage**



- Radiation protection
- Isolation, control, and surveillance
- Central organisation for managing radioactive waste
- Onshore long-term retrievable disposal
- Ongoing research in finding acceptable waste management solutions

Dutch Programmes on Geological Disposal



Academic research
Disposal concepts

Safety
Assessment

Retrievable disposal
Societal effects, ethics

Safety Case

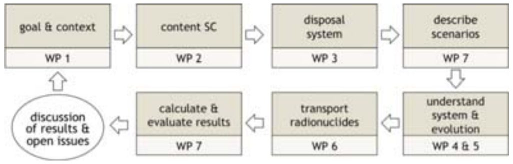
- 2001 – 2011:
  - o No national disposal programmes on salt disposal
  - o Participation in EU Framework projects: *PAMINA, NF-PRO, BAMBUS-II, THERESA*

ICK : Interdepartmental Nuclear Energy Commission
OPLA : Commission on Onshore Disposal – Phases 1/1A
CORA : Commission on Disposal of Radioactive Waste

Reports available at
www.covra.nl

OPERA: Research Plan (OPERA-PG-COV004)

- Result of *OPERA*:
  Detailing a first roadmap for the long-term research on geological disposal of radioactive waste in the Netherlands
- Financed by the government (Ministry of Economic Affairs) and the energy sector
- Coordinated by *COVRA*, the Dutch WM organization



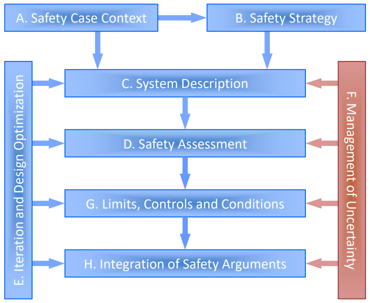
OPERA

OPERA WP 2 – Contents Safety Case

Safety Case: “The collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility“

- Methodology based on IAEA SSG-23
- *Components* of the Safety Case

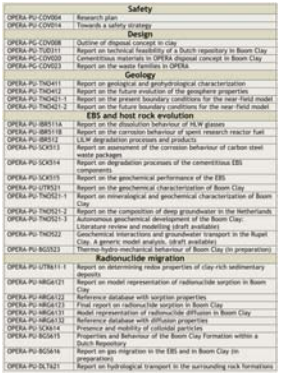
OPERA-PU-NRG2111
Report on the OPERA Safety Case structure



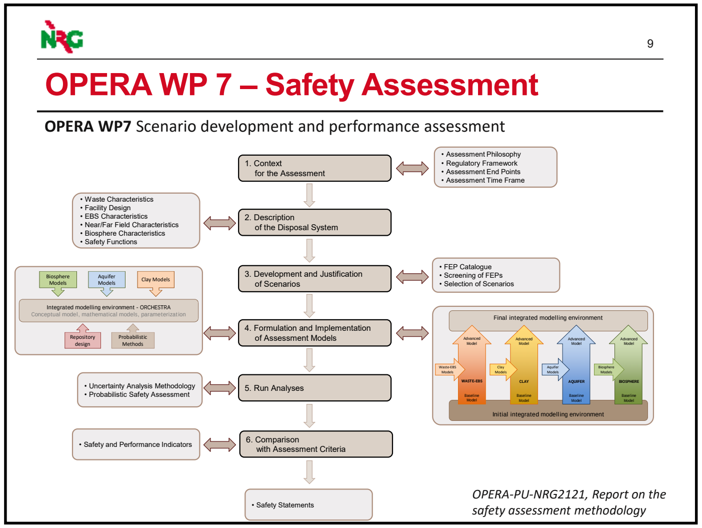
IAEA, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, Specific Safety Guide No. SSG-23, STI/PUB/1553, Vienna, September 2012

OPERA WP 1-6: basis for the PA

32 technical OPERA reports available for download from www.covra.nl



Safety	
OPERA-PU-COV004	Research plan
OPERA-PU-COV014	Towards a safety strategy
Design	
OPERA-PG-COV008	Outline of disposal concept in clay
OPERA-PU-TUD311	Report on technical feasibility of a Dutch repository in Boom Clay
OPERA-PG-COV020	Cementitious materials in OPERA disposal concept in Boom Clay
OPERA-PG-COV023	Report on the waste families in OPERA
Geology	
OPERA-PU-TNO411	Report on geological and geohydrological characterization
OPERA-PU-TNO412	Report on the future evolution of the geosphere properties
OPERA-PU-TNO421-1	Report on the present boundary conditions for the near-field model
OPERA-PU-TNO421-2	Report on the future boundary conditions for the near-field model
EBS and host rock evolution	
OPERA-PU-IBR511A	Report on the dissolution behaviour of HLW glasses
OPERA-PU-IBR511B	Report on the corrosion behaviour of spent research reactor fuel
OPERA-PU-IBR512	LILW degradation processes and products
OPERA-PU-SCK513	Report on assessment of the corrosion behaviour of carbon steel waste packages
OPERA-PU-SCK514	Report on degradation processes of the cementitious EBS components
OPERA-PU-SCK515	Report on the geochemical performance of the EBS
OPERA-PU-UTR521	Report on the geochemical characterization of Boom Clay
OPERA-PU-TNO521-1	Report on mineralogical and geochemical characterization of Boom Clay
OPERA-PU-TNO521-2	Report on the composition of deep groundwater in the Netherlands
OPERA-PU-TNO521-3	Autonomous geochemical development of the Boom Clay: Literature review and modelling (draft available)
OPERA-PU-TNO522	Geochemical interactions and groundwater transport in the Rupel Clay. A generic model analysis. (draft available)
OPERA-PU-BGS523	Thermo-hydro-mechanical behaviour of Boom Clay (in preparation)
Radionuclide migration	
OPERA-PU-UTR611-1	Report on determining redox properties of clay-rich sedimentary deposits
OPERA-PU-NRG6121	Report on model representation of radionuclide sorption in Boom Clay
OPERA-PU-NRG6122	Reference database with sorption properties
OPERA-PU-NRG6123	Final report on radionuclide sorption in Boom Clay
OPERA-PU-NRG6131	Model representation of radionuclide diffusion in Boom Clay
OPERA-PU-NRG6132	Reference database with diffusion properties
OPERA-PU-SCK614	Presence and mobility of colloidal particles
OPERA-PU-BGS615	Properties and Behaviour of the Boom Clay Formation within a Dutch Repository
OPERA-PU-BGS616	Report on gas migration in the EBS and in Boom Clay (in preparation)
OPERA-PU-DLT621	Report on hydrological transport in the surrounding rock formations



OPERA WP 7 – Safety Assessment

OPERA WP7 Scenario development and performance assessment

1. Context for the Assessment
- Assessment Philosophy
- Regulatory Framework
- Assessment End Points
- Assessment Time Frame

2. Description of the Disposal System
- Waste Characteristics
- Facility Design
- EBS Characteristics
- Near/Far Field Characteristics
- Biosphere Characteristics
- Safety Functions

3. Development and Justification of Scenarios
- FEP Catalogue
- Screening of FEPs
- Selection of Scenarios

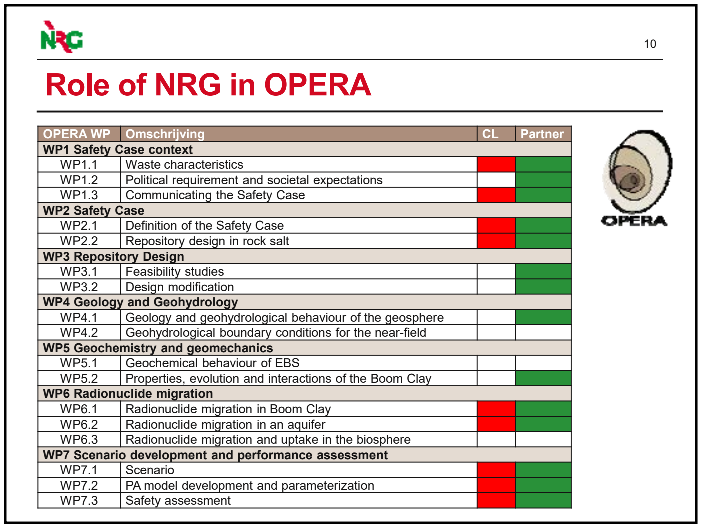
4. Formulation and Implementation of Assessment Models

5. Run Analyses
- Uncertainty Analysis Methodology
- Probabilistic Safety Assessment

6. Comparison with Assessment Criteria
- Safety and Performance Indicators

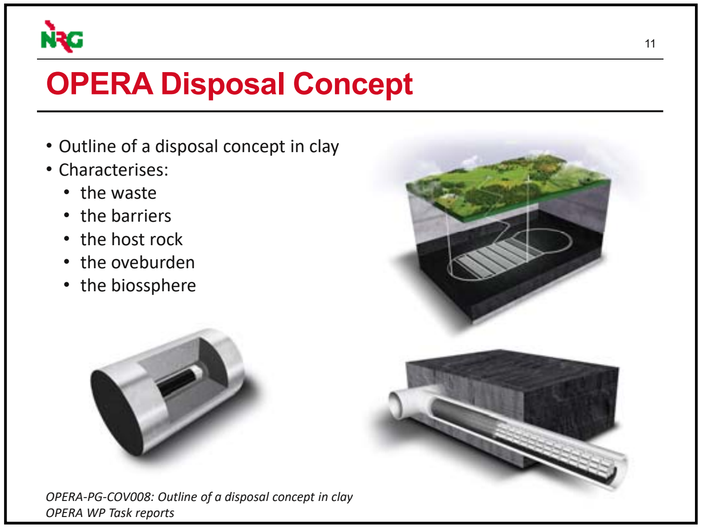
- Safety Statements

OPERA-PU-NRG2121, Report on the safety assessment methodology



Role of NRG in OPERA

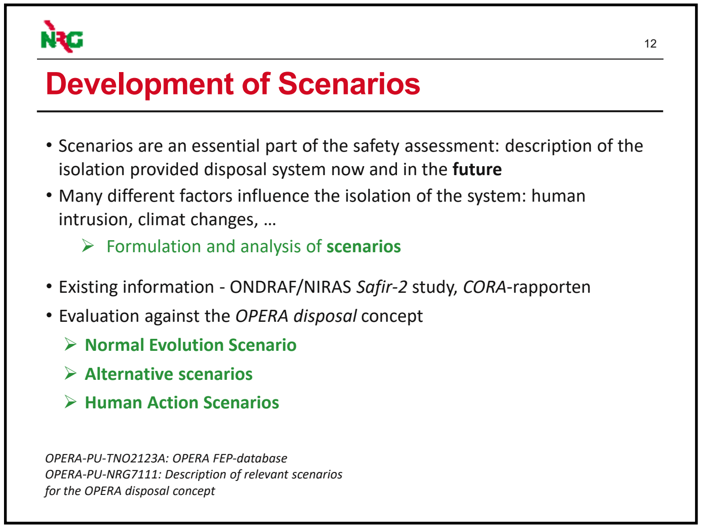
OPERA WP	Omschrijving	CL	Partner
WP1 Safety Case context			
WP1.1	Waste characteristics	🟥	🟩
WP1.2	Political requirement and societal expectations		🟩
WP1.3	Communicating the Safety Case	🟥	🟩
WP2 Safety Case			
WP2.1	Definition of the Safety Case	🟥	🟩
WP2.2	Repository design in rock salt	🟥	🟩
WP3 Repository Design			
WP3.1	Feasibility studies		🟩
WP3.2	Design modification		🟩
WP4 Geology and Geohydrology			
WP4.1	Geology and geohydrological behaviour of the geosphere		🟩
WP4.2	Geohydrological boundary conditions for the near-field		
WP5 Geochemistry and geomechanics			
WP5.1	Geochemical behaviour of EBS		
WP5.2	Properties, evolution and interactions of the Boom Clay		🟩
WP6 Radionuclide migration			
WP6.1	Radionuclide migration in Boom Clay	🟥	🟩
WP6.2	Radionuclide migration in an aquifer	🟥	🟩
WP6.3	Radionuclide migration and uptake in the biosphere		
WP7 Scenario development and performance assessment			
WP7.1	Scenario	🟥	🟩
WP7.2	PA model development and parameterization	🟥	🟩
WP7.3	Safety assessment	🟥	🟩



OPERA Disposal Concept

- Outline of a disposal concept in clay
- Characterises:
  - the waste
  - the barriers
  - the host rock
  - the overburden
  - the biossphere

OPERA-PG-COV008: Outline of a disposal concept in clay
OPERA WP Task reports



Development of Scenarios

- Scenarios are an essential part of the safety assessment: description of the isolation provided disposal system now and in the **future**
- Many different factors influence the isolation of the system: human intrusion, climat changes, …
  - ➢ Formulation and analysis of **scenarios**
- Existing information - ONDRAF/NIRAS *Safir-2* study, *CORA*-rapporten
- Evaluation against the *OPERA disposal* concept
  - ➢ **Normal Evolution Scenario**
  - ➢ **Alternative scenarios**
  - ➢ **Human Action Scenarios**

OPERA-PU-TNO2123A: OPERA FEP-database
OPERA-PU-NRG7111: Description of relevant scenarios for the OPERA disposal concept

Development of Scenarios

- **Normal Evolution Scenario**; likely future development (split into 5 assessment cases)
- **Alternative Evolution Scenario's , unlikely future developments** e.g.:
  - Abandonment of a facility before proper closure
  - Early failure of seals
  - Undetected faults in the host rock
  - Intense glacification involving massive ice covers and abundant melt water, glacial valleys
- **Human Action Scenarios**; drilling and mining activities, injection and.or extraction of fluids, …

➢ **In total 24 assessment cases have been identified**

OPERA-PU-NRG7111: Final report on the description of relevant scenarios for the OPERA reference concept in Boom Clay

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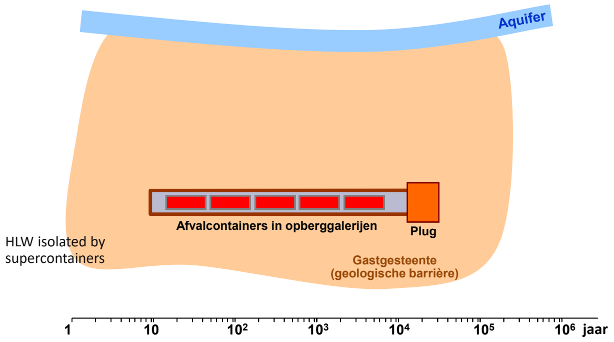
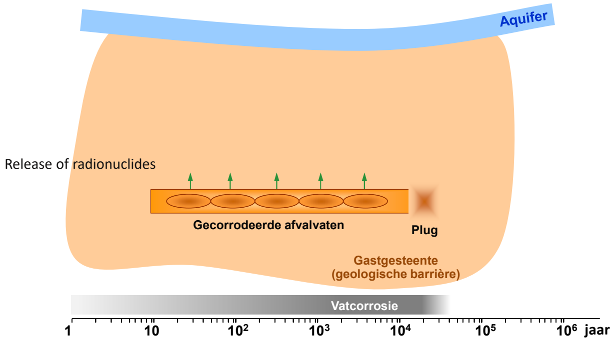
Normal Evolution

Initial condition – after emplacment of the waste



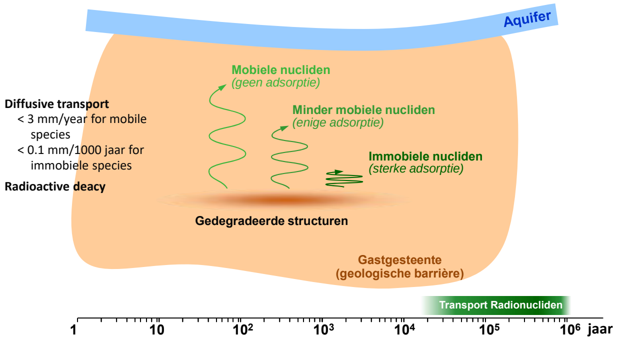
Normal Evolution

After some thousands of years



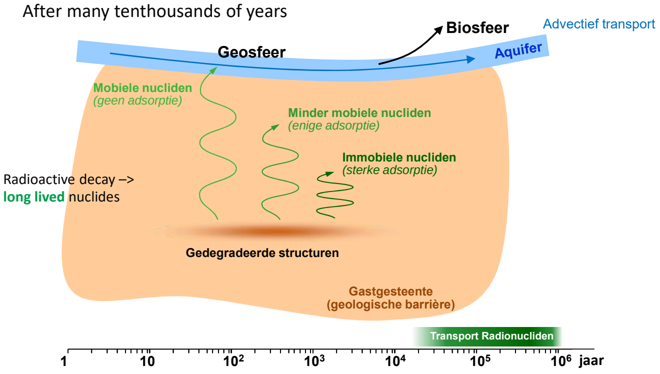
Normal Evolution

After some tenthousands of years



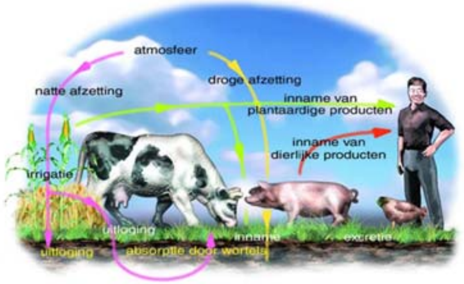
Normal Evolution

After many tenthousands of years

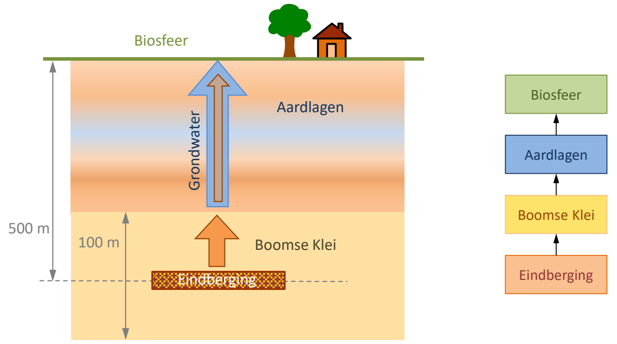


Normal Evolution - Biosphere

- Radionucliden reach the biospherte through groundwater
- A small fraction of the groundwater enters the food chain
- Exposure by consumption
- Changes in biosphere (climat, etc) influence the exposure

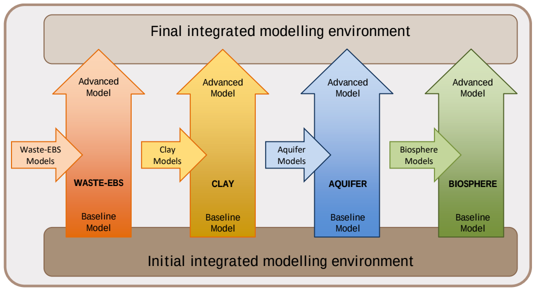


Normal Evolution - OPERA

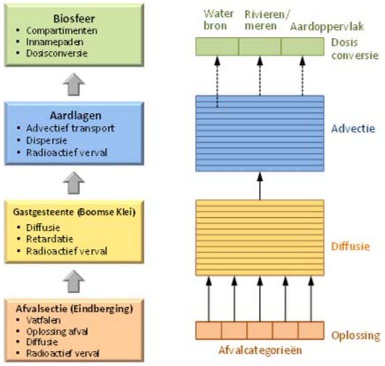


Formulation and implementation of PA-model

Translation of the the information from OPERA tasks
to a PA calcualtuon model



ORCHESTRA Integral PA Model



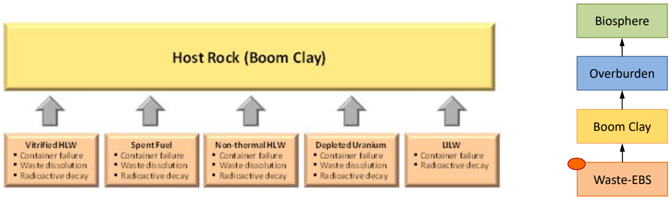
ORCHESTRA:
Objects Representing CHEmical Speciation and TRAnsport

- Open source code
- Modelling of most relevant processes that affect the radionuclidetransport

www.orchestra.meeussen.nl

Compartment *Waste-EBS*

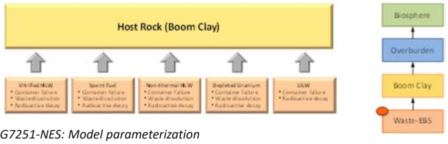
- RN inventories – OPERA waste categories ("*Waste Families*")
- distinguished by:
  - Conditioning of the waste – Supercontainer *vs* compacted
  - Release – instantaneous *vs* long-term



OPERA-PG-COV023: Waste families in OPERA
OPERA-PU-IBR511A: HLW glass dissolution
OPERA-PU-IBR511B: Corrosion of spent research reactor fuels

Compartment *Waste-EBS*

Afvalsectie	Conditioning	Failure [year]	Release [1/year]
Vitrified HLW	OPERA Supercontainer	15’000	$1.54 \cdot 10^{-4}$
Spent Fuel	OPERA Supercontainer	15’000	∞
Non heat producing HLW	OPERA Supercontainer	15’000	∞
Depleted uranium	KONRAD-II container	1500	∞
LILW	Beton	0	∞



OPERA-PU-NRG7251-NES: Model parameterization

ADSORPTION IN BOOM CLAY

Speciation

The term ‘speciation’ describes the distribution of an element over different chemical bindings or forms. E.g. uranium can – dependent on the chemical conditions - be present as mineral phase UO2, as charged soluble ion UO22+, as uncharged soluble UO2(OH)2, or, most likely, as a mixture of these (and other) species. The speciation determines which part is ‘mobile’ (i.e. present in solution) and which part is immobile (i.e. part of the solid

Redox chemistry

The term ‘redox chemistry’ describes the altering speciation of elements under variable oxygen concentrations.

Colloids

Of particular interest for this study are colloids that have strong adsorption capabilities, e.g. amorphous iron(hydr)oxide or dissolved organic carbon (DOC). These colloids can affect the migration behaviour of radionuclides: while adsorption in general leads to immobilisation, adsorption to (mobile) colloids might increase the mobility of radionuclides, denoted in literature as ‘facilitated transport’.

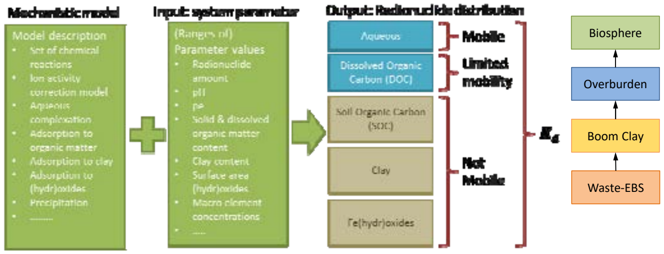
Adsorption reactions

In adsorption literature, usually two types of sorption processes are distinguished:

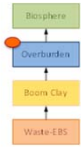
- sorption in the electrostatic double layer of a particle, often expressed as “ion exchange”
- specific interaction with surface groups of the sorbent, often expressed as “surface complexation”

PA-COMPARTMENT BOOM CLAY

- Mechanistic model calculates distribution of nuclides over different system phases using set of thermodynamic and physical parameters as input
- This information is used to calculate mobility (retardation factor), using ORCHESTRA

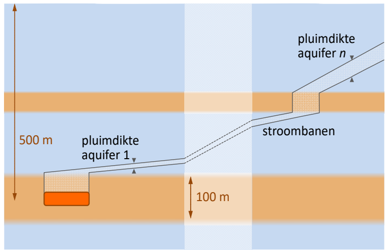


Compartment *Overburden*



Hydrologic model

- Geohydrologic model based on existing national model NHI (Netherlands Hydrological Instrument)
- **Flow path** analyse
- Important processes/parameters:
  - Advectieve flow
  - Path length
  - Effective flow velocity
- Climate scenario's
  - moderate climat
  - cold climat without ice cover (permafrost)
  - cold climat with ice cover
  - warm climat



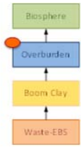
OPERA-PU-DLT621: Hydrological transport in the rock formations surrounding the host rock
OPERA-IR-NRG623: Modelling of radionuclide migration in the rock formations surrounding the host rock

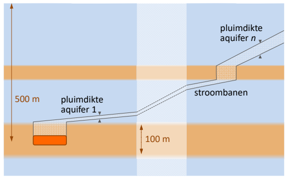
---

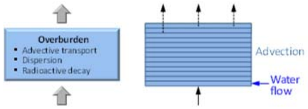
Compartment *Overburden*

- Hydrologic model flow path
- **Large distribution** in path length en residence times

Flow path	Residence time [year]	Path length [km]	Effective speed [m/year]
Fast	30'700	23.3	0.288
Median	164'000	14.0	0.0239
Slow	853'000	28.2	0.0993







OPERA-PU-DLT621: Hydrological transport in the rock formations surrounding the host rock

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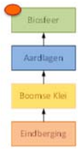
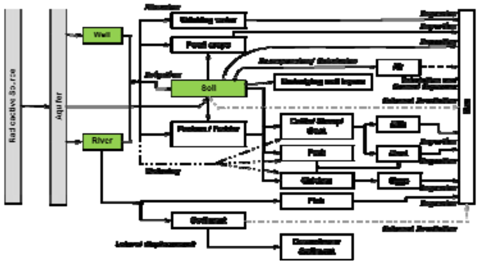
Compartment Biosphere

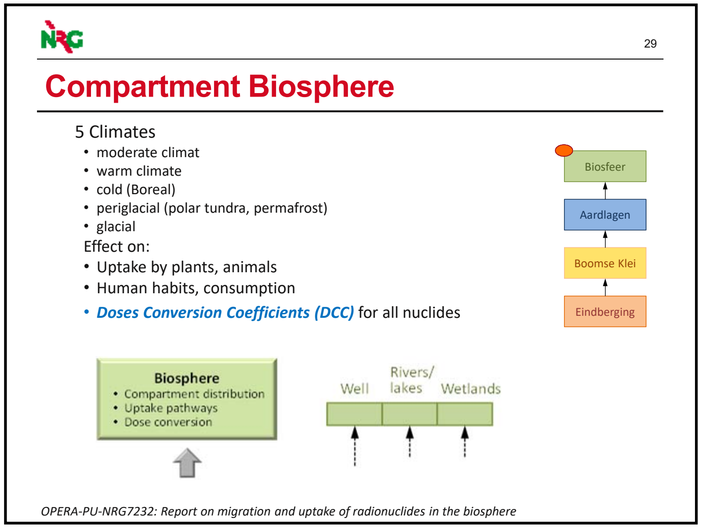
- Radionuclide concentrations in the source of water for the biotope
  - Dilution
- Water uptake into the biosphere
  - Well
  - River/lakes
  - Wetlands





➢Blootstelling aan radionucliden
Dosis Conversie Coefficient DCC

OPERA-PU-SCK631: Radionuclide migration and uptake in the biosphere

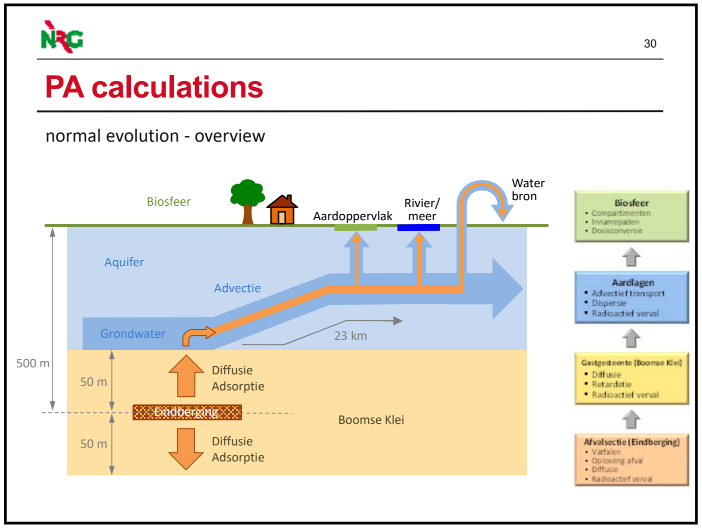


Compartment Biosphere

5 Climates
- moderate climat
- warm climate
- cold (Boreal)
- periglacial (polar tundra, permafrost)
- glacial

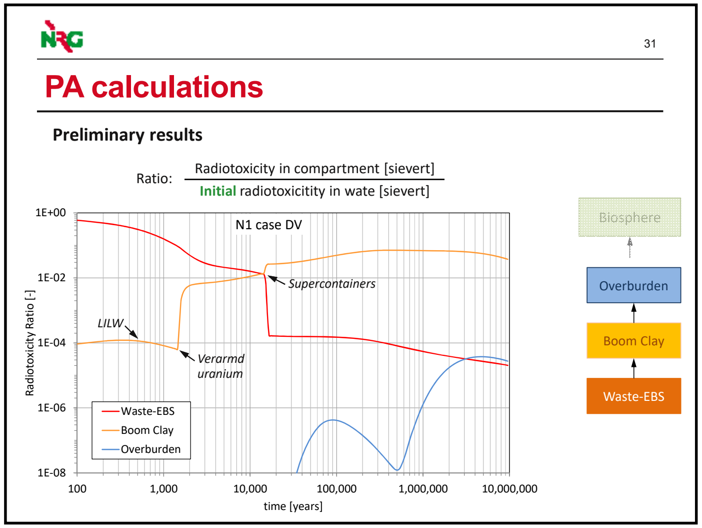
Effect on:
- Uptake by plants, animals
- Human habits, consumption
- ***Doses Conversion Coefficients (DCC)*** for all nuclides

OPERA-PU-NRG7232: Report on migration and uptake of radionuclides in the biosphere



PA calculations

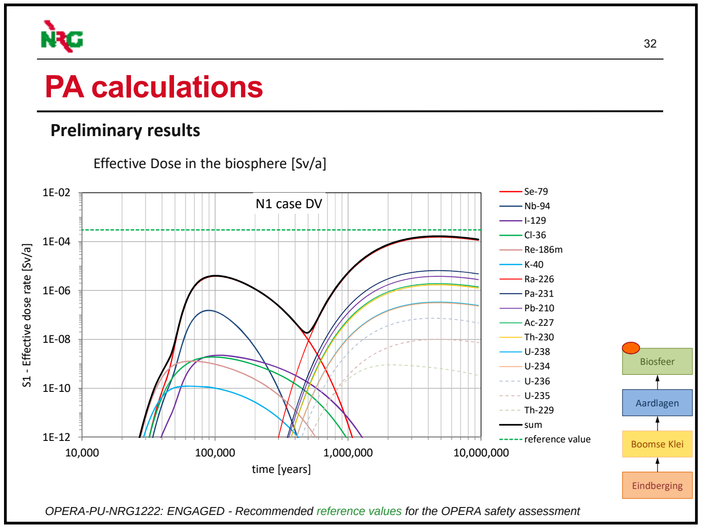
normal evolution - overview



PA calculations

Preliminary results

Ratio: $\frac{\text{Radiotoxicity in compartment [sievert]}}{\text{Initial radiotoxicitity in wate [sievert]}}$



PA calculations

Preliminary results

Effective Dose in the biosphere [Sv/a]

OPERA-PU-NRG1222: ENGAGED - Recommended reference values for the OPERA safety assessment

Evaluation of the preliminary results

- Only a **a few** (long lived) radionuclides contribute to the dose in the biosphere
- Calculations show two peaks in the effective dose:
  - For mobile nuclides (mostly anions) ~ 70’000 - 200’000 year
  - For long lived nuclides and decay chins (depleted uranium) > 1 million years; adsorption to Boom Clay
- For waste categories other than depleted uranium blijft the effectieve dose is far below reference values and legal limits
- For the waste category **depleted uranium** the effective dose can approach refernce values in the very long term (> 1 million years)

Experiences

The development of PA models in OPERA is a two track process.

- The first track, which is the main ingredient of this presentation, uses the available mathematical PA-models developed in previous research programmes, which have been further refined during the OPERA Programme.
- The second track, starts with the scenario narratives, and is based on process experts’ determination which processes need to be addressed quantitatively in the scenario model.

It is difficult to have all experts in the program cooperate effectively. As stated in the 2015 IGSC Scenario Development Workshop:

“Further development may be helpful in areas including communicating the role and choice of scenarios between experts within a waste-management programme and also to wider audiences;”

Conclusion

Assessment Basis (OPERA WP 1-6) finished - reports available for download

PA calculations (WP 7 **Safety Assessment**) are being finalised and reported

The **Safety Case Report** is being drafted by members the OPERA Safety Case group (i.e. not the researchers)

Acknowledgement

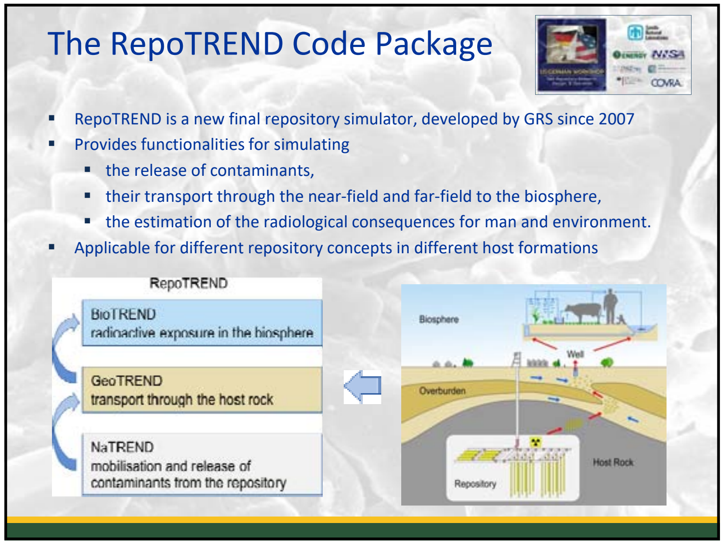
The research leading to these results has received funding from:

- The Dutch research programme on geological disposal OPERA. OPERA is financed by the Dutch Ministry of Economic Affairs and the public limited liability company Elektriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA
- The Dutch Ministry of Economic Affairs as part of the Research Programme EZS – Economische Zaken Subsidie

8th US/German Workshop on Salt Repository Research, Design, and Operation
PFLOTRAN-RepoTREND code intercomparison

Dirk-A. Becker
GRS

Middelburg, The Netherlands
September 5-7, 2017



The RepoTREND Code Package

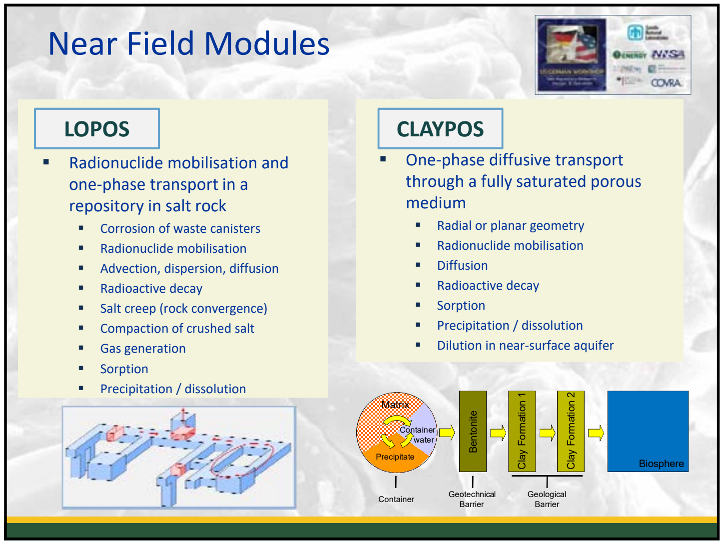
- RepoTREND is a new final repository simulator, developed by GRS since 2007
- Provides functionalities for simulating
  - the release of contaminants,
  - their transport through the near-field and far-field to the biosphere,
  - the estimation of the radiological consequences for man and environment.
- Applicable for different repository concepts in different host formations

RepoTREND

BioTREND
radioactive exposure in the biosphere

GeoTREND
transport through the host rock

NaTREND
mobilisation and release of contaminants from the repository



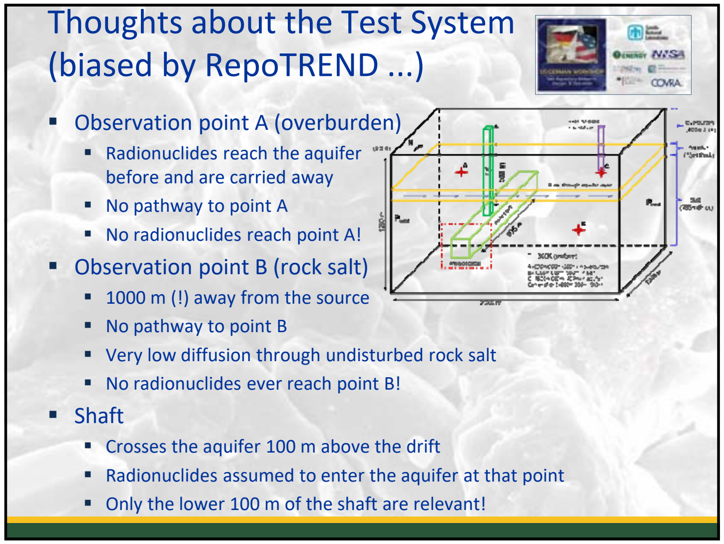
Near Field Modules

LOPOS

- Radionuclide mobilisation and one-phase transport in a repository in salt rock
  - Corrosion of waste canisters
  - Radionuclide mobilisation
  - Advection, dispersion, diffusion
  - Radioactive decay
  - Salt creep (rock convergence)
  - Compaction of crushed salt
  - Gas generation
  - Sorption
  - Precipitation / dissolution

CLAYPOS

- One-phase diffusive transport through a fully saturated porous medium
  - Radial or planar geometry
  - Radionuclide mobilisation
  - Diffusion
  - Radioactive decay
  - Sorption
  - Precipitation / dissolution
  - Dilution in near-surface aquifer

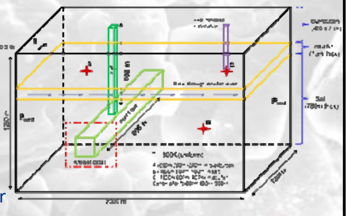


Thoughts about the Test System (biased by RepoTREND ...)

- Observation point A (overburden)
  - Radionuclides reach the aquifer before and are carried away
  - No pathway to point A
  - No radionuclides reach point A!
- Observation point B (rock salt)
  - 1000 m (!) away from the source
  - No pathway to point B
  - Very low diffusion through undisturbed rock salt
  - No radionuclides ever reach point B!
- Shaft
  - Crosses the aquifer 100 m above the drift
  - Radionuclides assumed to enter the aquifer at that point
  - Only the lower 100 m of the shaft are relevant!

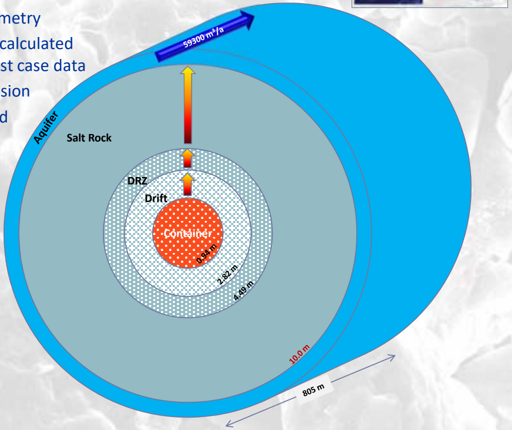
RepoTREND Models

- CLAYPOS model
  - No shaft
  - Diffusion through Drift – DRZ – Salt
- LOPOS model 1
  - No shaft
  - Drift directly connected to aquifer
  - Convergence-driven advective flow
- LOPOS model 2
  - Like LOPOS model 1 but with shaft
  - Shaft connected to the aquifer
- LOPOS model 3
  - Like LOPOS model 2 but with discretization of drift

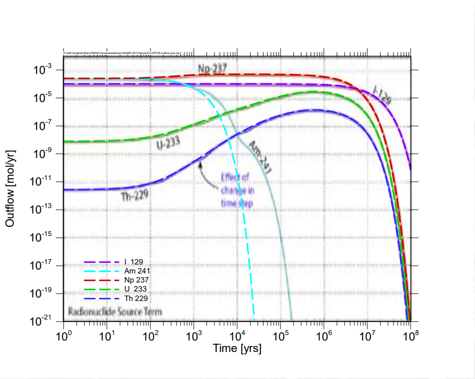


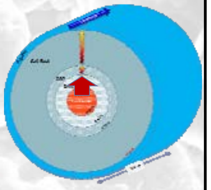
CLAYPOS Model (Diffusion)

- Cylindrical geometry
- Cross-sections calculated from agreed test case data
- Radial 1D-Diffusion
- Salt rock limited to 10 m
- Salt rock fully surrounded by aquifer
- Calculation of diffusive flows



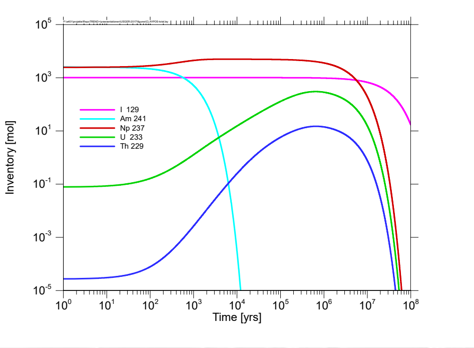
CLAYPOS Model: Outflow from Waste Form

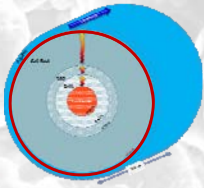


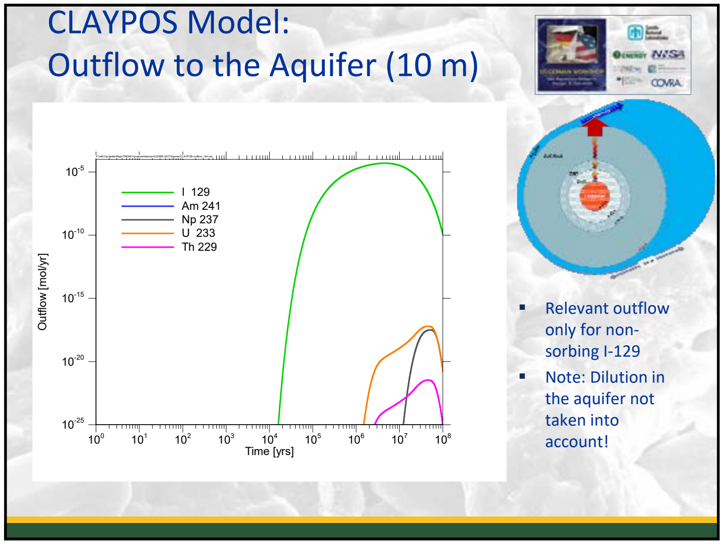


- Close agreement with SNL results
- Except Am-241

CLAYPOS Model: Total Radionuclide Content

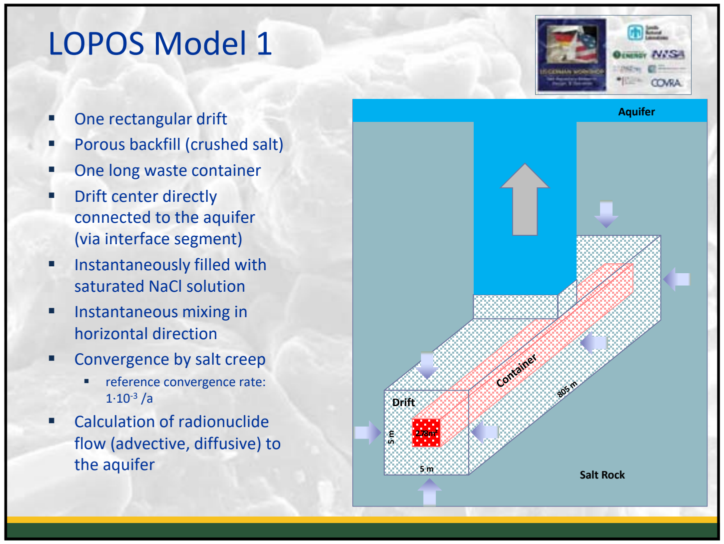






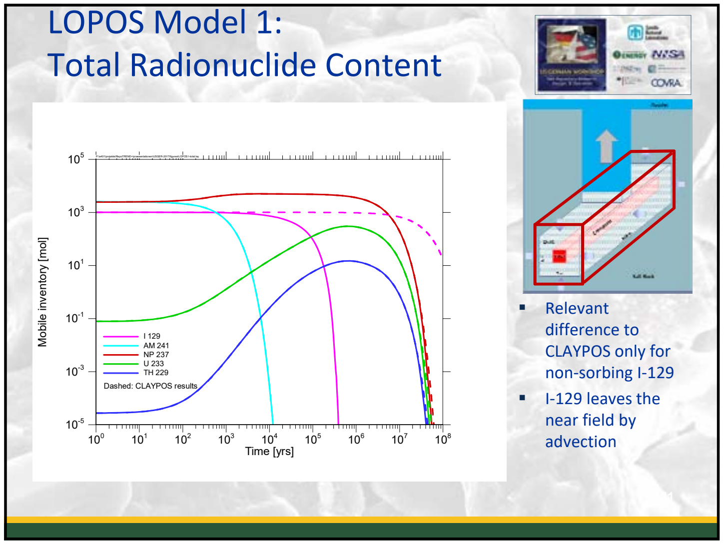
CLAYPOS Model: Outflow to the Aquifer (10 m)

- Relevant outflow only for non-sorbing I-129
- Note: Dilution in the aquifer not taken into account!



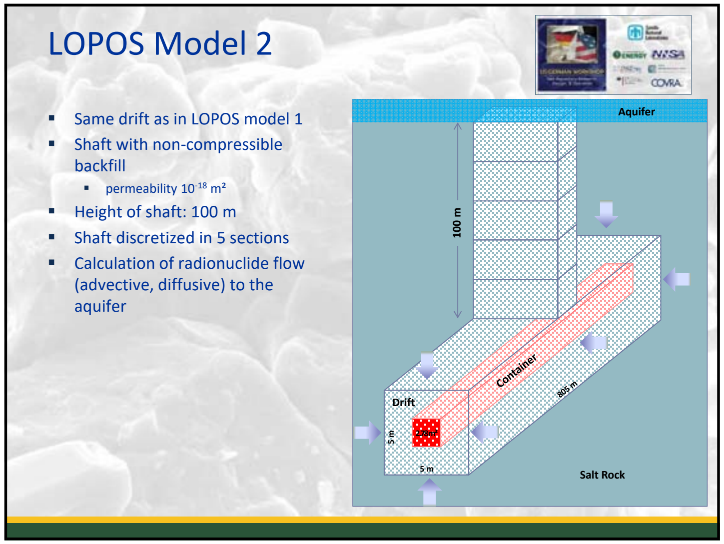
LOPOS Model 1

- One rectangular drift
- Porous backfill (crushed salt)
- One long waste container
- Drift center directly connected to the aquifer (via interface segment)
- Instantaneously filled with saturated NaCl solution
- Instantaneous mixing in horizontal direction
- Convergence by salt creep
  - reference convergence rate: $1 \cdot 10^{-3}$ /a
- Calculation of radionuclide flow (advective, diffusive) to the aquifer



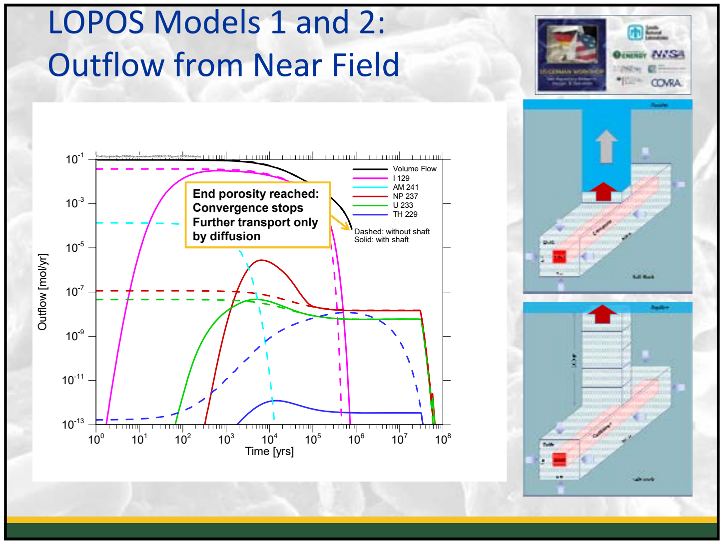
LOPOS Model 1: Total Radionuclide Content

- Relevant difference to CLAYPOS only for non-sorbing I-129
- I-129 leaves the near field by advection



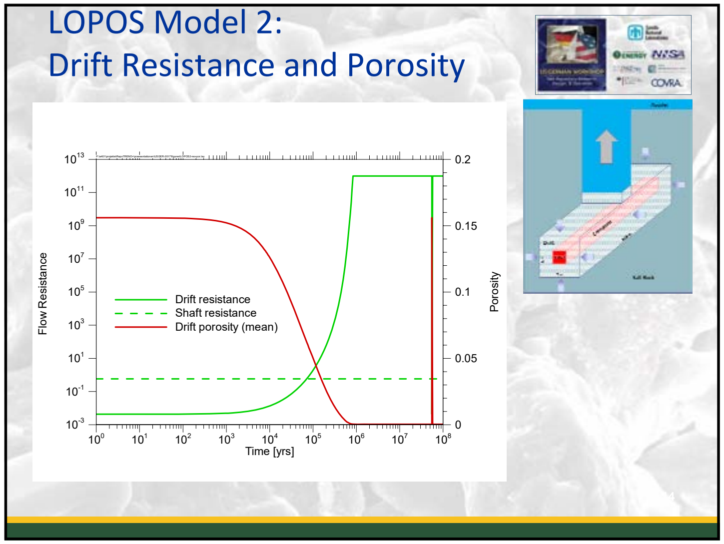
LOPOS Model 2

- Same drift as in LOPOS model 1
- Shaft with non-compressible backfill
  - permeability 10^{-18} m²
- Height of shaft: 100 m
- Shaft discretized in 5 sections
- Calculation of radionuclide flow (advective, diffusive) to the aquifer

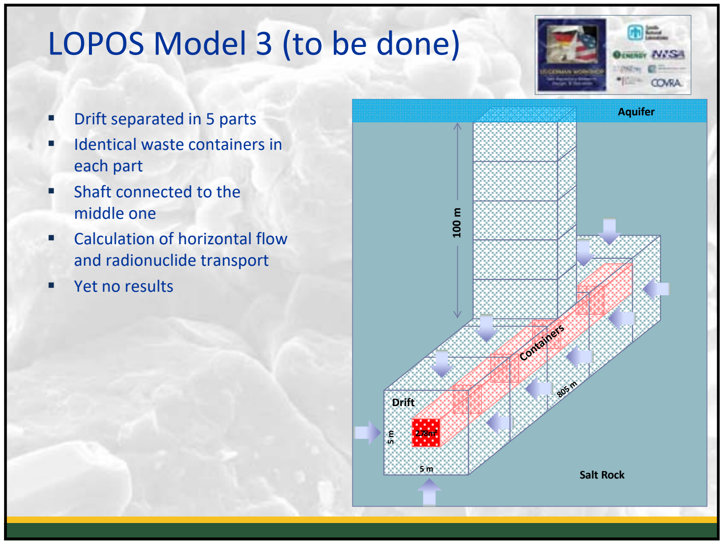


LOPOS Models 1 and 2: Outflow from Near Field

End porosity reached: Convergence stops Further transport only by diffusion

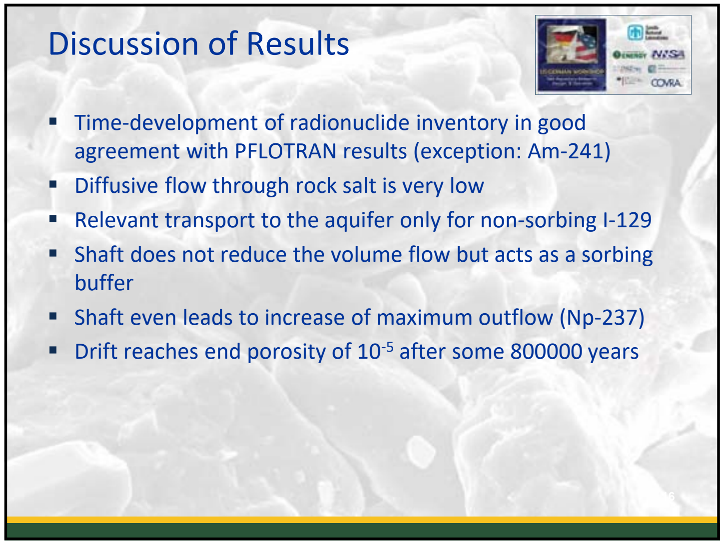


LOPOS Model 2: Drift Resistance and Porosity



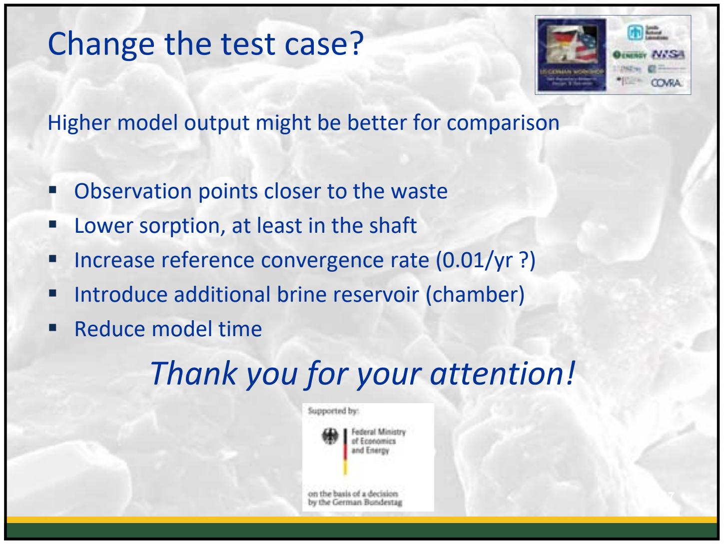
LOPOS Model 3 (to be done)

- Drift separated in 5 parts
- Identical waste containers in each part
- Shaft connected to the middle one
- Calculation of horizontal flow and radionuclide transport
- Yet no results



Discussion of Results

- Time-development of radionuclide inventory in good agreement with PFLOTRAN results (exception: Am-241)
- Diffusive flow through rock salt is very low
- Relevant transport to the aquifer only for non-sorbing I-129
- Shaft does not reduce the volume flow but acts as a sorbing buffer
- Shaft even leads to increase of maximum outflow (Np-237)
- Drift reaches end porosity of 10^{-5} after some 800000 years



Change the test case?

Higher model output might be better for comparison

- Observation points closer to the waste
- Lower sorption, at least in the shaft
- Increase reference convergence rate (0.01/yr ?)
- Introduce additional brine reservoir (chamber)
- Reduce model time

Thank you for your attention!

Supported by:
Federal Ministry of Economics and Energy
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PFLOTRAN-RepoTREND Code Inter-comparison:
Inter-comparison Plan & First PFLOTRAN Results

Jennifer M. Frederick, Emily R. Stein,
and S. David Sevougian
Sandia National Laboratories

Middelburg, The Netherlands
September 5-7, 2017

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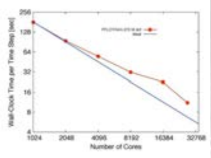
Code Inter-comparison Plan

- **What is a code inter-comparison?**
  - A comparison between two or more codes (software or programs) meant to *verify** or benchmark the codes
    ensure mathematical equations are being solved correctly
  - Based on results of the *same** simulation
    Same problem set-up or description, but implemented in each code independently
- PFLOTRAN (used and partially developed at Sandia National Laboratories, New Mexico, USA)
- RepoTREND (used and developed by GRS, Germany)
- *Do you want to join with your software?* **Contact David Sevougian sdsevou@sandia.gov**

PFLOTRAN

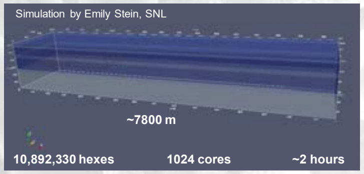
- Reactive multiphase flow and transport code for porous media
- Open source license (GNU LGPL 2.0)
- Object-oriented Fortran 2003/2008
  - Pointers to procedures
  - Classes (extendable derived types with member procedures)

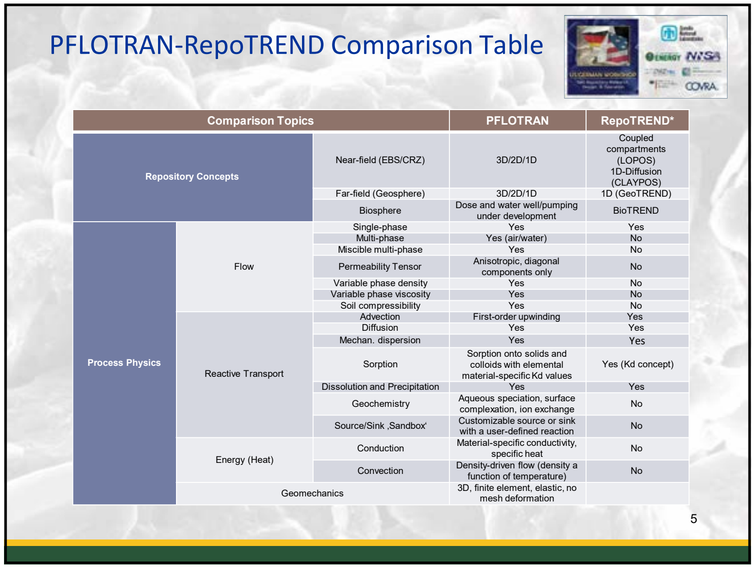


- Founded upon well-known (supported) open source libraries
  - MPI, PETSc, HDF5, METIS/ParMETIS/CMAKE
- Demonstrated performance
  - Maximum # processes: 262,144 (Jaguar supercomputer)
  - Maximum problem size: 3.34 billion degrees of freedom
  - Scales well to over 10K cores

PFLOTRAN

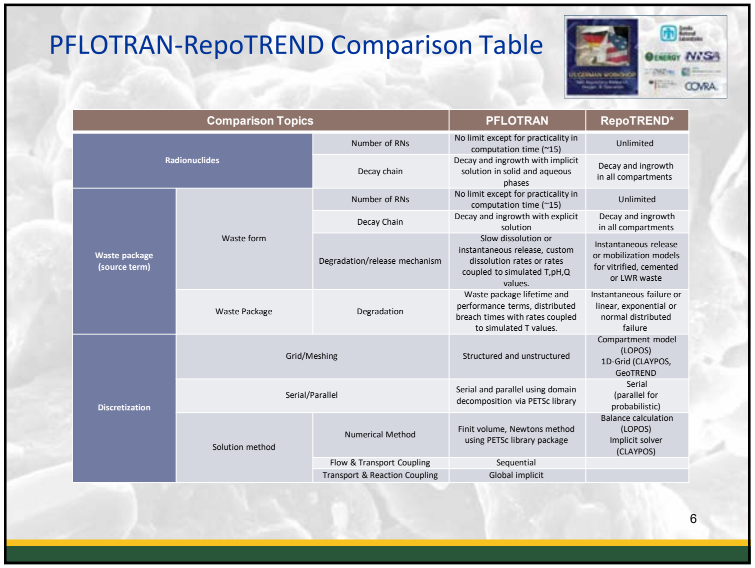
- Nuclear waste disposal
  - Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM
  - DOE Spent Fuel and Waste Science & Technology Program
  - SKB Forsmark Spent Fuel Nuclear Waste Repository (Sweden, Amphos^{21})
- Climate: coupled overland/groundwater flow; CLM
  - Next Generation Ecosystem Experiments (NGEE) Arctic
  - DOE Earth System Modeling (ESM) Program
- Biogeochemical transport modeling
- CO_2 sequestration
- Enhanced geothermal energy
- Radioisotope tracers
- Colloid-facilitated transport


Simulation by Emily Stein, SNL



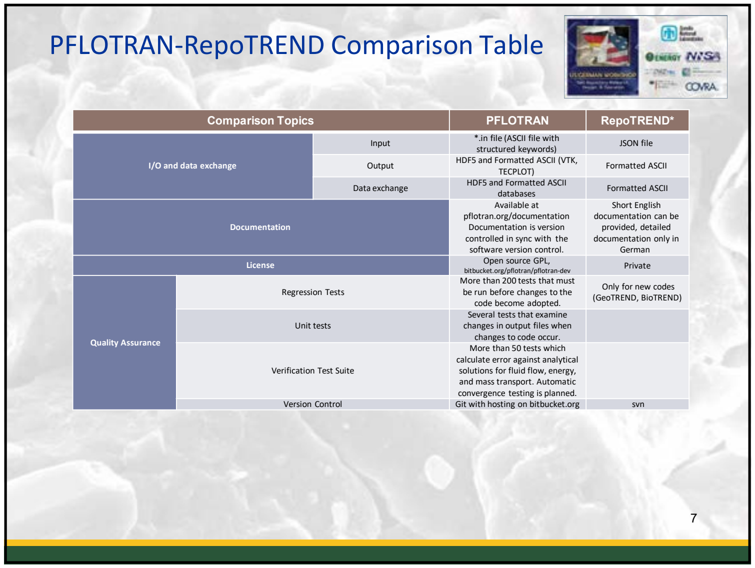
PFLOTRAN-RepoTREND Comparison Table

Comparison Topics			PFLOTRAN	RepoTREND*
Repository Concepts		Near-field (EBS/CRZ)	3D/2D/1D	Coupled compartments (LOPOS) 1D-Diffusion (CLAYPOS)
		Far-field (Geosphere)	3D/2D/1D	1D (GeoTREND)
		Biosphere	Dose and water well/pumping under development	BioTREND
Process Physics	Flow	Single-phase	Yes	Yes
		Multi-phase	Yes (air/water)	No
		Miscible multi-phase	Yes	No
		Permeability Tensor	Anisotropic, diagonal components only	No
		Variable phase density	Yes	No
		Variable phase viscosity	Yes	No
		Soil compressibility	Yes	No
	Reactive Transport	Advection	First-order upwinding	Yes
		Diffusion	Yes	Yes
		Mechan. dispersion	Yes	Yes
		Sorption	Sorption onto solids and colloids with elemental material-specific Kd values	Yes (Kd concept)
		Dissolution and Precipitation	Yes	Yes
		Geochemistry	Aqueous speciation, surface complexation, ion exchange	No
		Source/Sink ‚Sandbox'	Customizable source or sink with a user-defined reaction	No
	Energy (Heat)	Conduction	Material-specific conductivity, specific heat	No
		Convection	Density-driven flow (density a function of temperature)	No
	Geomechanics		3D, finite element, elastic, no mesh deformation	



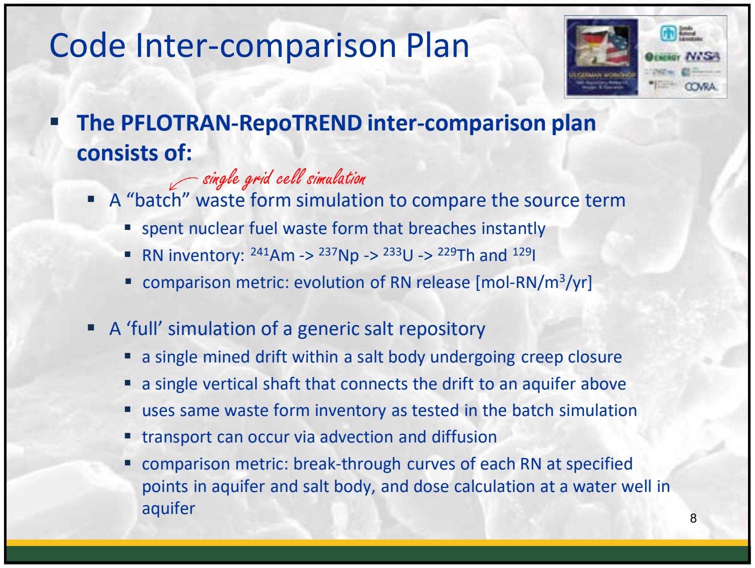
PFLOTRAN-RepoTREND Comparison Table

Comparison Topics			PFLOTRAN	RepoTREND*
Radionuclides		Number of RNs	No limit except for practicality in computation time (~15)	Unlimited
		Decay chain	Decay and ingrowth with implicit solution in solid and aqueous phases	Decay and ingrowth in all compartments
Waste package (source term)	Waste form	Number of RNs	No limit except for practicality in computation time (~15)	Unlimited
		Decay Chain	Decay and ingrowth with explicit solution	Decay and ingrowth in all compartments
		Degradation/release mechanism	Slow dissolution or instantaneous release, custom dissolution rates or rates coupled to simulated T,pH,Q values.	Instantaneous release or mobilization models for vitrified, cemented or LWR waste
	Waste Package	Degradation	Waste package lifetime and performance terms, distributed breach times with rates coupled to simulated T values.	Instantaneous failure or linear, exponential or normal distributed failure
Discretization	Grid/Meshing		Structured and unstructured	Compartment model (LOPOS) 1D-Grid (CLAYPOS, GeoTREND
	Serial/Parallel		Serial and parallel using domain decomposition via PETSc library	Serial (parallel for probabilistic)
	Solution method	Numerical Method	Finit volume, Newtons method using PETSc library package	Balance calculation (LOPOS) Implicit solver (CLAYPOS)
		Flow & Transport Coupling	Sequential	
		Transport & Reaction Coupling	Global implicit	



PFLOTRAN-RepoTREND Comparison Table

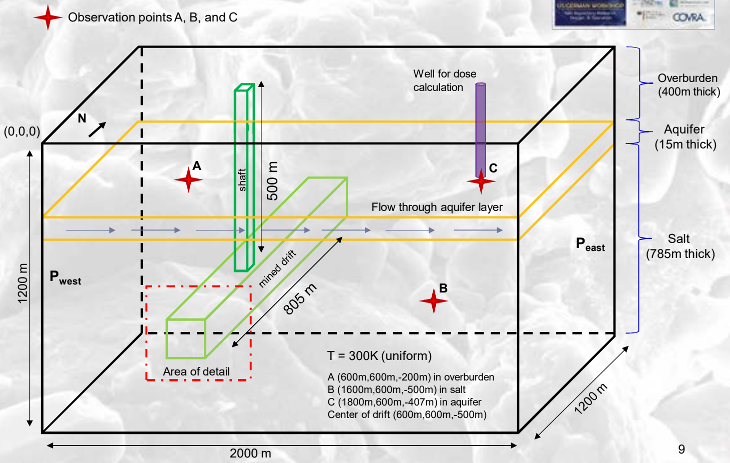
Comparison Topics			PFLOTRAN	RepoTREND*
I/O and data exchange		Input	*.in file (ASCII file with structured keywords)	JSON file
		Output	HDF5 and Formatted ASCII (VTK, TECPLOT)	Formatted ASCII
		Data exchange	HDF5 and Formatted ASCII databases	Formatted ASCII
Documentation			Available at pflotran.org/documentation Documentation is version controlled in sync with the software version control.	Short English documentation can be provided, detailed documentation only in German
License			Open source GPL, bitbucket.org/pflotran/pflotran-dev	Private
Quality Assurance	Regression Tests		More than 200 tests that must be run before changes to the code become adopted.	Only for new codes (GeoTREND, BioTREND)
	Unit tests		Several tests that examine changes in output files when changes to code occur.	
	Verification Test Suite		More than 50 tests which calculate error against analytical solutions for fluid flow, energy, and mass transport. Automatic convergence testing is planned.	
	Version Control		Git with hosting on bitbucket.org	svn



Code Inter-comparison Plan

- **The PFLOTRAN-RepoTREND inter-comparison plan consists of:**
  - single grid cell simulation
  - A "batch" waste form simulation to compare the source term
    - spent nuclear fuel waste form that breaches instantly
    - RN inventory: ^{241}Am -> ^{237}Np -> ^{233}U -> ^{229}Th and ^{129}I
    - comparison metric: evolution of RN release [mol-RN/m^3/yr]
  - A 'full' simulation of a generic salt repository
    - a single mined drift within a salt body undergoing creep closure
    - a single vertical shaft that connects the drift to an aquifer above
    - uses same waste form inventory as tested in the batch simulation
    - transport can occur via advection and diffusion
    - comparison metric: break-through curves of each RN at specified points in aquifer and salt body, and dose calculation at a water well in aquifer

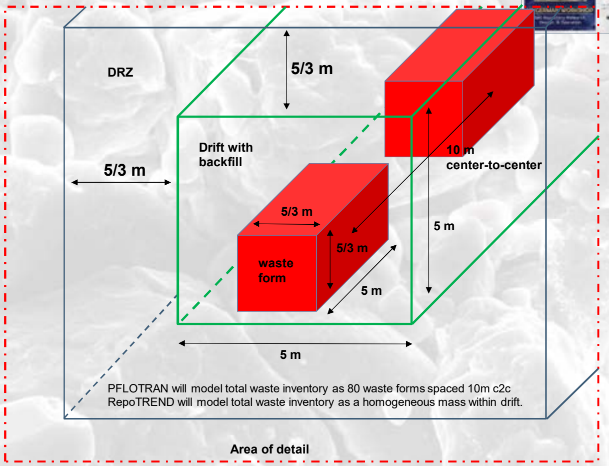
“Full” Salt Repository Simulation



T = 300K (uniform)

A (600m,600m,-200m) in overburden
B (1600m,600m,-500m) in salt
C (1800m,600m,-407m) in aquifer
Center of drift (600m,600m,-500m)

“Full” Salt Repository Simulation



PFLOTRAN will model total waste inventory as 80 waste forms spaced 10m c2c
RepoTREND will model total waste inventory as a homogeneous mass within drift.

Material Properties

MATERIAL	PERMEABILITY [M²]	EFFECTIVE POROSITY [-]	TORTUOSITY [-]	GRAIN DENSITY [KG/M³]
Salt	3.1e-23	0.018	0.01	2710
DRZ	1.1e-16 @ t=0yr 1.0e-19 @ t=200yr	0.013	0.23	2170
Overburden	1e-17	0.20	0.20	2700
Aquifer	1e-12	0.15	0.15	2820
Drift Backfill	?	?	?	2170
Shaft Backfill	1e-18	0.10	?	2170
Waste Form (SNF)	1e-17	0.50	1	5000

* Calculate effective diffusion coefficient: D_e=(porosity)(tortuosity)(2.3×10^{-9}) m^2/s

Waste Inventory

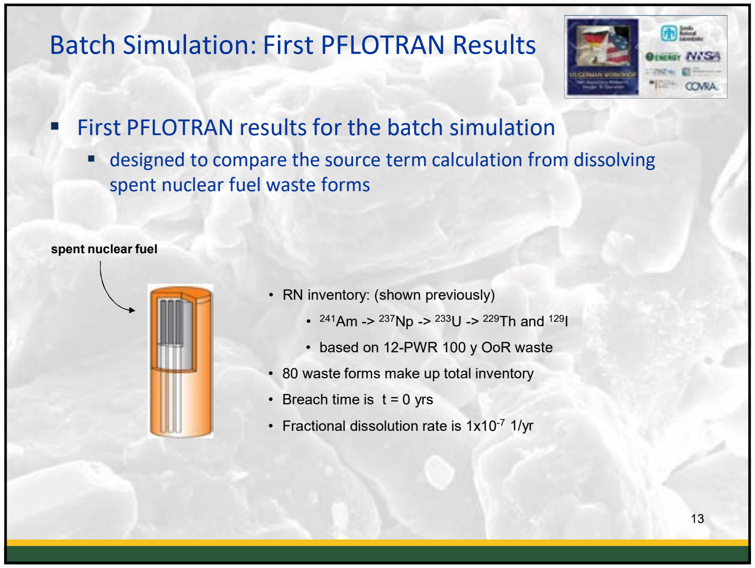
RNs considered as waste

	129I	241Am	237Np	233U	229Th
Kd value [mL/g]	0	62.5	5.5	0.6	550
Decay rate [1/s]	1.29e-15	5.08e-11	1.03e-14	1.38e-13	2.78e-12
Element solubility limit [mol/L]	unlimited	6e-6	1e-9	4e-10	4e-7
Mass fraction in waste form* [g/g]	2.17e-4	1.01e-3	9.72e-4	3.01e-8	1.03e-11
Total inventory (g)	1.3e5	6.07e5	5.85e5	1.81e1	6.19e-3

extra RNs for more accurate solubility calculation

	243Am	234U	236U	238U	230Th
Kd value [mL/g]	62.5	0.6	0.6	0.6	550
Decay rate [1/s]	2.98e-12	8.90e-14	9.20e-16	4.87e-18	2.75e-13
Element solubility limit [mol/L]	6e-6	4e-10	4e-10	4e-10	4e-7
Mass fraction in waste form* [g/g]	1.87e-4	3.55e-4	4.35e-4	6.32e-1	7.22e-8
Total inventory (g)	1.125e5	2.135e5	2.616e5	3.8e8	4.342e1

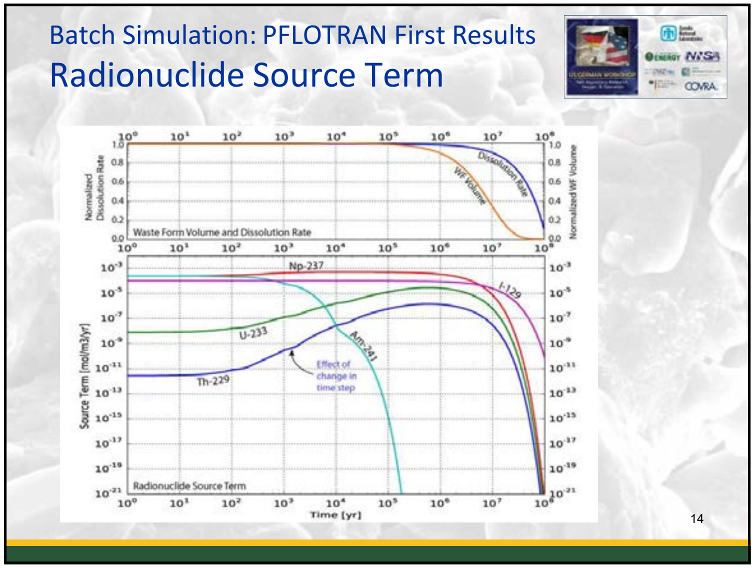
* PFLOTRAN requires a mass fraction, but RepoTREND should use the next row, total inventory.
* These mass fractions are based on 12-PWR 100 y OoR waste.



Batch Simulation: First PFLOTRAN Results

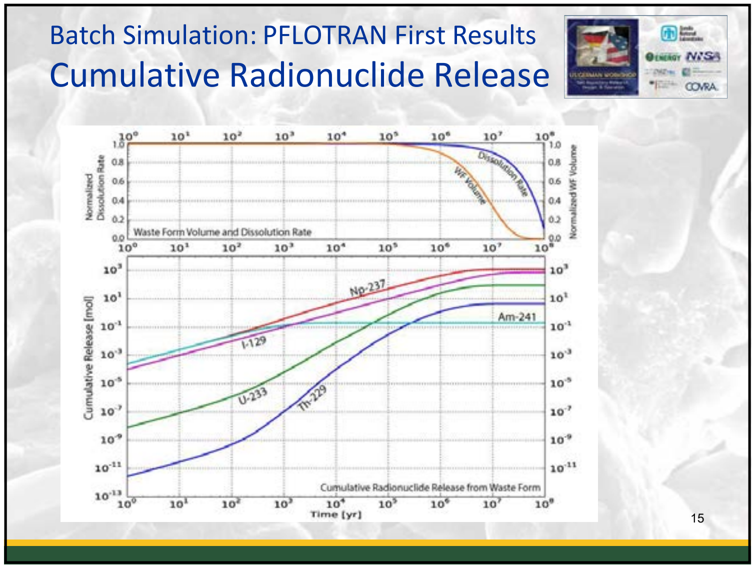
- First PFLOTRAN results for the batch simulation
  - designed to compare the source term calculation from dissolving spent nuclear fuel waste forms

- RN inventory: (shown previously)
  - ^{241}Am -> ^{237}Np -> ^{233}U -> ^{229}Th and ^{129}I
  - based on 12-PWR 100 y OoR waste
- 80 waste forms make up total inventory
- Breach time is t = 0 yrs
- Fractional dissolution rate is 1x10^{-7} 1/yr



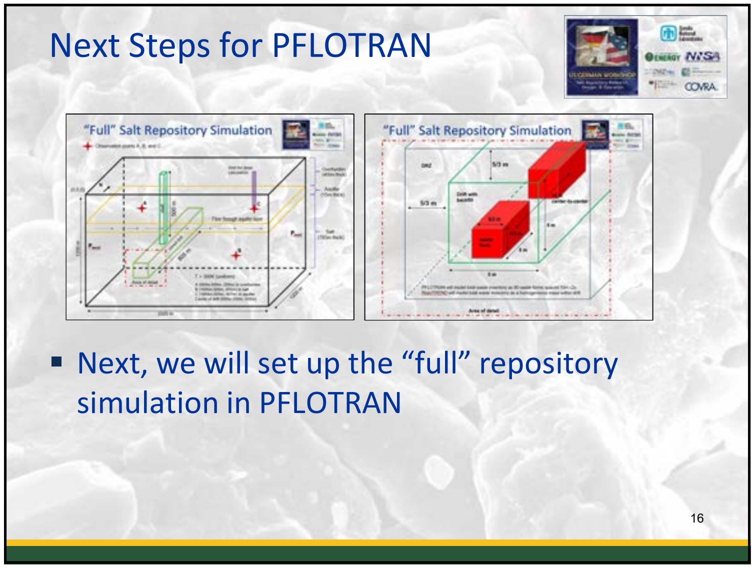
Batch Simulation: PFLOTRAN First Results

Radionuclide Source Term



Batch Simulation: PFLOTRAN First Results

Cumulative Radionuclide Release



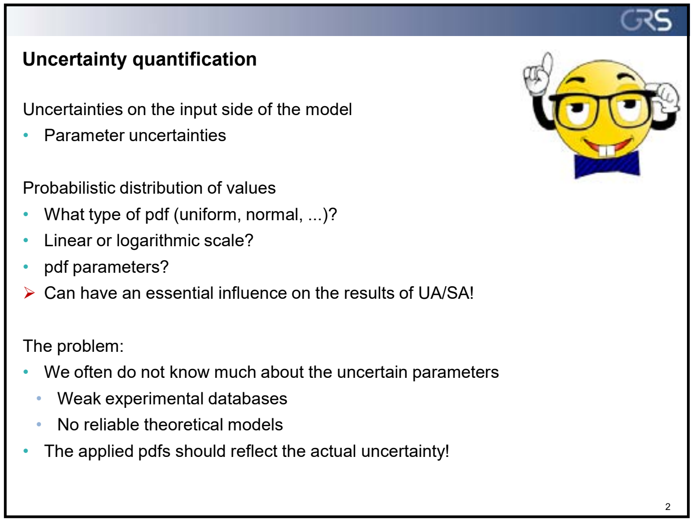
Next Steps for PFLOTRAN

- Next, we will set up the "full" repository simulation in PFLOTRAN

8th US/German Workshop on Salt Repository Research, Design, and Operation
Handling of Uncertainties in the Safety Case

Dirk-A. Becker
GRS

Middelburg, The Netherlands
September 5-7, 2017

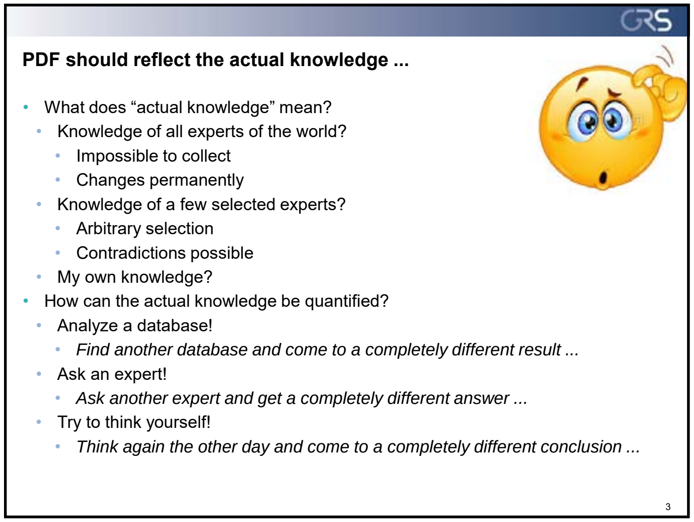


Uncertainty quantification

Uncertainties on the input side of the model
- Parameter uncertainties

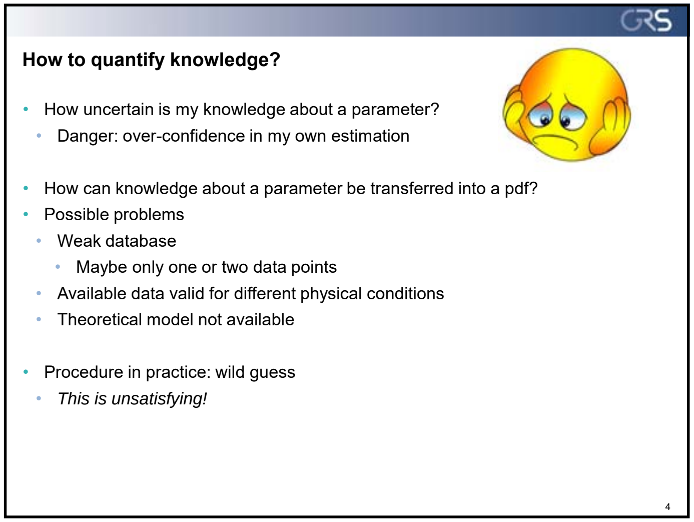
Probabilistic distribution of values
- What type of pdf (uniform, normal, ...)?
- Linear or logarithmic scale?
- pdf parameters?
- ➢ Can have an essential influence on the results of UA/SA!

The problem:
- We often do not know much about the uncertain parameters
  - Weak experimental databases
  - No reliable theoretical models
- The applied pdfs should reflect the actual uncertainty!



PDF should reflect the actual knowledge ...

- What does “actual knowledge” mean?
  - Knowledge of all experts of the world?
    - Impossible to collect
    - Changes permanently
  - Knowledge of a few selected experts?
    - Arbitrary selection
    - Contradictions possible
  - My own knowledge?
- How can the actual knowledge be quantified?
  - Analyze a database!
    - *Find another database and come to a completely different result ...*
  - Ask an expert!
    - *Ask another expert and get a completely different answer ...*
  - Try to think yourself!
    - *Think again the other day and come to a completely different conclusion ...*

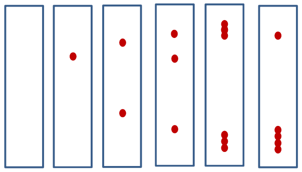


How to quantify knowledge?

- How uncertain is my knowledge about a parameter?
  - Danger: over-confidence in my own estimation
- How can knowledge about a parameter be transferred into a pdf?
- Possible problems
  - Weak database
    - Maybe only one or two data points
  - Available data valid for different physical conditions
  - Theoretical model not available
- Procedure in practice: wild guess
  - *This is unsatisfying!*

How to derive a pdf from given data?

- Assumption: weak (or nonexistent) database!
- Any additional knowledge?
  - Comparable data?
  - Theoretical model?
  - Plausibility limits?
- Linear or logarithmic scale?
- How to identify outliers?



Suppose all pdfs are properly defined ...

- Draw a sample
  - random sampling
  - stratified sampling
  - quasirandom sampling
- Perform many model runs with distributed input parameter values
- Uncertainty analysis: analyze uncertainty of the model output
  - statistical moments (mean, variance, skewness, ...)
  - quantiles
  - graphical presentation: histograms, (C)CDF, ...
- Sensitivity analysis: analyze behavior of model output under variation of input parameter values
  - local SA (derivatives ...)
  - global SA (regression, correlation, variance-based SA, ...)
  - graphical SA

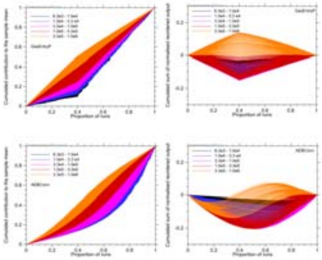
Graphical SA

- Scatterplots: model output vs. parameter value
  - ☺ Quickly produced from probabilistic data
  - ☺ Easy to understand
  - ☺ Clear qualitative message
  - ☺ Indicate parameter intervals of higher/lower sensitivity
  - ☹ Many plots necessary
  - ☹ Time-development hard to visualize
  - ☹ Plots with several parameters are confusing
- Conditional Cobweb plot / mean rank plot
  - ☺ Quick identification of most sensitive parameters
  - ☺ All parameters in one plot
  - ☹ Arbitrary condition, might be inadequate for the model
  - ☹ Not appropriate for visualizing time-development
  - ☹ Cobweb plot: confusing look
  - ☹ Cobweb plot: not appropriate for more than a few hundreds of model runs

---

Graphical SA

- CSM /CUSUNORO plot
  - ☺ Quick identification of most sensitive parameters
  - ☺ Appropriate for visualizing time-development
  - ☺ Several parameters in one plot
  - ☺ Indicate parameter intervals of higher/lower sensitivity
  - ☹ Smooth curves require big number of model runs
  - ☹ CSM: not invariant to constant shift in data
  - ☹ CSM: not possible for data with mean = 0
  - ☹ CUSUNORO: hard to explain

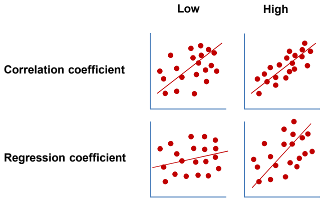


Numerical SA

- Calculation of sensitivity measures representing the total parameter interval
  - Values between -1 and 1 or between 0 and 1
  - ☺ Allows comparison and ranking
  - ☺ Allows presentation of time-development
  - ☺ Several parameters in one plot
  - ☹ Abstract, non-intuitive quantification of sensitivity
  - ☹ Sensitivity condensed to one value:
    no indication of parameter intervals of higher or lower sensitivity

Regression- and correlation-based SA

- Different concepts:



- Nevertheless: very similar results in practical cases!
- Sensitivity value between -1 and 1 for each parameter
  - ☺ Works with any sample
  - ☺ Indicates direction of influence
  - ☺ Better than often argued, even for nonlinear models
  - ☹ No detection of sensitivities that cannot be linearized

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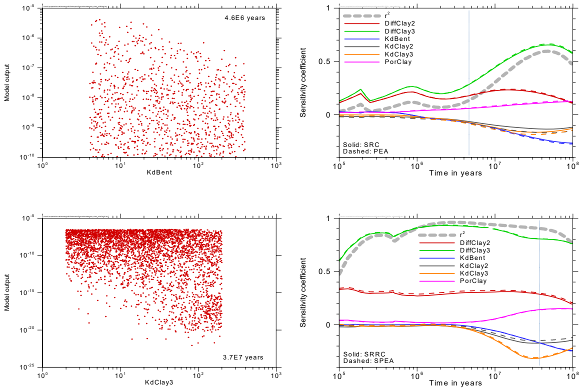
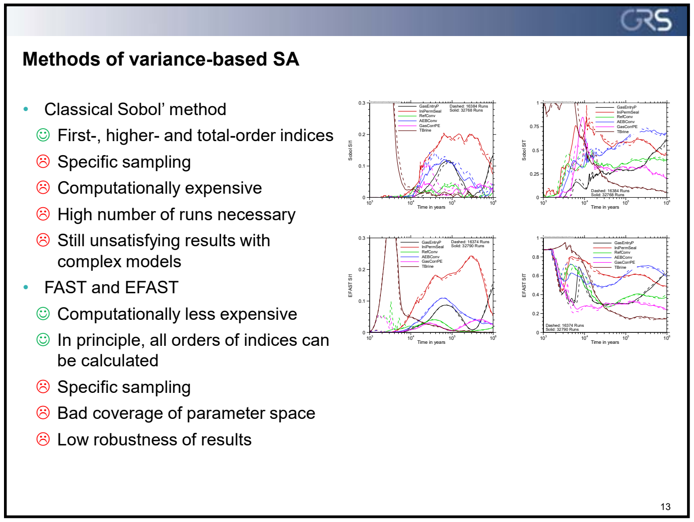
Direct vs. rank-based SA



Variance-based SA

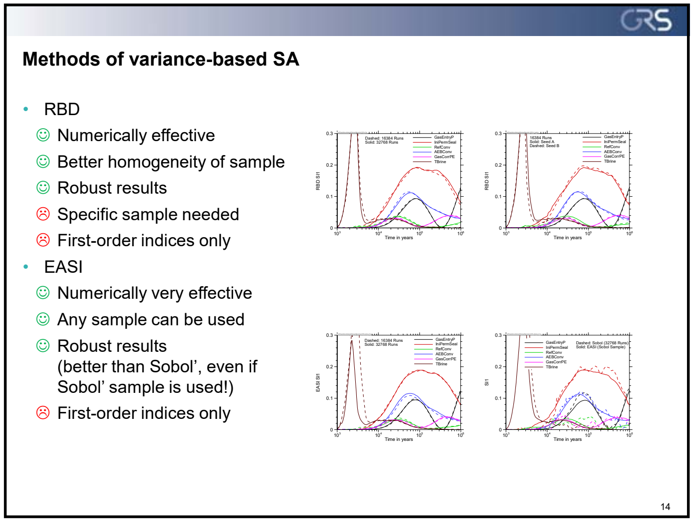
- Variance-based sensitivity indices
  - First order: influence of one parameter alone
  - Higher order: coupled influence of several parameters
  - Total order: influence of a parameter in interaction with all others
- Each index between 0 and 1 for each parameter
- Sum of all first- and higher-order indices = 1

  - ☺ Does not require model linearity or monotonicity
  - ☺ Information on influence of parameter interactions
  - ☹ No information on direction of influence



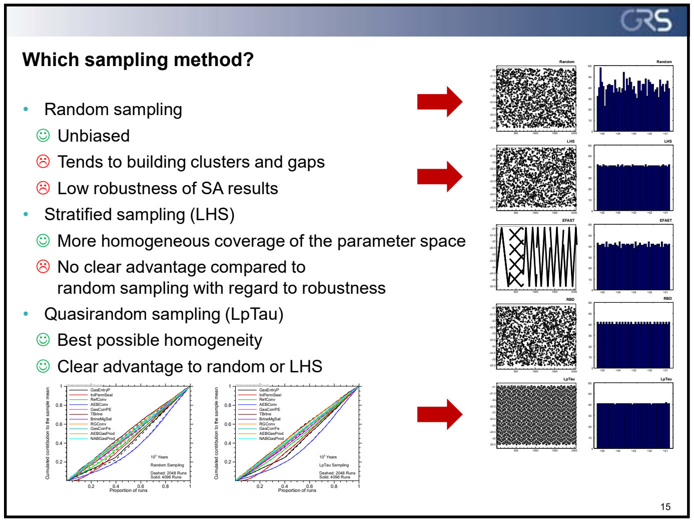
Methods of variance-based SA

- Classical Sobol' method
  - ☺ First-, higher- and total-order indices
  - ☹ Specific sampling
  - ☹ Computationally expensive
  - ☹ High number of runs necessary
  - ☹ Still unsatisfying results with complex models
- FAST and EFAST
  - ☺ Computationally less expensive
  - ☺ In principle, all orders of indices can be calculated
  - ☹ Specific sampling
  - ☹ Bad coverage of parameter space
  - ☹ Low robustness of results



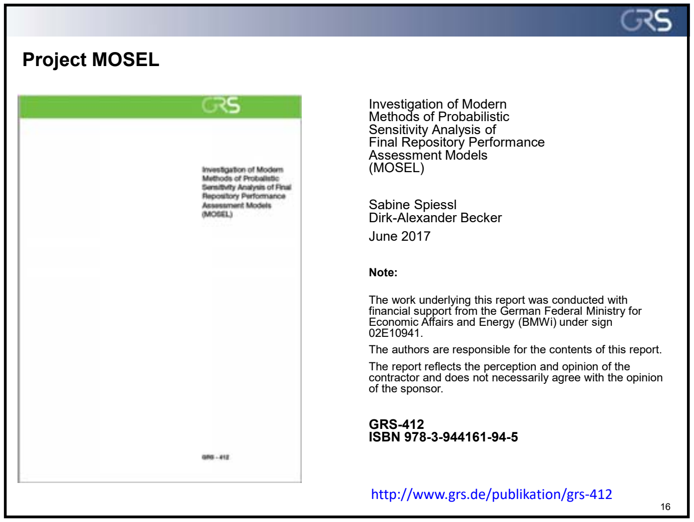
Methods of variance-based SA

- RBD
  - ☺ Numerically effective
  - ☺ Better homogeneity of sample
  - ☺ Robust results
  - ☹ Specific sample needed
  - ☹ First-order indices only
- EASI
  - ☺ Numerically very effective
  - ☺ Any sample can be used
  - ☺ Robust results (better than Sobol', even if Sobol' sample is used!)
  - ☹ First-order indices only



Which sampling method?

- Random sampling
  - ☺ Unbiased
  - ☹ Tends to building clusters and gaps
  - ☹ Low robustness of SA results
- Stratified sampling (LHS)
  - ☺ More homogeneous coverage of the parameter space
  - ☹ No clear advantage compared to random sampling with regard to robustness
- Quasirandom sampling (LpTau)
  - ☺ Best possible homogeneity
  - ☺ Clear advantage to random or LHS



Project MOSEL

Investigation of Modern
Methods of Probabilistic
Sensitivity Analysis of
Final Repository Performance
Assessment Models
(MOSEL)

Sabine Spiessl
Dirk-Alexander Becker

June 2017

Note:

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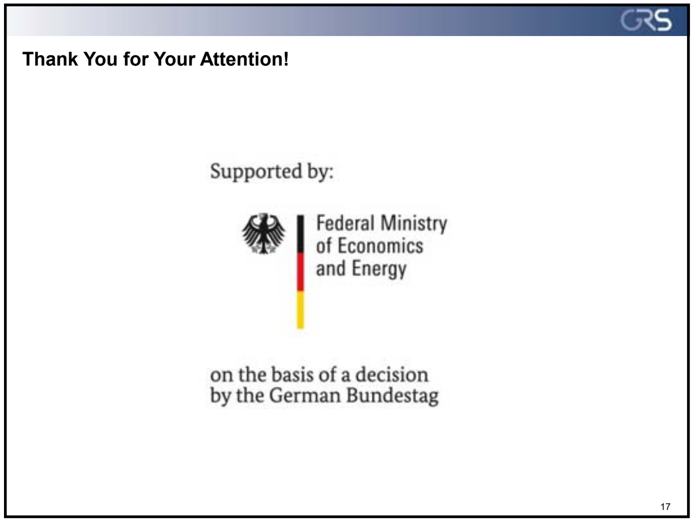

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FEP Catalogue, Database, and Knowledge Archive

Geoff Freeze, David Sevougian, Mike Gross, and Kris Kuhlman
Sandia National Laboratories (SNL)
Jens Wolf and Dieter Buhmann
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

8th US/German Workshop on Salt Repository Research, Design, and Operation
Middelburg, The Netherlands
September 5-7, 2017

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Outline

- **Objectives / Motivation for FEPs Collaboration**
- **Feature, Event, and Process (FEP) Matrix Review**
- **Update on Collaborative Results**
  - New structure/organization for FEPs and their Associated Processes
  - Full set of "generic" FEPs and Associated Processes
  - Advancements in SaltFEP Database and Salt Knowledge Archive
- **Future Work**
  - **Participants**
    - SNL: Geoff Freeze, David Sevougian, Michael Gross, Kris Kuhlman, Christi Leigh
      - DOE Spent Fuel and Waste Science and Technology (SFWST)
      - Waste Isolation Pilot Plant (WIPP)
    - GRS: Jens Wolf, Dieter Buhmann, Jörg Mönig
      - Gorleben (VSG) – domal salt
      - KOSINA – bedded salt

Objectives/Motivation for FEPs Collaboration

- **Produce a common FEP list**
  - Identify relevant FEPs for disposal of heat-generating waste (SNF and HLW) in salt
    - Applicable to all potential salt concepts and sites
    - Can support site selection
    - Now applicable to other host rocks (e.g., crystalline and argillite/shale)
  - Refine the FEP Matrix approach and organizational structure
    - Improves transparency and reduces redundancy
- **Develop an online FEP database and salt knowledge archive**
- **NEA Salt Club**
  - Produce a FEP Catalogue for use by all NEA Salt Club members
    - Countries with potential interest in salt repositories
  - Consistency with the pending update to the NEA International FEP Database

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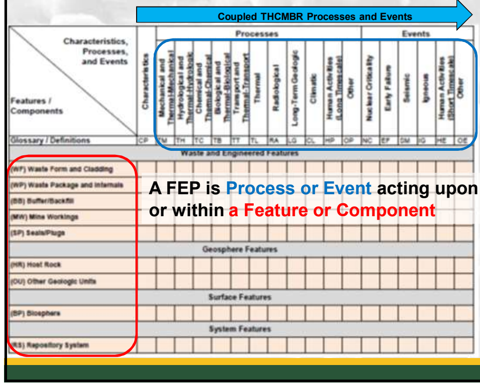
FEP Matrix Overview

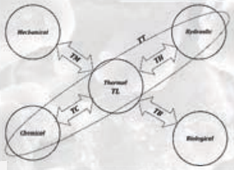
- **Two-dimensional FEP organizational structure:**
  - Columns = Process/Event Categories
  - Rows = Feature/Component Categories



Coupled THCMBR Processes and Events

Characteristics, Processes, and Events / Features / Components		Processes											Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Glossary / Definitions	CP	TM	TH	TC	TB	TT	TL	RA	LG	CL	HP	OP	NC	EF	SM	IG	HE	OE
Waste and Engineered Features																		
(WF) Waste Form and Cladding																		
(WP) Waste Package and Internals																		
(BB) Buffer/Backfill																		
(MW) Mine Workings																		
(SP) Seals/Plugs																		
Geosphere Features																		
(HR) Host Rock																		
(OU) Other Geologic Units																		
Surface Features																		
(BP) Biosphere																		
System Features																		
(RS) Repository System																		

A FEP is Process or Event acting upon or within a Feature or Component

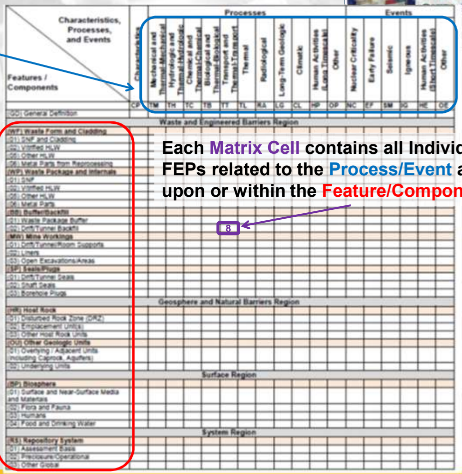


Thermal-centric organization of the processes and process coupling

Full FEP Matrix

Processes and Events
- **2-letter identifier (TM, TC, etc.)**
- **General Definition (GD)**

Features and Components
- **2-digit identifier (00, 01, etc.)**
- **Characteristic (CP)**



Each Matrix Cell contains all Individual FEPs related to the Process/Event acting upon or within the Feature/Component

Individual FEPs

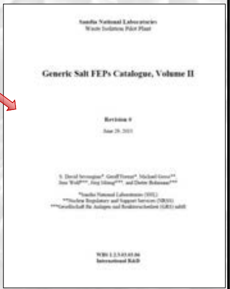
- **Each individual FEP has a unique alpha-numeric identifier**
  - Traceable to location in the FEP Matrix (row and column)
    - e.g., BB.02.TT.01, BB.02.TT.02, …
    - BB = Buffer/Backfill feature
    - BB.02 = Backfill (component 02 of the buffer/backfill feature)
    - TT = Transport process
    - 01 = first FEP in the BB.02.TT Matrix Cell
  - More descriptive than strictly numeric identifiers
  - Can still be traced to NEA FEP Database numbering scheme
- **Related FEPs can be found**
  - In the same Matrix Cell
  - Along a Row, for FEPs affecting the same feature/component
  - Along a Column, for FEPs driven by the same process/event

Associated Processes

- **Each Individual FEP defined by one or more “Associated Processes”**
  - **BB.02.TT.01 (Transport of Dissolved Radionuclides in the Liquid Phase in Backfill)**
    - (A) Advection
    - (B) Dispersion
    - (C) Diffusion
    - (D) Matrix diffusion
    - (E) Intra-aqueous complexation
    - (F) Isotopic dilution
    - (G) Dilution by mixing with formation waters
    - (H) Solubility of radionuclides and other species
  - **BB.02.TT.02 (Transport of Dissolved Radionuclides with Stationary Phases in Backfill)**
  - **….**
  - **BB.02.TT.08 (Interaction of Colloids with Other Phases in Backfill)**
- **Screening (inclusion/exclusion in PA model and/or scenario development) occurs at the “Associated Process” level**

Accomplishments

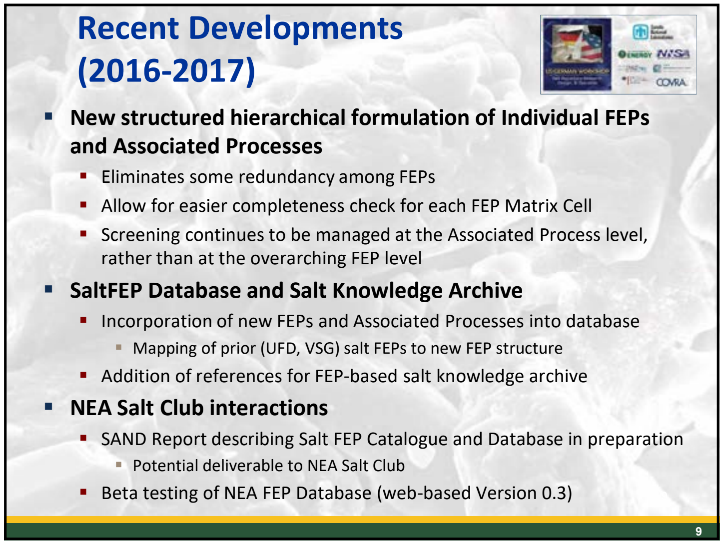
- **Combined Salt FEPs (2015)**
  - Derived from prior U.S. and German FEPs
    - Informed by NEA FEPs
  - Focus on FEPs which emphasize differences between bedded and domal salt
  - Documented in Sevougian et al. (2015)
    - FEP Descriptions
    - Preliminary, generic screening
- **Generic Repository FEPs (2016)**
  - FEP Matrix redesigned to be generally applicable to any mined concept and host rock
    - Features/components made more general, e.g.,
      - Host Rock (HR) component “Bedded or domal salt” changed to “Emplacement Unit(s)”
    - Various individual FEPs made less “salt-centric” and more general



Sandia National Laboratories
Waste Isolation Pilot Plant

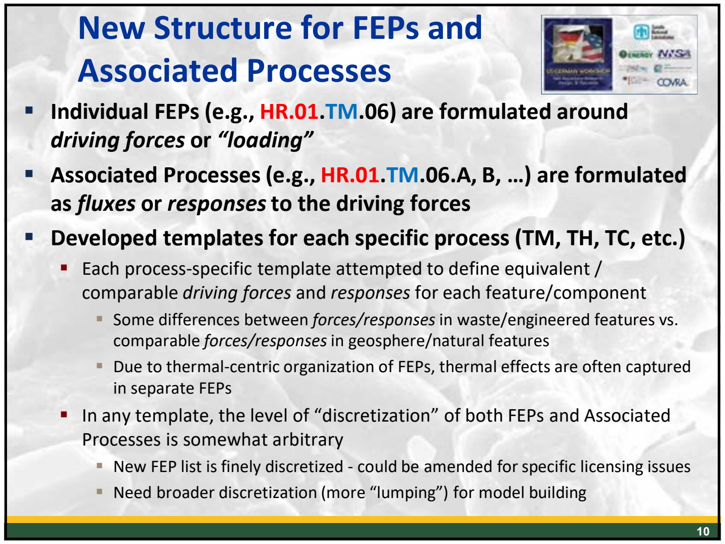
Generic Salt FEPs Catalogue, Volume II

Revision 0



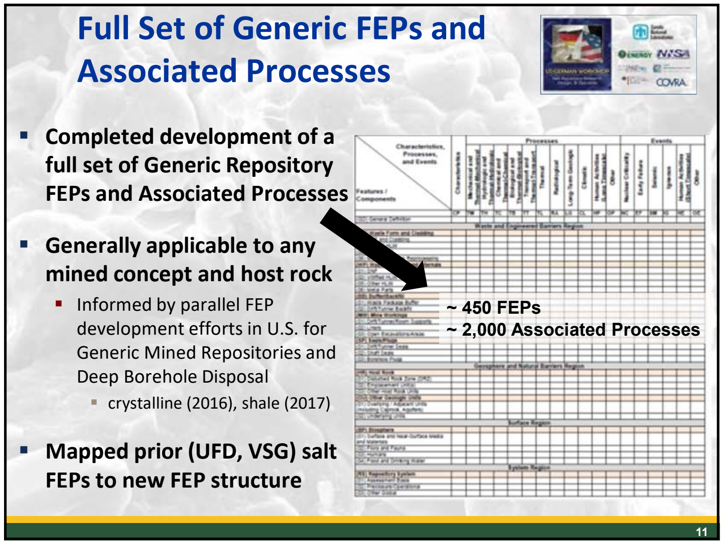
Recent Developments (2016-2017)

- **New structured hierarchical formulation of Individual FEPs and Associated Processes**
  - Eliminates some redundancy among FEPs
  - Allow for easier completeness check for each FEP Matrix Cell
  - Screening continues to be managed at the Associated Process level, rather than at the overarching FEP level
- **SaltFEP Database and Salt Knowledge Archive**
  - Incorporation of new FEPs and Associated Processes into database
    - Mapping of prior (UFD, VSG) salt FEPs to new FEP structure
  - Addition of references for FEP-based salt knowledge archive
- **NEA Salt Club interactions**
  - SAND Report describing Salt FEP Catalogue and Database in preparation
    - Potential deliverable to NEA Salt Club
  - Beta testing of NEA FEP Database (web-based Version 0.3)



New Structure for FEPs and Associated Processes

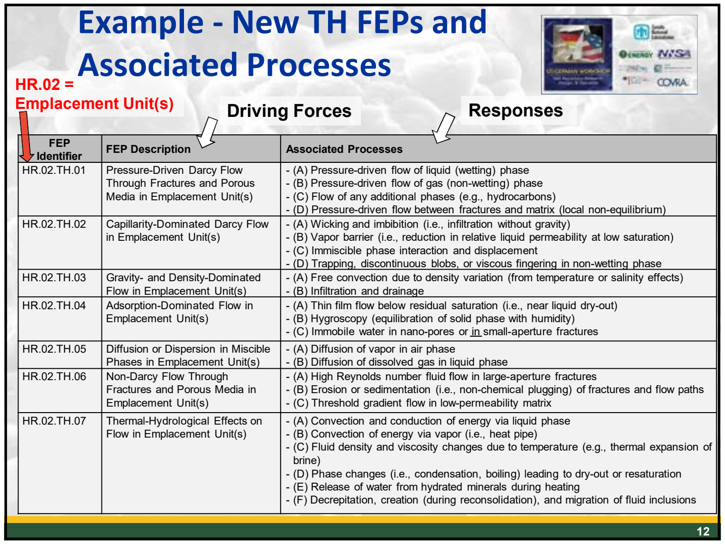
- **Individual FEPs (e.g., HR.01.TM.06) are formulated around *driving forces* or *"loading"***
- **Associated Processes (e.g., HR.01.TM.06.A, B, …) are formulated as *fluxes* or *responses* to the driving forces**
- **Developed templates for each specific process (TM, TH, TC, etc.)**
  - Each process-specific template attempted to define equivalent / comparable *driving forces* and *responses* for each feature/component
    - Some differences between *forces/responses* in waste/engineered features vs. comparable *forces/responses* in geosphere/natural features
    - Due to thermal-centric organization of FEPs, thermal effects are often captured in separate FEPs
  - In any template, the level of "discretization" of both FEPs and Associated Processes is somewhat arbitrary
    - New FEP list is finely discretized - could be amended for specific licensing issues
    - Need broader discretization (more "lumping") for model building



Full Set of Generic FEPs and Associated Processes

- **Completed development of a full set of Generic Repository FEPs and Associated Processes**
- **Generally applicable to any mined concept and host rock**
  - Informed by parallel FEP development efforts in U.S. for Generic Mined Repositories and Deep Borehole Disposal
    - crystalline (2016), shale (2017)
- **Mapped prior (UFD, VSG) salt FEPs to new FEP structure**

~ 450 FEPs
~ 2,000 Associated Processes



Example - New TH FEPs and Associated Processes

HR.02 = Emplacement Unit(s)

Driving Forces

Responses

FEP Identifier	FEP Description	Associated Processes
HR.02.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in Emplacement Unit(s)	- (A) Pressure-driven flow of liquid (wetting) phase - (B) Pressure-driven flow of gas (non-wetting) phase - (C) Flow of any additional phases (e.g., hydrocarbons) - (D) Pressure-driven flow between fractures and matrix (local non-equilibrium)
HR.02.TH.02	Capillarity-Dominated Darcy Flow in Emplacement Unit(s)	- (A) Wicking and imbibition (i.e., infiltration without gravity) - (B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation) - (C) Immiscible phase interaction and displacement - (D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase
HR.02.TH.03	Gravity- and Density-Dominated Flow in Emplacement Unit(s)	- (A) Free convection due to density variation (from temperature or salinity effects) - (B) Infiltration and drainage
HR.02.TH.04	Adsorption-Dominated Flow in Emplacement Unit(s)	- (A) Thin film flow below residual saturation (i.e., near liquid dry-out) - (B) Hygroscopy (equilibration of solid phase with humidity) - (C) Immobile water in nano-pores or in small-aperture fractures
HR.02.TH.05	Diffusion or Dispersion in Miscible Phases in Emplacement Unit(s)	- (A) Diffusion of vapor in air phase - (B) Diffusion of dissolved gas in liquid phase
HR.02.TH.06	Non-Darcy Flow Through Fractures and Porous Media in Emplacement Unit(s)	- (A) High Reynolds number fluid flow in large-aperture fractures - (B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths - (C) Threshold gradient flow in low-permeability matrix
HR.02.TH.07	Thermal-Hydrological Effects on Flow in Emplacement Unit(s)	- (A) Convection and conduction of energy via liquid phase - (B) Convection of energy via vapor (i.e., heat pipe) - (C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine) - (D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation - (E) Release of water from hydrated minerals during heating - (F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions

Example - New TM FEPs and Associated Processes

HR.01 = DRZ

Driving Forces

Responses

FEP Identifier	FEP Description	Associated Processes
HR.01.TM.01	External Stress Causes Elastic Deformation of the DRZ	(A) Closure of the excavations causes elastic deformation of the DRZ (B) Closure of the excavations opens or compresses the fractures in the DRZ (C) Failure of the drift liners or mine workings causes elastic deformation of the DRZ
HR.01.TM.02	External Stress Causes Plastic Deformation and/or Localized Failure of the DRZ	(A) Closure of the excavations causes permanent displacements along fractures in the DRZ (B) Closure of the excavations heals fractures in the DRZ (C) Backstress from backfill, drift/tunnel seals, drift supports, or drift liners accelerates healing of fractures in DRZ (D) Floor heave or spalling from the walls and back changes the cross-section or depth of the DRZ. (E) Non-thermally-induced volume changes (e.g., from closure of fractures) alter the mechanical properties of DRZ (F) Erosion or dissolution of the DRZ surrounding the Mine Workings changes the mechanical loads on the DRZ
HR.01.TM.03	Gravitational Force Causes Deformation or Failure of the DRZ	(A) Rockfall changes the cross-section and depth of the DRZ (B) Drift collapse changes the cross-section and depth of the DRZ (C) Separation and failure of a roof beam changes the cross-section and depth of the DRZ
HR.01.TM.04	Mechanical Effects of Gas Pressure on the DRZ	(A) Internal pressurization caused by gas generation, gas explosion, or closure of excavations alters the internal stress on the DRZ
HR.01.TM.05	Mechanical Effects of Liquid Pressure on the DRZ	(A) Internal pressurization caused by compression of pore water in the emplacement drifts alters the internal stress on the DRZ (B) Swelling of clay-based materials may increase pore pressure and change the effective stress on or in the DRZ and its fractures (C) Smectite illitization or other chemical reactions may increase pore pressure and change the effective stress on or in the DRZ and its fractures
HR.01.TM.06	Thermal-Mechanical Effects on the Evolution of the DRZ	(A) Thermally-enhanced closure rates / rockfall / drift collapse / floor buckling / backfill consolidation alter the stress state in the DRZ (B) Thermally-induced volume changes(thermal expansion/thermal stress/thermally-induced cracking) alter the stress state in the DRZ (C) Temperature dependence of thermal or mechanical properties may alter the response of the DRZ

Example - New TM FEPs and Associated Processes

HR.02 = Emplacement Unit(s)

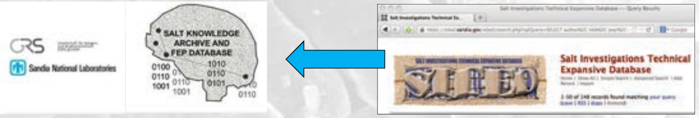
Driving Forces

Responses

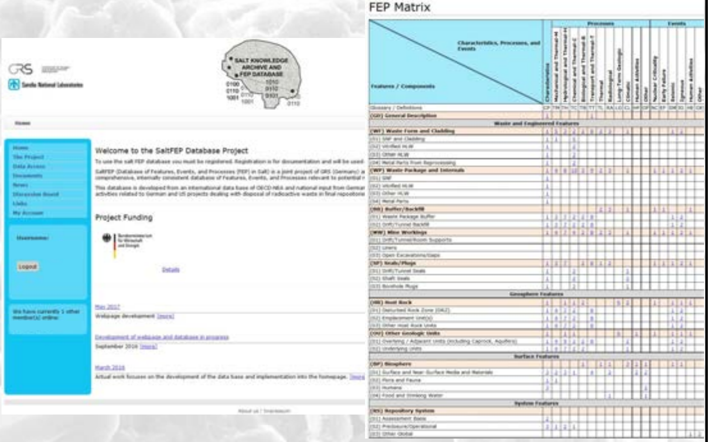
FEP Identifier	FEP Description	Associated Processes
HR.02.TM.01	External Stress Causes Elastic Deformation of the Emplacement Unit(s)	-(A) Closure of the excavations causes stress redistribution and elastic deformation of the Emplacement Unit(s) -(B) Failure of the drift liners or mine workings causes stress redistribution and elastic deformation of the Emplacement Unit(s)
HR.02.TM.02	External Stress Causes Plastic Deformation and/or Localized Failure of the Emplacement Unit(s)	-(A) Closure of the excavations causes stress redistribution and plastic deformation and/or failure of the Emplacement Unit(s) - (B) Non-thermally-induced volume changes (e.g., from swelling or cracking) in the Emplacement Unit(s) -(C) Closure of the excavations causes subsidence in the Emplacement Unit(s)
HR.02.TM.03	Gravitational Force Causes Deformation or Failure of the Emplacement Unit(s)	- (A) Formation of a rock chimney alters the mechanical state of the Emplacement Unit(s)
HR.02.TM.04	Mechanical Effects of Gas Pressure on the Emplacement Unit(s)	-(A) Internal pressurization caused by gas generation, gas explosion, or by closure of excavations alters stress in the Emplacement Unit(s) beyond the DRZ
HR.02.TM.05	Mechanical Effects of Liquid Pressure on the Emplacement Unit(s)	-(A) Internal pressurization caused by compression of pore waters in the emplacement drifts or Emplacement Unit(s) alters stress in the Emplacement Unit(s) -(B) Swelling of clay-based materials may increase pore pressure and change the effective stress in the Emplacement Unit(s) -(C) Smectite illitization or other chemical reactions may increase pore pressure and change the effective stress in the Emplacement Unit(s)
HR.02.TM.06	Thermal-Mechanical Effects in the Emplacement Unit(s)	-(A) Thermally-accelerated closure rates / rockfall / drift collapse alter the stresses in the Emplacement Unit(s) - (B) Thermally-induced volume changes (thermal expansion/thermal stress/thermally-induced cracking) alter the stresses in the Emplacement Unit(s) -(C) Temperature dependence of thermal or mechanical properties may alter the response of the Emplacement Unit(s) (D) Dryout may change the mechanical properties of the Emplacement Unit(s)

SaltFEP Database and Salt Knowledge Archive

- **www.saltfep.org**
- **Incorporation of new FEPs and Associated Processes into database**
  - Complete list of new FEPs fully incorporated into electronic database
  - Mapping of prior (UFD, VSG) salt FEPs to new FEP structure
- **New database search and evaluation functions added**
- **Addition of references for FEP-based salt knowledge archive**
  - Replaces SNL's SITED on-line archive
    - SITED has been taken offline and would require significant effort to comply with SNL network security requirements



SaltFEP Database Project



Salt Knowledge Archive

- **Add salt knowledge references from SITED**
- **SITED (web frontend to a MySQL bibliographic database, like used at libraries) had:**
  - Large number of documents (most obtained through query of other databases)
  - Many false hits (e.g., “salton sea”, “molten salt reactors”)
  - Some carefully curated content
- **Salt Knowledge Archive (as part of the saltFEP Database) will have:**
  - Smaller number of documents
  - More relevant documents
  - Linking directly to FEPs

Future Developments

- **Salt FEP Catalogue and Database**
  - Fuller description/definition of FEPs and Associated Processes
    - requires significant resources
  - Preliminary screening for salt repository
    - generic FEPs only, hard to screen without a site or design
- **Salt FEP Database and Knowledge Archive**
  - Improve database functionality
  - Add salt knowledge references from SITED
- **NEA Participation**
  - Exchange with NEA FEP Group
  - Finalize deliverable SAND Report

Acknowledgements

Supported by:

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on the basis of a decision by the German Bundestag

U.S. DEPARTMENT OF ENERGY Nuclear Energy

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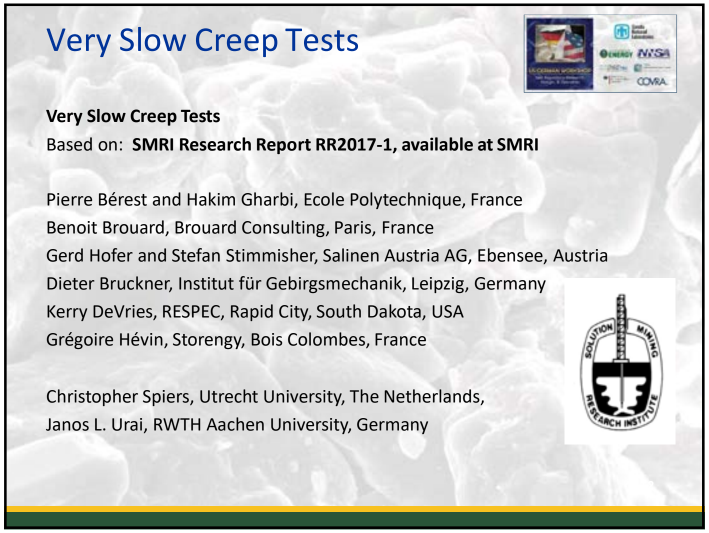

Very Slow Creep Tests

Very Slow Creep Tests
Based on: **SMRI Research Report RR2017-1, available at SMRI**

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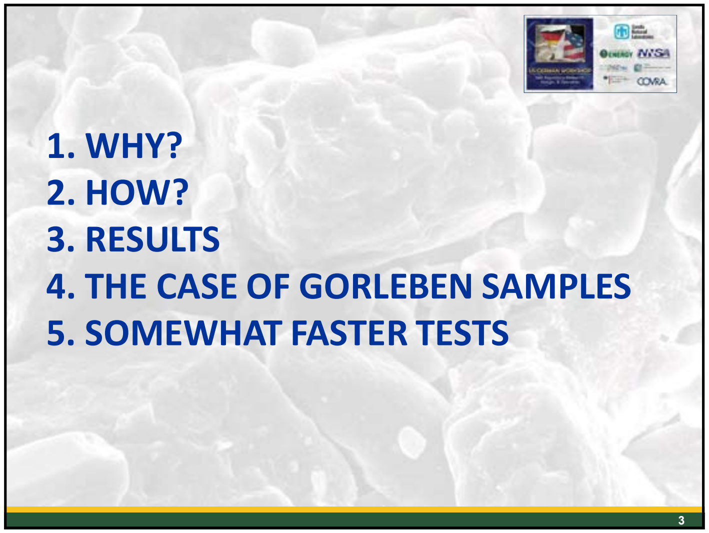


1. WHY?
2. HOW?
3. RESULTS
4. THE CASE OF GORLEBEN SAMPLES
5. SOMEWHAT FASTER TESTS

1. WHY?

It is generally accepted that (at least) the main features of the steady-state behavior of salt can be captured by the Norton-Hoff ("power") law

$$\dot{\varepsilon}^{ss} = A(T)\ \sigma^n$$

$$n = 3 - 6$$

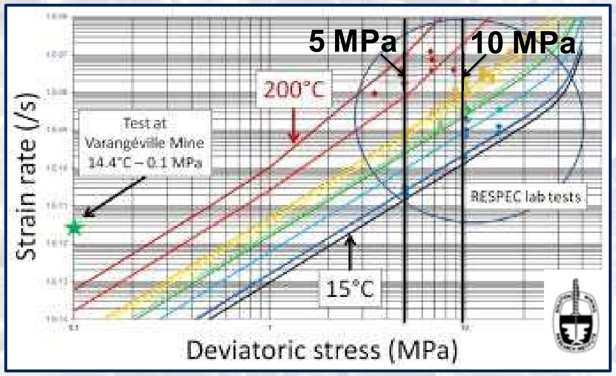
σ: deviatoric stress **T: absolute temperature**

$$\dot{\varepsilon}^{ss} = A(T)\ \sigma^n$$

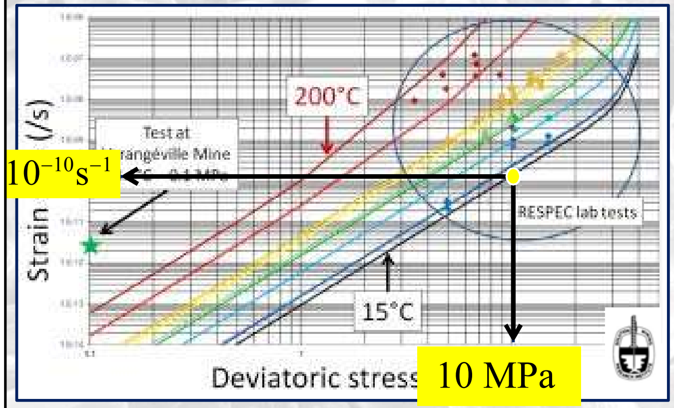
or:

$$\log \dot{\varepsilon}^{ss} = \log A(T) + n \log \quad \sigma$$

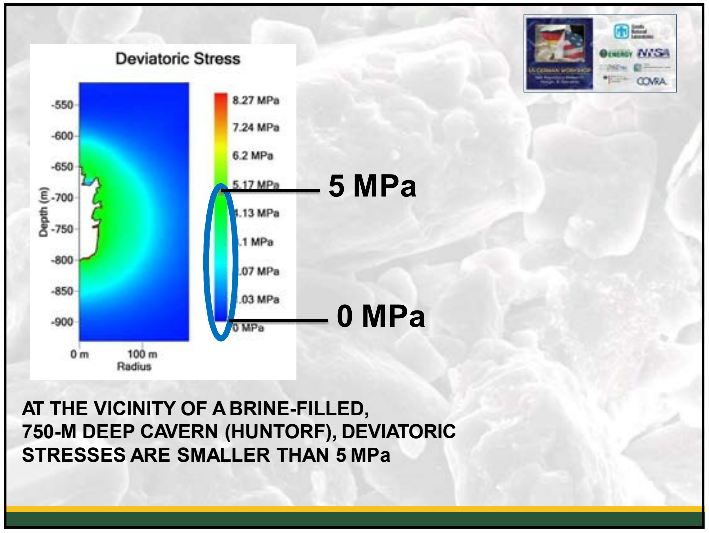
$$\log \dot{\varepsilon}^{ss} = \log A(T) + n \log \quad \sigma$$



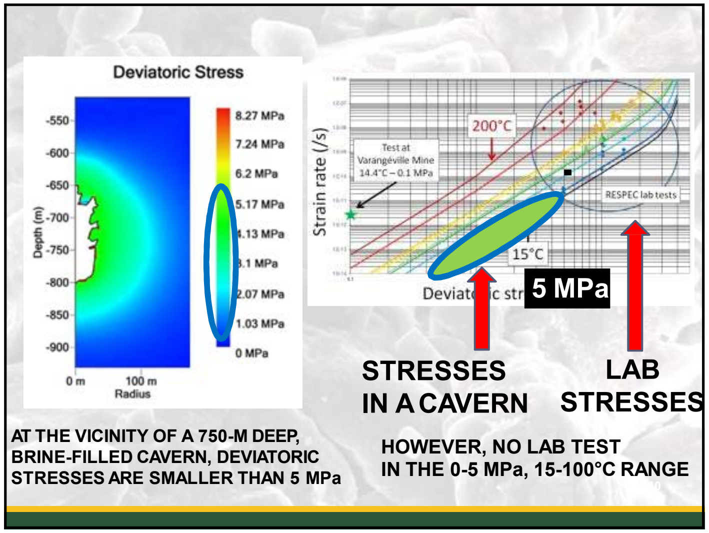
AVERY ISLAND SALT (RESPEC)



AVERY ISLAND SALT (RESPEC)

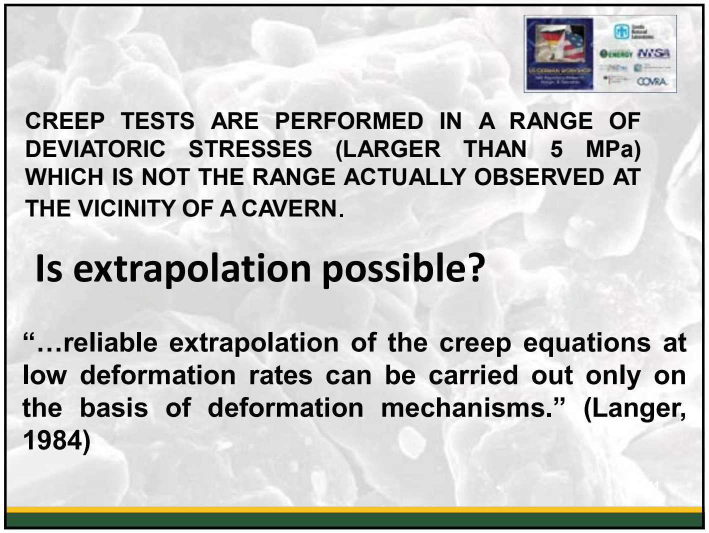


AT THE VICINITY OF A BRINE-FILLED, 750-M DEEP CAVERN (HUNTORF), DEVIATORIC STRESSES ARE SMALLER THAN 5 MPa



AT THE VICINITY OF A 750-M DEEP, BRINE-FILLED CAVERN, DEVIATORIC STRESSES ARE SMALLER THAN 5 MPa

HOWEVER, NO LAB TEST IN THE 0-5 MPa, 15-100°C RANGE

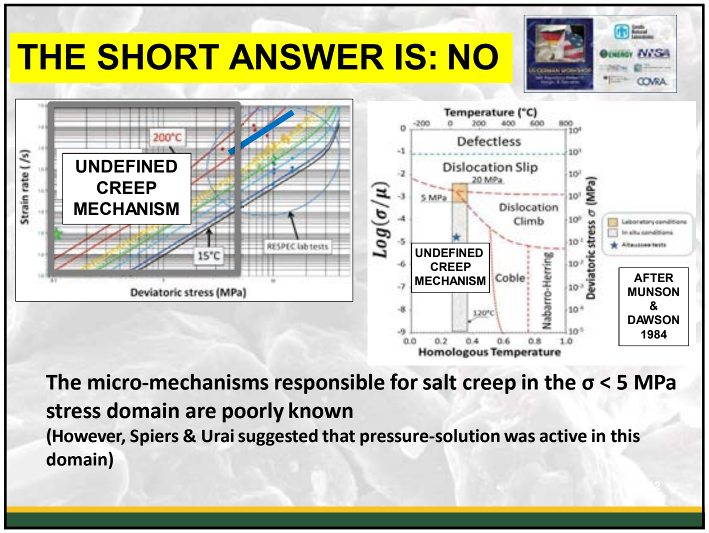


CREEP TESTS ARE PERFORMED IN A RANGE OF DEVIATORIC STRESSES (LARGER THAN 5 MPa) WHICH IS NOT THE RANGE ACTUALLY OBSERVED AT THE VICINITY OF A CAVERN.

Is extrapolation possible?

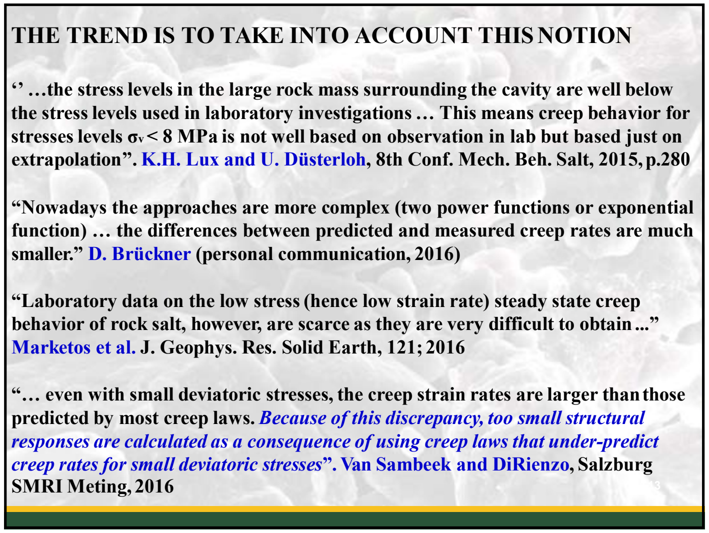
"…reliable extrapolation of the creep equations at low deformation rates can be carried out only on the basis of deformation mechanisms." (Langer, 1984)

THE SHORT ANSWER IS: NO



The micro-mechanisms responsible for salt creep in the σ < 5 MPa stress domain are poorly known

(However, Spiers & Urai suggested that pressure-solution was active in this domain)



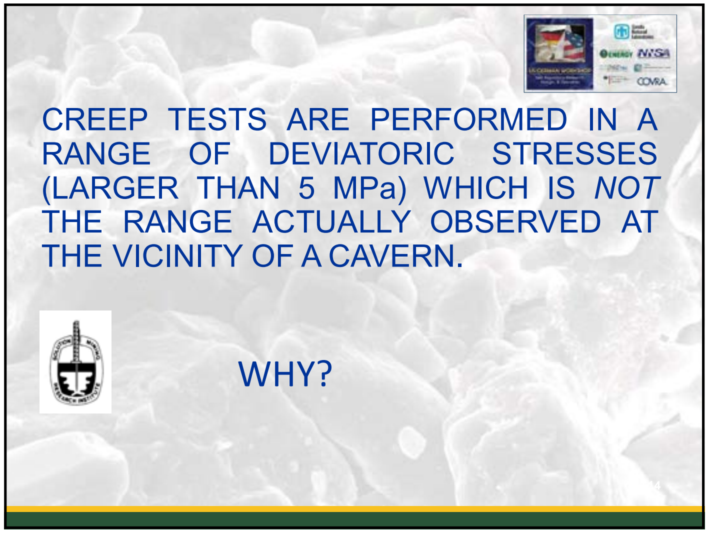
THE TREND IS TO TAKE INTO ACCOUNT THIS NOTION

‘’ …the stress levels in the large rock mass surrounding the cavity are well below the stress levels used in laboratory investigations … This means creep behavior for stresses levels $\sigma_v < 8$ MPa is not well based on observation in lab but based just on extrapolation”. K.H. Lux and U. Düsterloh, 8th Conf. Mech. Beh. Salt, 2015, p.280

“Nowadays the approaches are more complex (two power functions or exponential function) … the differences between predicted and measured creep rates are much smaller.” D. Brückner (personal communication, 2016)

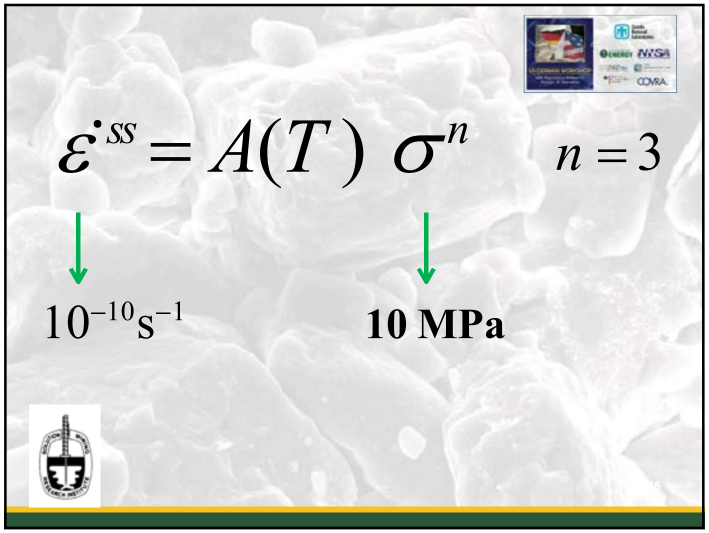
“Laboratory data on the low stress (hence low strain rate) steady state creep behavior of rock salt, however, are scarce as they are very difficult to obtain …” Marketos et al. J. Geophys. Res. Solid Earth, 121; 2016

“… even with small deviatoric stresses, the creep strain rates are larger than those predicted by most creep laws. *Because of this discrepancy, too small structural responses are calculated as a consequence of using creep laws that under-predict creep rates for small deviatoric stresses*”. Van Sambeek and DiRienzo, Salzburg SMRI Meting, 2016



CREEP TESTS ARE PERFORMED IN A RANGE OF DEVIATORIC STRESSES (LARGER THAN 5 MPa) WHICH IS *NOT* THE RANGE ACTUALLY OBSERVED AT THE VICINITY OF A CAVERN.

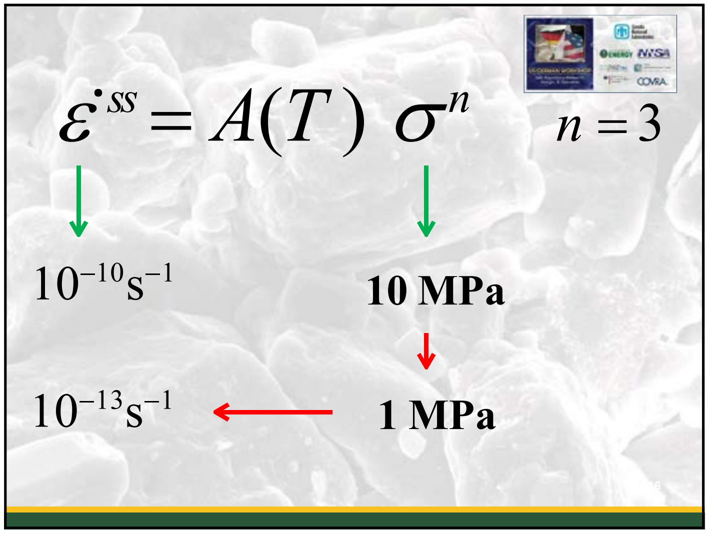
WHY?



$$\dot{\varepsilon}^{ss} = A(T)\ \sigma^n \qquad n = 3$$

$10^{-10}s^{-1}$

10 MPa



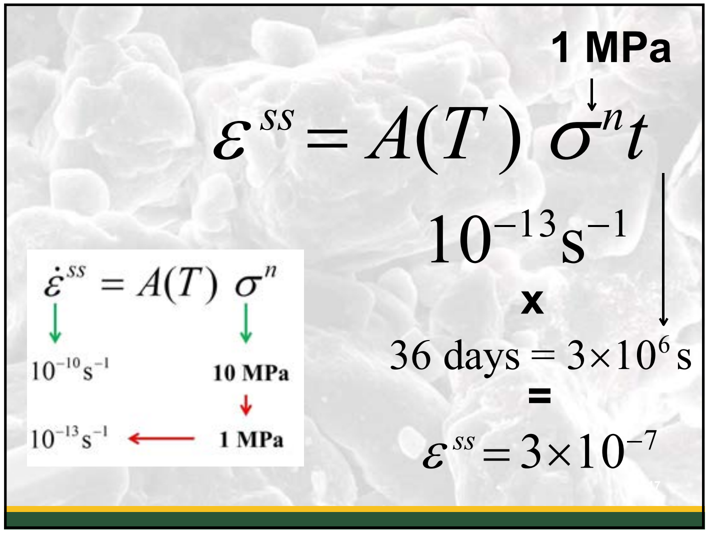
$$\dot{\varepsilon}^{ss} = A(T)\ \sigma^n \qquad n = 3$$

$10^{-10}s^{-1}$

10 MPa

1 MPa

$10^{-13}s^{-1}$



1 MPa

$$\varepsilon^{ss} = A(T)\ \sigma^n t$$

10^{-13}s^{-1}

x

36 days = 3×10^{6} s

=

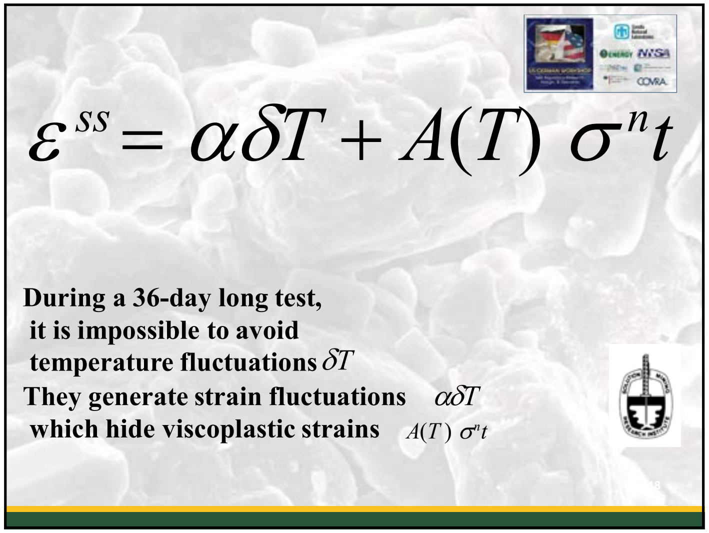
$\varepsilon^{ss} = 3\times10^{-7}$

$\dot{\varepsilon}^{ss} = A(T)\ \sigma^n$

$\downarrow$ 10^{-10}s^{-1} $\qquad$ $\downarrow$ 10 MPa

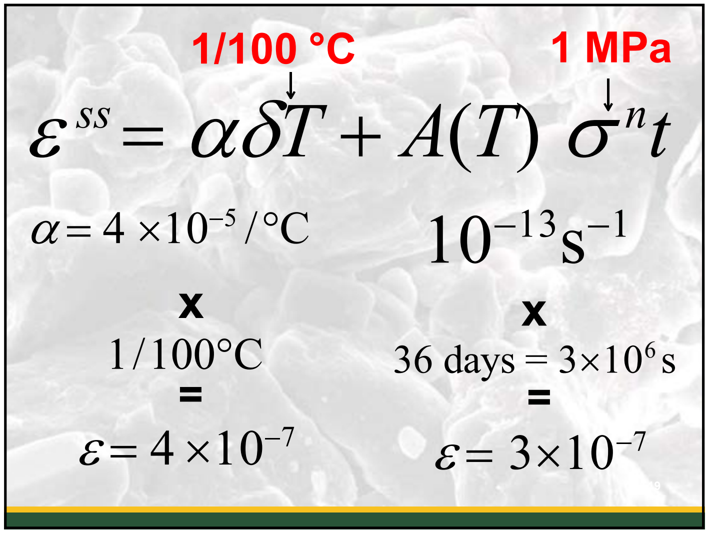
$\downarrow$ 1 MPa

10^{-13}s^{-1} ← 1 MPa



$$\varepsilon^{ss} = \alpha\delta T + A(T)\ \sigma^n t$$

During a 36-day long test,
it is impossible to avoid
temperature fluctuations δT
They generate strain fluctuations $\alpha\delta T$
which hide viscoplastic strains $A(T)\ \sigma^n t$



1/100 °C $\qquad$ 1 MPa

$$\varepsilon^{ss} = \alpha\delta T + A(T)\ \sigma^n t$$

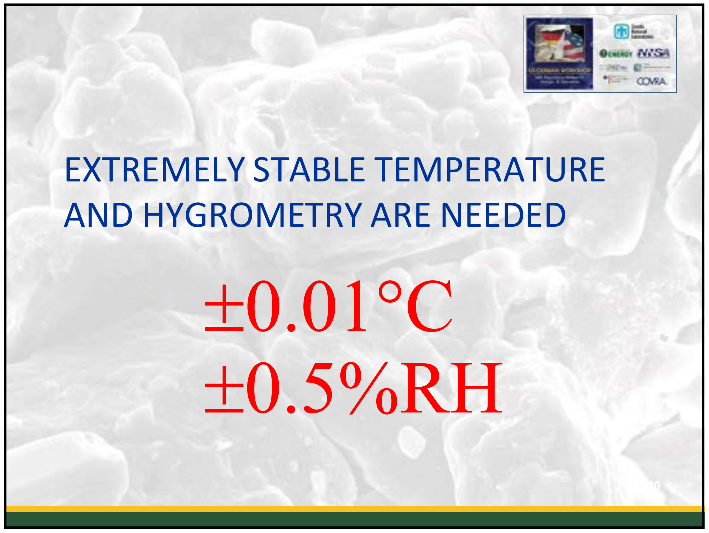
$\alpha = 4\times10^{-5}/°\text{C}$ $\qquad$ 10^{-13}s^{-1}

x $\qquad$ x

$1/100°\text{C}$ $\qquad$ 36 days = 3×10^{6} s

= $\qquad$ =

$\varepsilon = 4\times10^{-7}$ $\qquad$ $\varepsilon = 3\times10^{-7}$



EXTREMELY STABLE TEMPERATURE
AND HYGROMETRY ARE NEEDED

±0.01°C
±0.5%RH

2. HOW?

TWO POSSIBLE PATHS

Design a special device in which temperature is controlled accurately (1/1000 ° C)

One week-long tests, 7x10-12/s, from 40° C to 350° C

(Hunsche, BGR, 1988)

Set a creep test device in an environnement whose temperature is very stable

Several year long tests, 3x10-13/s, 8° C and 13,5° C

(LMS, 1998)

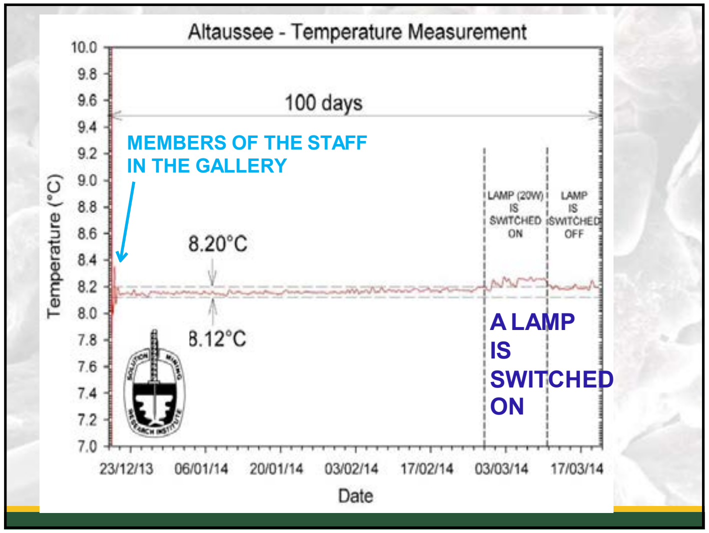
Creep testing devices are set in remote, dead-end galleries of two salt mines, in Austria and France, where temperature fluctuations are +/- 0.01°C

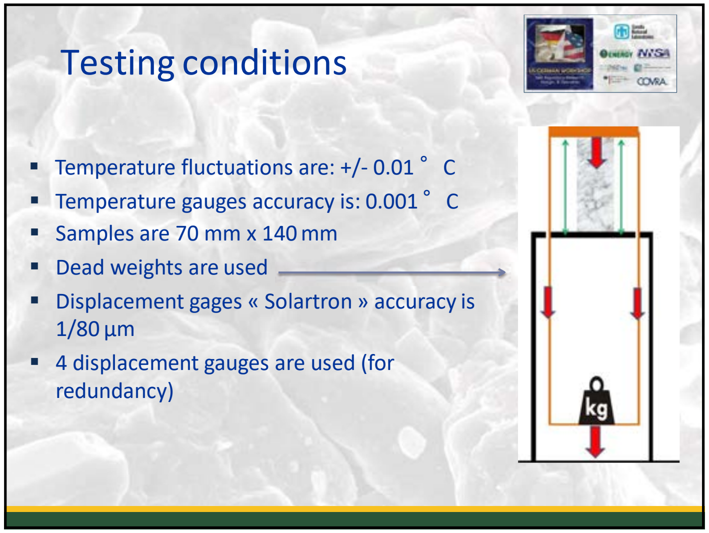
Acknowledgements: Salinen Austria AG, CSME

Two sites

Varangéville Mine (France)

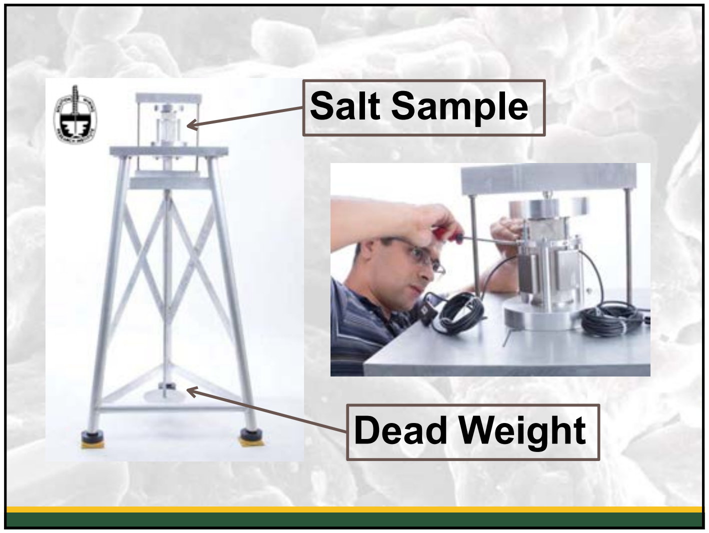
Altaussee Mine (Austria)

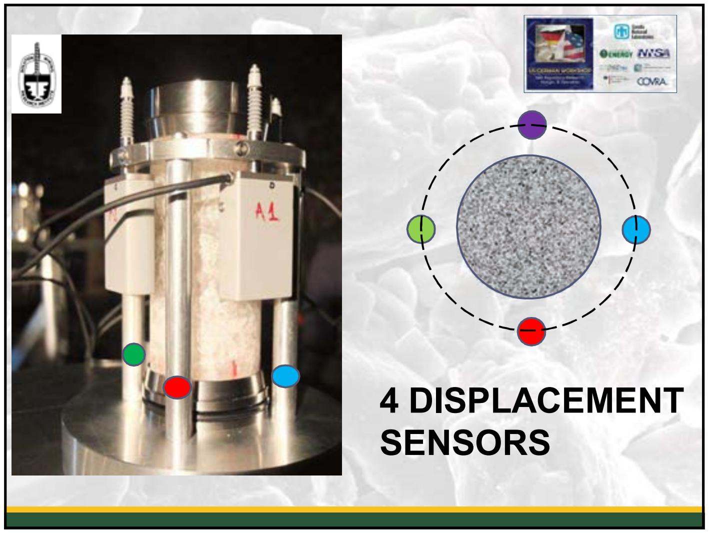


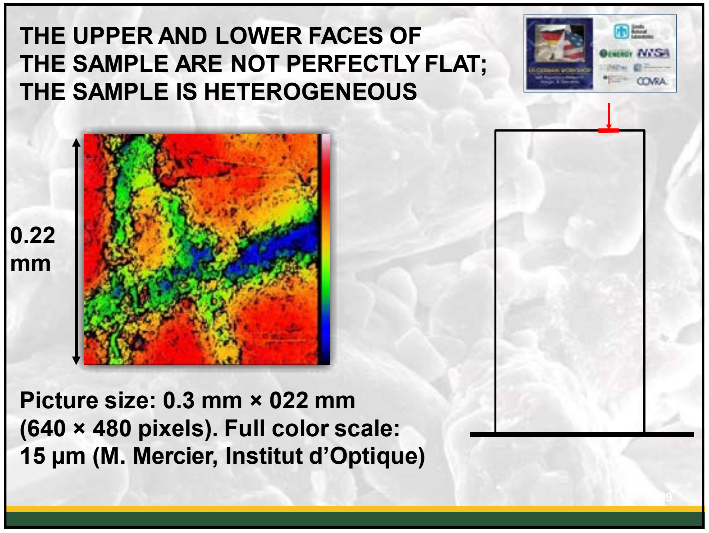


Testing conditions

- Temperature fluctuations are: +/- 0.01 ° C
- Temperature gauges accuracy is: 0.001 ° C
- Samples are 70 mm x 140 mm
- Dead weights are used
- Displacement gages « Solartron » accuracy is 1/80 µm
- 4 displacement gauges are used (for redundancy)

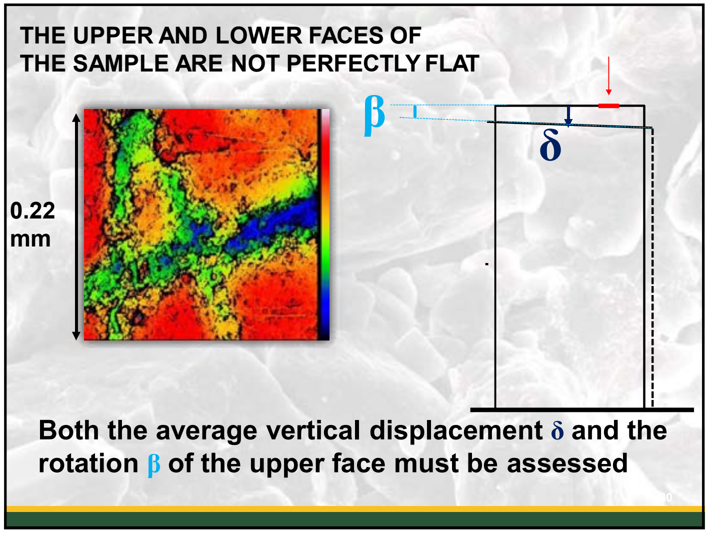






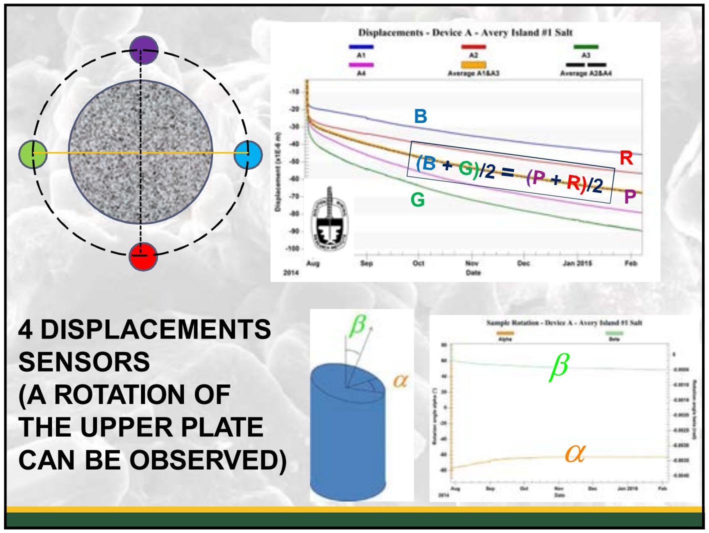
THE UPPER AND LOWER FACES OF THE SAMPLE ARE NOT PERFECTLY FLAT; THE SAMPLE IS HETEROGENEOUS

Picture size: 0.3 mm × 022 mm
(640 × 480 pixels). Full color scale:
15 µm (M. Mercier, Institut d'Optique)

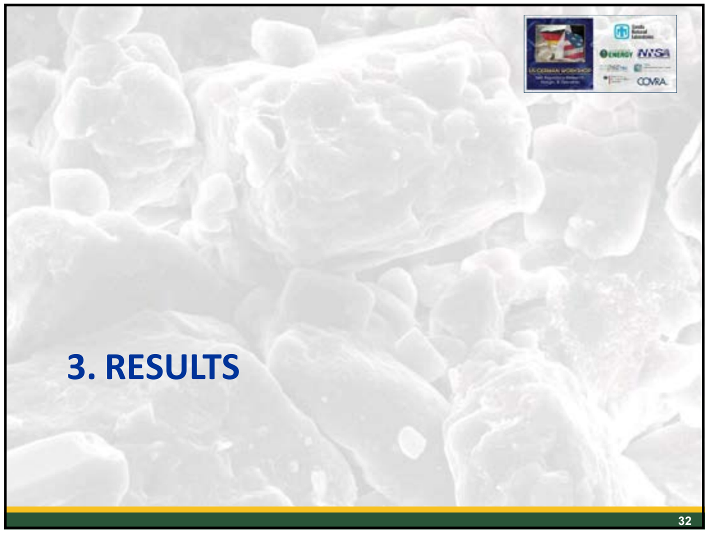


THE UPPER AND LOWER FACES OF THE SAMPLE ARE NOT PERFECTLY FLAT

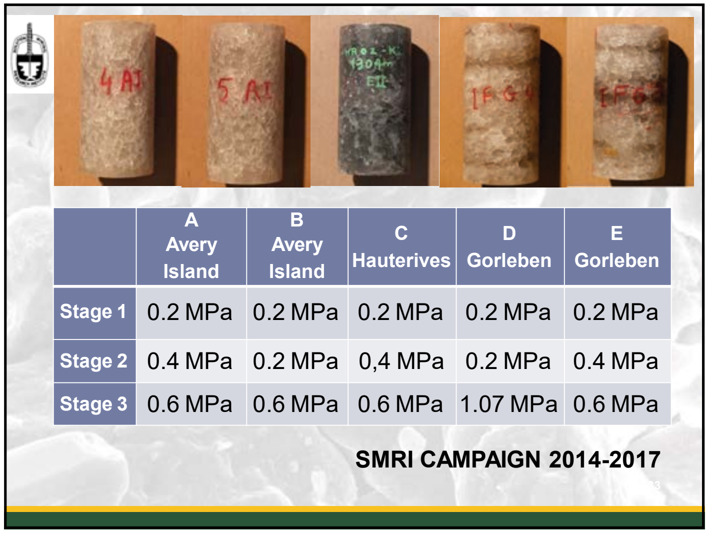
Both the average vertical displacement δ and the rotation β of the upper face must be assessed



4 DISPLACEMENTS SENSORS
(A ROTATION OF THE UPPER PLATE CAN BE OBSERVED)

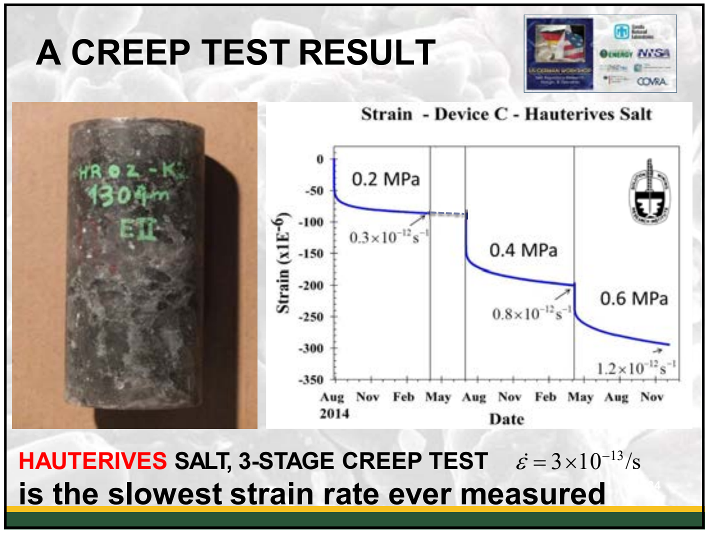


3. RESULTS



	A Avery Island	B Avery Island	C Hauterives	D Gorleben	E Gorleben
Stage 1	0.2 MPa	0.2 MPa	0.2 MPa	0.2 MPa	0.2 MPa
Stage 2	0.4 MPa	0.2 MPa	0,4 MPa	0.2 MPa	0.4 MPa
Stage 3	0.6 MPa	0.6 MPa	0.6 MPa	1.07 MPa	0.6 MPa

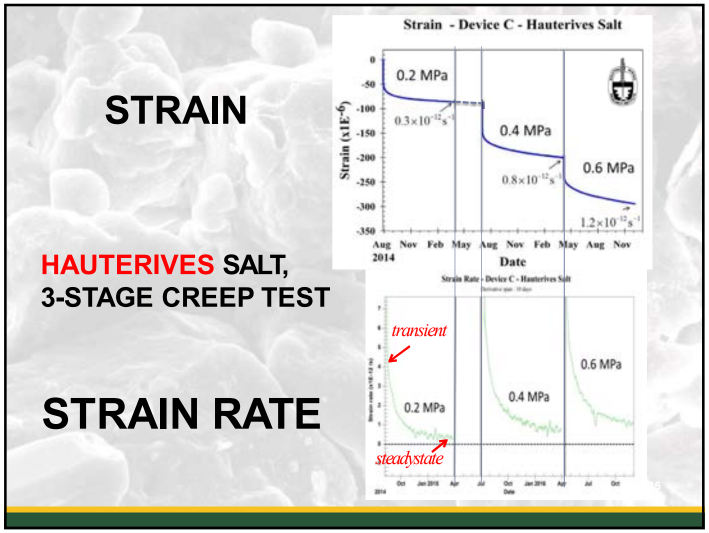
SMRI CAMPAIGN 2014-2017



A CREEP TEST RESULT

HAUTERIVES SALT, 3-STAGE CREEP TEST $\dot{\varepsilon} = 3\times10^{-13}/s$

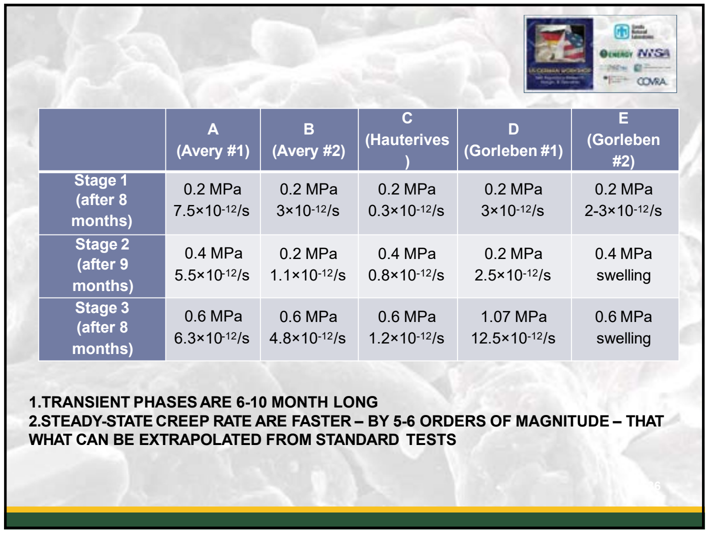
is the slowest strain rate ever measured



STRAIN

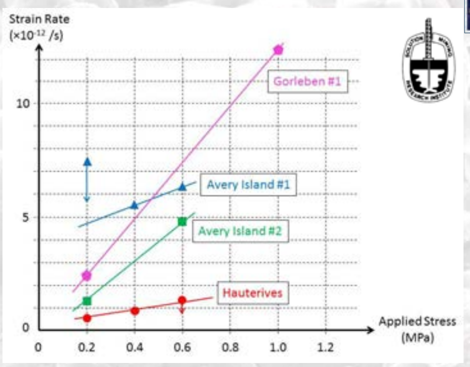
HAUTERIVES SALT,
3-STAGE CREEP TEST

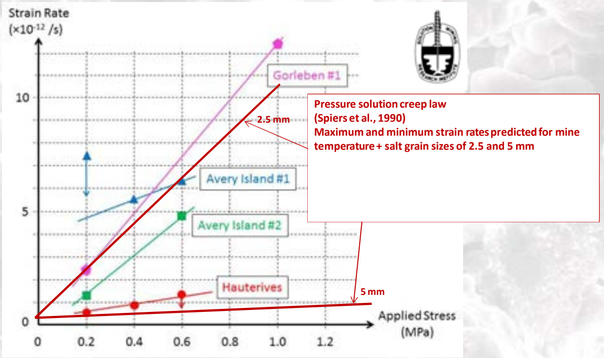
STRAIN RATE



	A (Avery #1)	B (Avery #2)	C (Hauterives)	D (Gorleben #1)	E (Gorleben #2)
Stage 1 (after 8 months)	0.2 MPa $7.5\times10^{-12}/s$	0.2 MPa $3\times10^{-12}/s$	0.2 MPa $0.3\times10^{-12}/s$	0.2 MPa $3\times10^{-12}/s$	0.2 MPa $2\text{-}3\times10^{-12}/s$
Stage 2 (after 9 months)	0.4 MPa $5.5\times10^{-12}/s$	0.2 MPa $1.1\times10^{-12}/s$	0.4 MPa $0.8\times10^{-12}/s$	0.2 MPa $2.5\times10^{-12}/s$	0.4 MPa swelling
Stage 3 (after 8 months)	0.6 MPa $6.3\times10^{-12}/s$	0.6 MPa $4.8\times10^{-12}/s$	0.6 MPa $1.2\times10^{-12}/s$	1.07 MPa $12.5\times10^{-12}/s$	0.6 MPa swelling

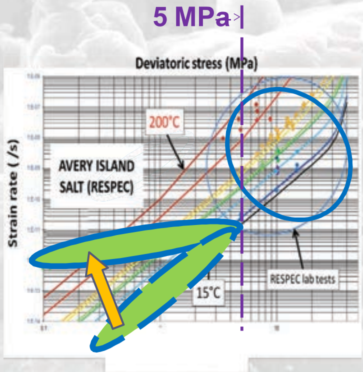
1. **TRANSIENT PHASES ARE 6-10 MONTH LONG**
2. **STEADY-STATE CREEP RATE ARE FASTER – BY 5-6 ORDERS OF MAGNITUDE – THAT WHAT CAN BE EXTRAPOLATED FROM STANDARD TESTS**

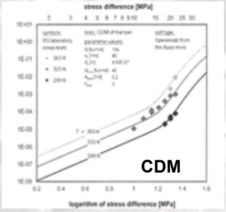




Pressure solution creep law
(Spiers et al., 1990)
Maximum and minimum strain rates predicted for mine temperature + salt grain sizes of 2.5 and 5 mm

**THESE RESULTS ARE CONSISTENT WITH SPIER'S APPROACH
(AT LOW STRESS, PRESSURE-SOLUTION IS THE GOVERNING MECHANIS M)**





**Cf: CDM
Lubby2
Carreau Law**

$$\dot{\varepsilon}^{ss} = B\sigma/D^3 + A\sigma^n$$

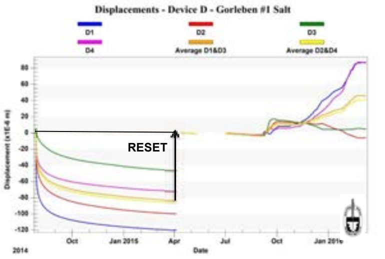
WHAT CAN BE EXPECTED FROM THESE RESULTS?

- **A much better agreement between lab test data and field measurements, especially when caverns less than 3000 ft-deep are concerned**
- **A better prediction of long-term behavior (when deviatoric stresses are small)**
- **A better understanding of creep mechanisms**

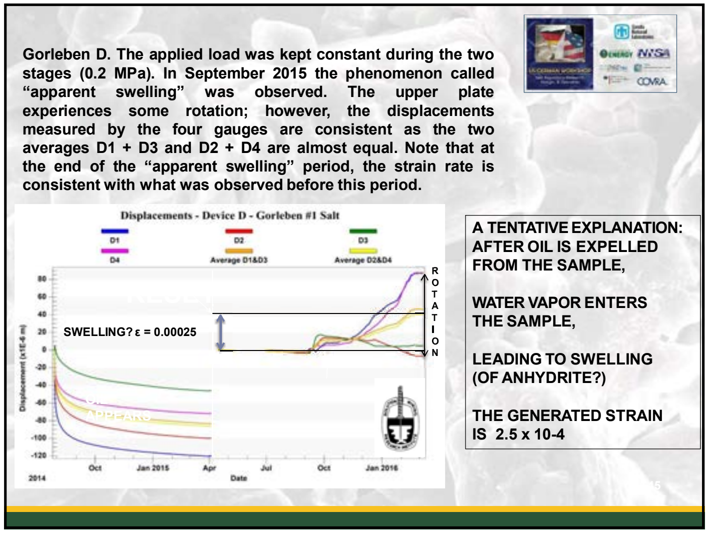
4. THE CASE OF THE GORLEBEN SAMPLE

GORLEBEN D1: AFTER A COUPLE OF MONTHS, OIL WAS FOUND AT SAMPLE BOTTOM

"blocks of primary rock salt crystals, and shredded and crushed fragments of anhydrite lines, float in a matrix of recrystallized rock salt"; … "[hydrocarbons] appear mostly in the form of streaks, dispersed clouds, clusters and islands. .. hydrocarbons are located 1) along grain boundaries of halite and/or anhydrite crystals 2) in newly formed artificial microcracks due to drilling and preparation 3) in µcapillary tubes of anhydrite crystals and 4) rarely in µ-porous parts of the Hauptsalz … the content (up to several hundreds ppm) is too low to affect the geomechanical behavior of rock salt." (Hammer et al., 2012)".



Ackn: Dieter Brückner



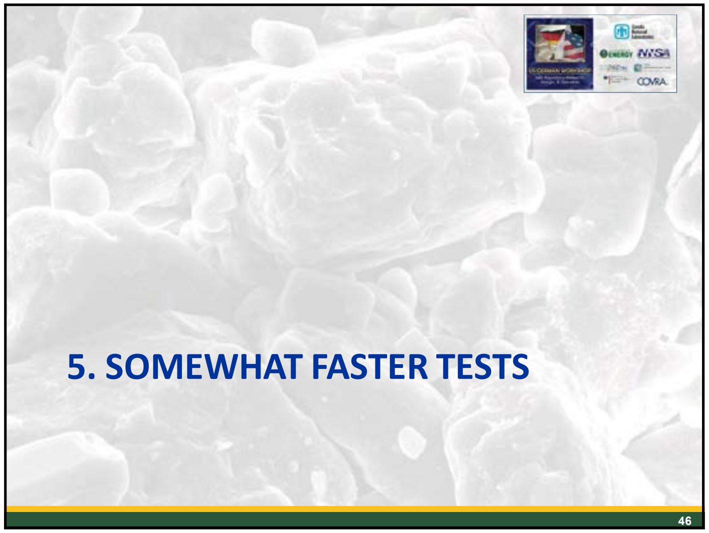
Gorleben D. The applied load was kept constant during the two stages (0.2 MPa). In September 2015 the phenomenon called “apparent swelling” was observed. The upper plate experiences some rotation; however, the displacements measured by the four gauges are consistent as the two averages D1 + D3 and D2 + D4 are almost equal. Note that at the end of the “apparent swelling” period, the strain rate is consistent with what was observed before this period.

A TENTATIVE EXPLANATION:
AFTER OIL IS EXPELLED FROM THE SAMPLE,

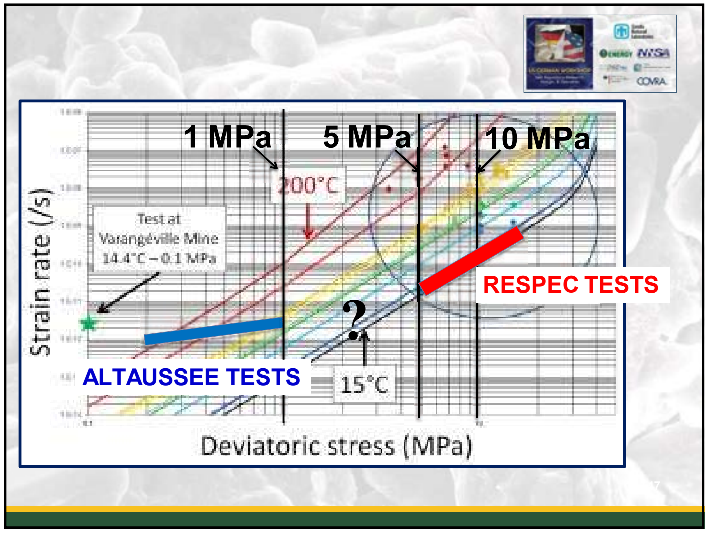
WATER VAPOR ENTERS THE SAMPLE,

LEADING TO SWELLING (OF ANHYDRITE?)

THE GENERATED STRAIN IS 2.5 x 10-4

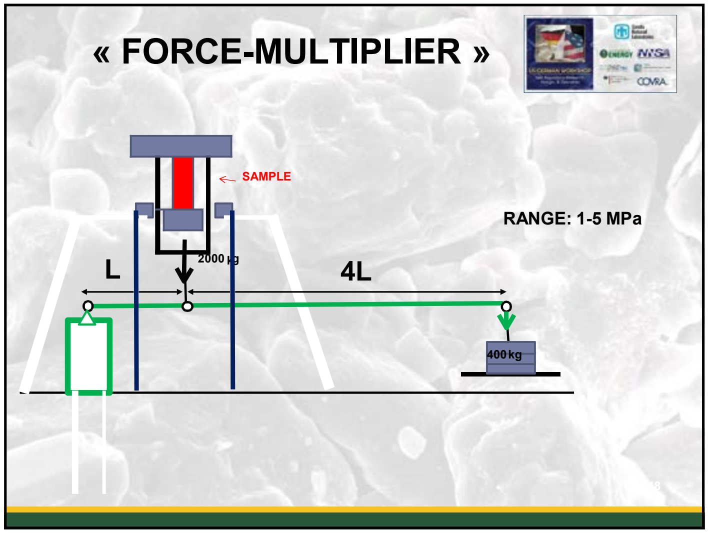


5. SOMEWHAT FASTER TESTS



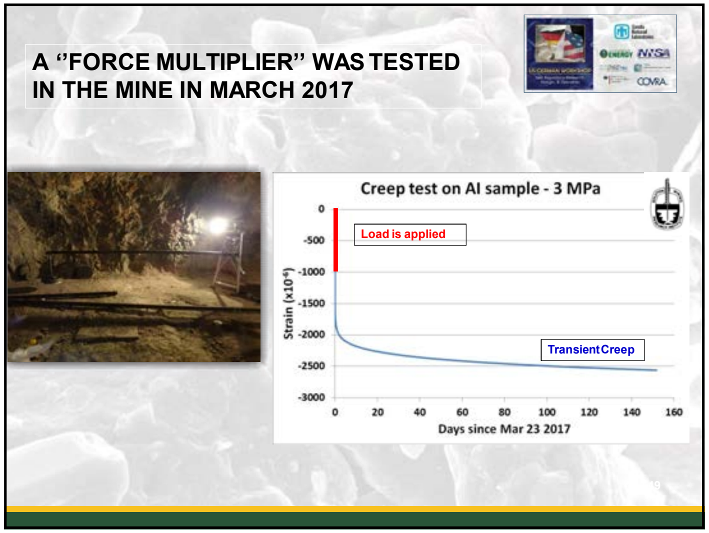
ALTAUSSEE TESTS

RESPEC TESTS

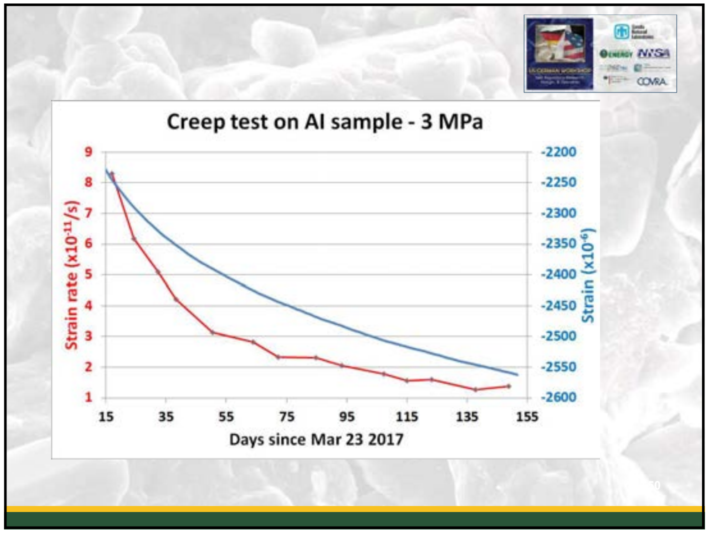


« FORCE-MULTIPLIER »

RANGE: 1-5 MPa



A "FORCE MULTIPLIER" WAS TESTED IN THE MINE IN MARCH 2017



Full Report available at: https://www.solutionmining.org/

QUESTIONS?

8th US/German Workshop on Salt Repository Research, Design, and Operation

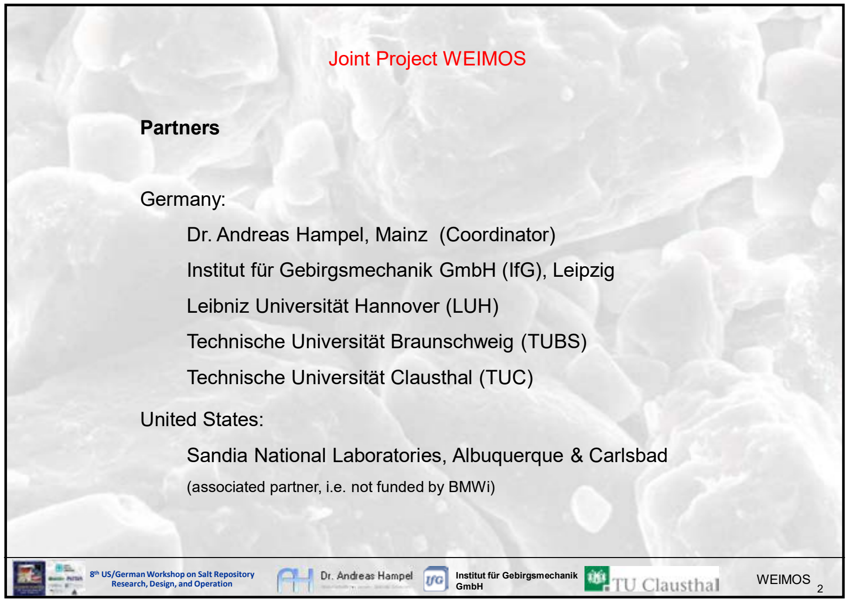
Middelburg, The Netherlands
September 5-7, 2017

Current Status of Research in the Joint Project WEIMOS

Andreas Hampel (Consultant), Till Popp (IfG), Kai Herchen (TUC)

WEIMOS:
Verbundprojekt: **Wei**terentwicklung und Qualifikation der gebirgsmechanischen **Mo**dellierung für die HAW-Endlagerung im **S**teinsalz
Joint Project: Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Gefördert durch: Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages
Betreut vom PTKA Projektträger Karlsruhe Karlsruher Institut für Technologie



Joint Project WEIMOS

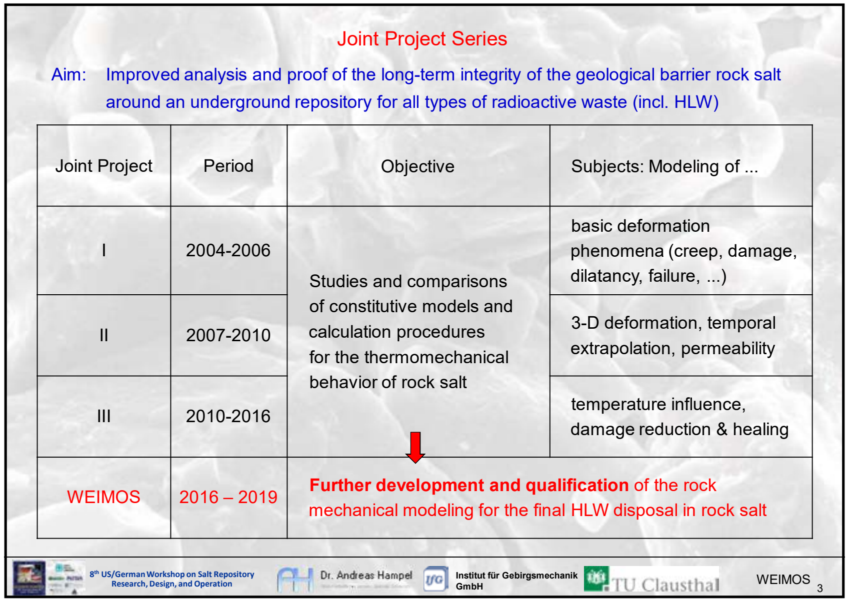
Partners

Germany:

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

United States:

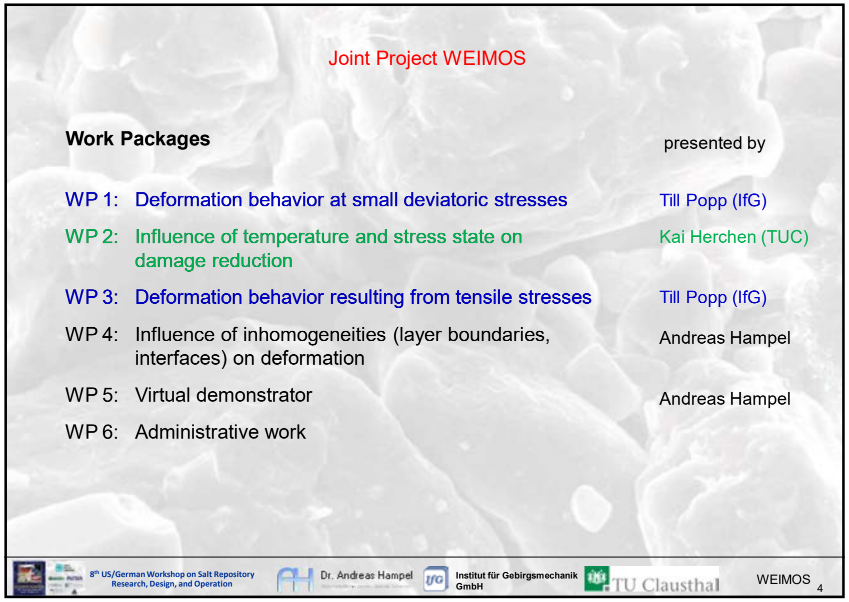
- Sandia National Laboratories, Albuquerque & Carlsbad
  (associated partner, i.e. not funded by BMWi)



Joint Project Series

Aim: Improved analysis and proof of the long-term integrity of the geological barrier rock salt around an underground repository for all types of radioactive waste (incl. HLW)

Joint Project	Period	Objective	Subjects: Modeling of ...
I	2004-2006	Studies and comparisons of constitutive models and calculation procedures for the thermomechanical behavior of rock salt	basic deformation phenomena (creep, damage, dilatancy, failure, ...)
II	2007-2010		3-D deformation, temporal extrapolation, permeability
III	2010-2016		temperature influence, damage reduction & healing
WEIMOS	2016 – 2019	**Further development and qualification** of the rock mechanical modeling for the final HLW disposal in rock salt	



Joint Project WEIMOS

Work Packages		presented by
WP 1:	Deformation behavior at small deviatoric stresses	Till Popp (IfG)
WP 2:	Influence of temperature and stress state on damage reduction	Kai Herchen (TUC)
WP 3:	Deformation behavior resulting from tensile stresses	Till Popp (IfG)
WP 4:	Influence of inhomogeneities (layer boundaries, interfaces) on deformation	Andreas Hampel
WP 5:	Virtual demonstrator	Andreas Hampel
WP 6:	Administrative work	

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

Important questions:

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

Experimental investigations

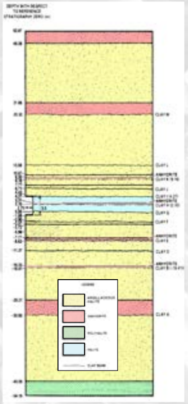
- ➢ RESPEC lab: shear tests on layered rock salt specimens
  current status:
  upcoming drilling of layered salt cores at Intrepid mine near WIPP:
  rock salt with clay seams, salt/anhydrite, salt/polyhalite interfaces
- ➢ Proposals of Sandia (1983, 2016): In-situ experiments

Objective:

- ➢ Study, develop further and improve the modeling

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

Stratigraphy at WIPP

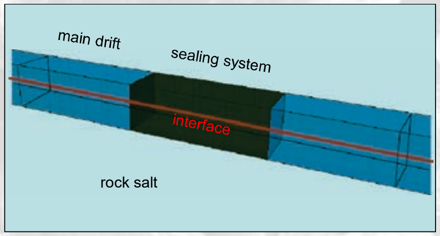


Munson et al. (1990):
Sandia Report SAND89-2671

WEIMOS WP 5: Virtual demonstrator

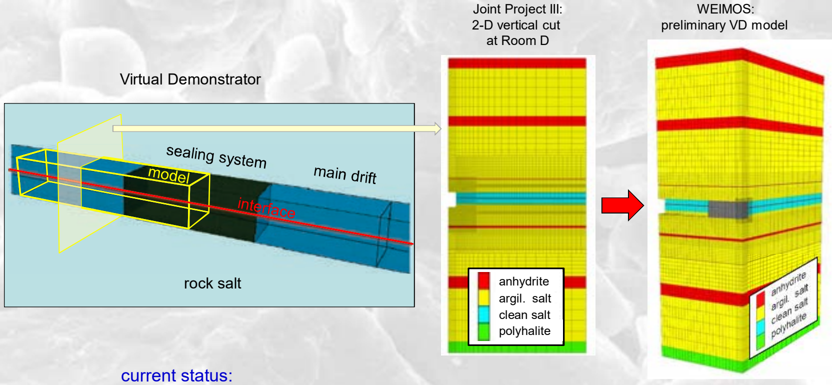
Objective: Simulation of a complex model to demonstrate the improved modeling of the various investigated phenomena:

- ➢ small deviatoric stresses
- ➢ damage reduction and healing
- ➢ influence of interfaces/layer boundaries
- ➢ influence of e.g. thermally induced tensile stresses



Simulations:
step 1: open drift
step 2: installation of the dam
step 3: post-operational phase & long-term behavior

WEIMOS WP 5: Virtual demonstrator



current status:
extrude the plane strain model of **Room D** from Joint Project III to 3-D,
add one or two clay seams,
perform test simulations (find appropriate discretization, ...)

Joint Project WEIMOS

Work Packages		presented by
WP 1:	Deformation behavior at small deviatoric stresses	Till Popp (IfG)
WP 2:	Influence of temperature and stress state on damage reduction	Kai Herchen (TUC)
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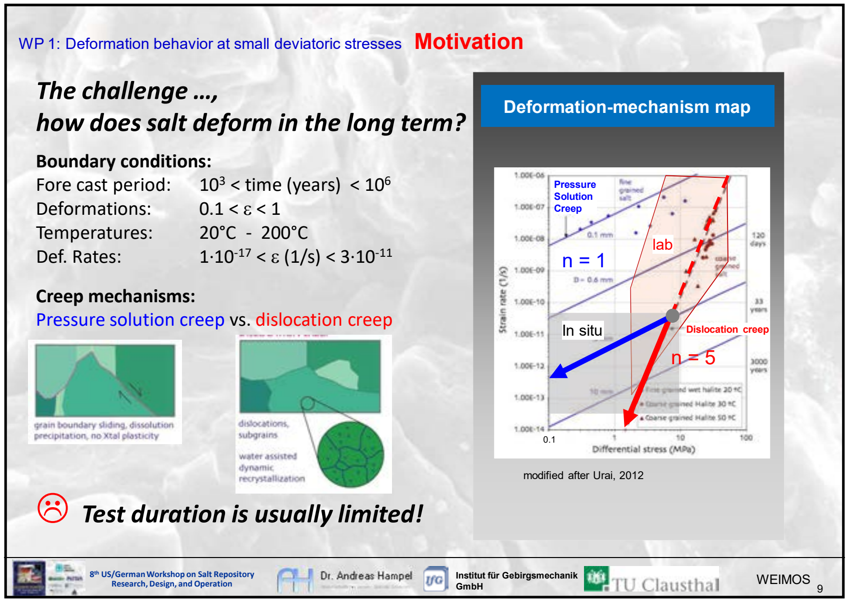


WP 1: Deformation behavior at small deviatoric stresses **Motivation**

The challenge …,
how does salt deform in the long term?

Boundary conditions:

Fore cast period:	10^3 < time (years) < 10^6
Deformations:	$0.1 < \varepsilon < 1$
Temperatures:	20°C - 200°C
Def. Rates:	$1 \cdot 10^{-17} < \varepsilon \; (1/s) < 3 \cdot 10^{-11}$

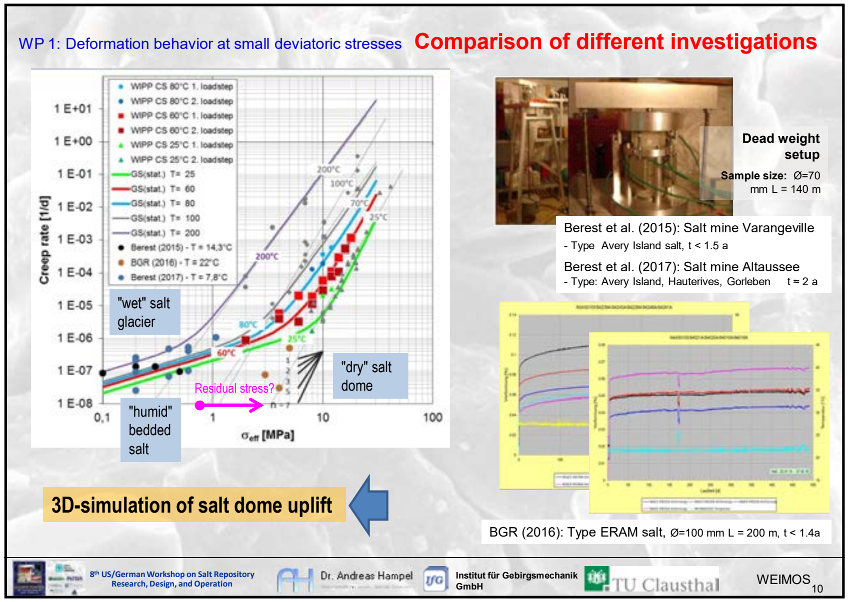
Creep mechanisms:

Pressure solution creep vs. dislocation creep

Deformation-mechanism map

modified after Urai, 2012

☹ ***Test duration is usually limited!***



WP 1: Deformation behavior at small deviatoric stresses **Comparison of different investigations**

3D-simulation of salt dome uplift

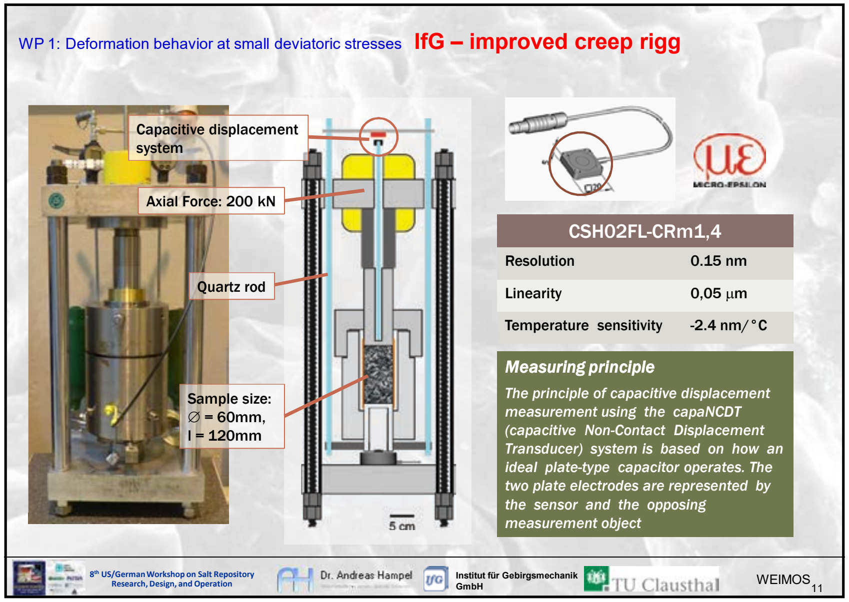
Dead weight setup

Sample size: Ø=70 mm L = 140 m

Berest et al. (2015): Salt mine Varangeville
- Type Avery Island salt, t < 1.5 a

Berest et al. (2017): Salt mine Altaussee
- Type: Avery Island, Hauterives, Gorleben t ≈ 2 a

BGR (2016): Type ERAM salt, Ø=100 mm L = 200 m, t < 1.4a

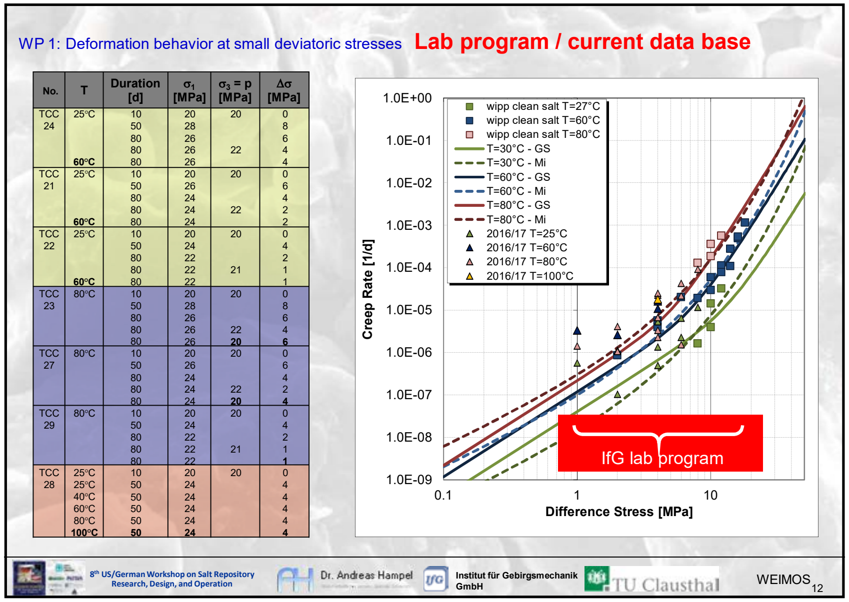


WP 1: Deformation behavior at small deviatoric stresses **IfG – improved creep rigg**

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

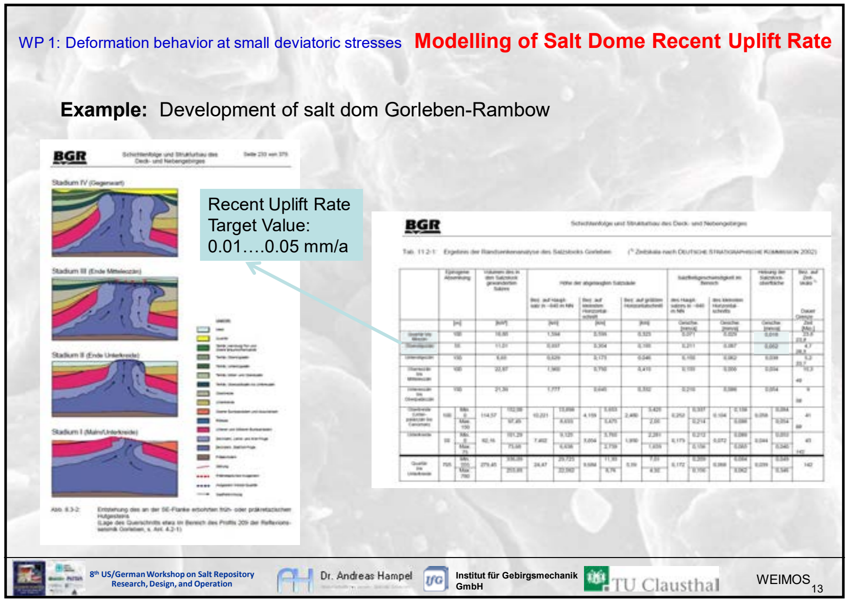
Measuring principle

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



WP 1: Deformation behavior at small deviatoric stresses **Lab program / current data base**

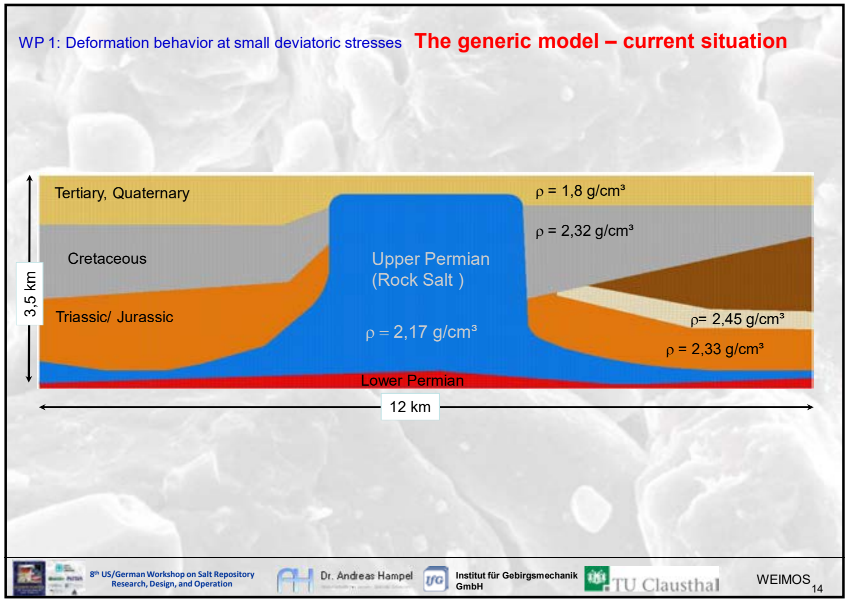
No.	T	Duration [d]	σ_1 [MPa]	$\sigma_3 = p$ [MPa]	$\Delta\sigma$ [MPa]
TCC 24	25°C	10	20	20	0
		50	28		8
		80	26		6
		80	26	22	4
	60°C	80	26		4
TCC 21	25°C	10	20	20	0
		50	26		6
		80	24		4
		80	24	22	2
	60°C	80	24		2
TCC 22	25°C	10	20	20	0
		50	24		4
		80	22		2
		80	22	21	1
	60°C	80	22		1
TCC 23	80°C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



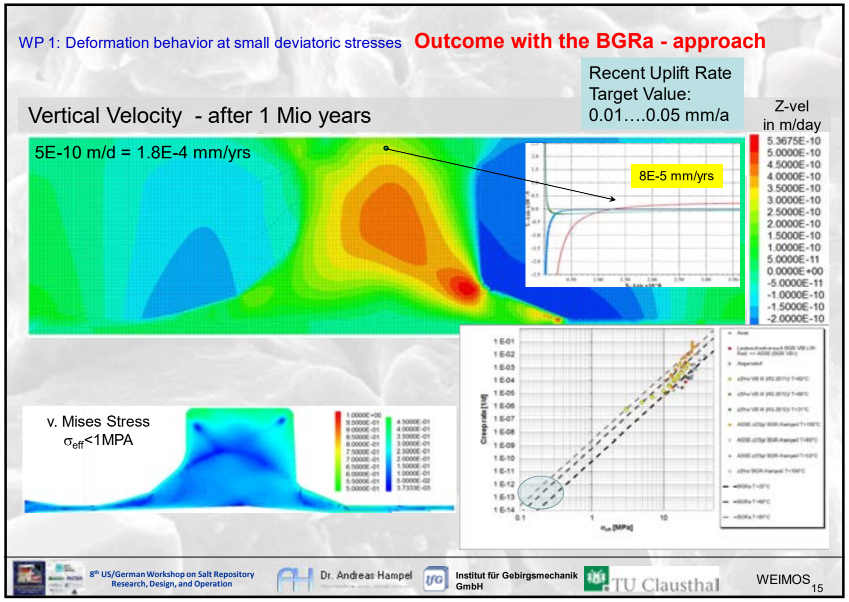
WP 1: Deformation behavior at small deviatoric stresses **Modelling of Salt Dome Recent Uplift Rate**

Example: Development of salt dom Gorleben-Rambow

Recent Uplift Rate
Target Value:
0.01….0.05 mm/a



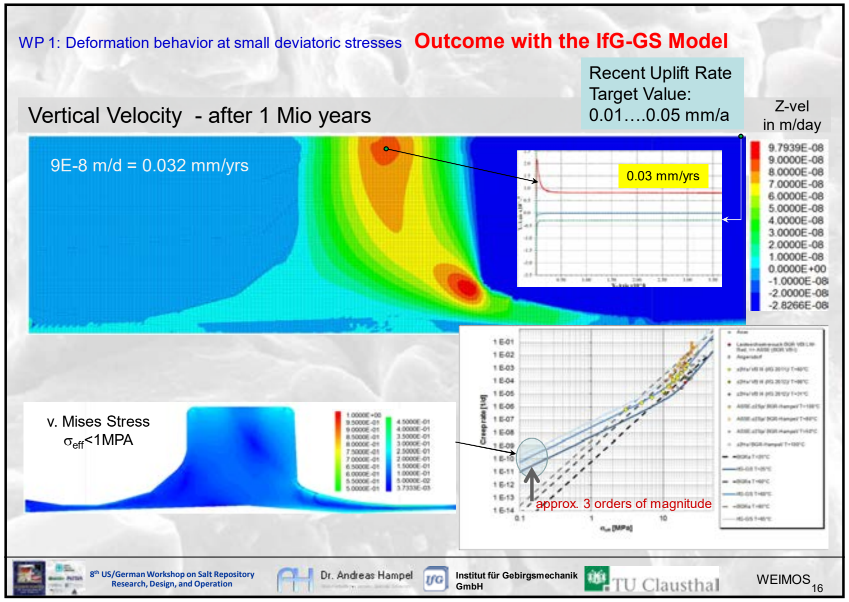
WP 1: Deformation behavior at small deviatoric stresses **The generic model – current situation**



WP 1: Deformation behavior at small deviatoric stresses **Outcome with the BGRa - approach**

Recent Uplift Rate
Target Value:
0.01….0.05 mm/a

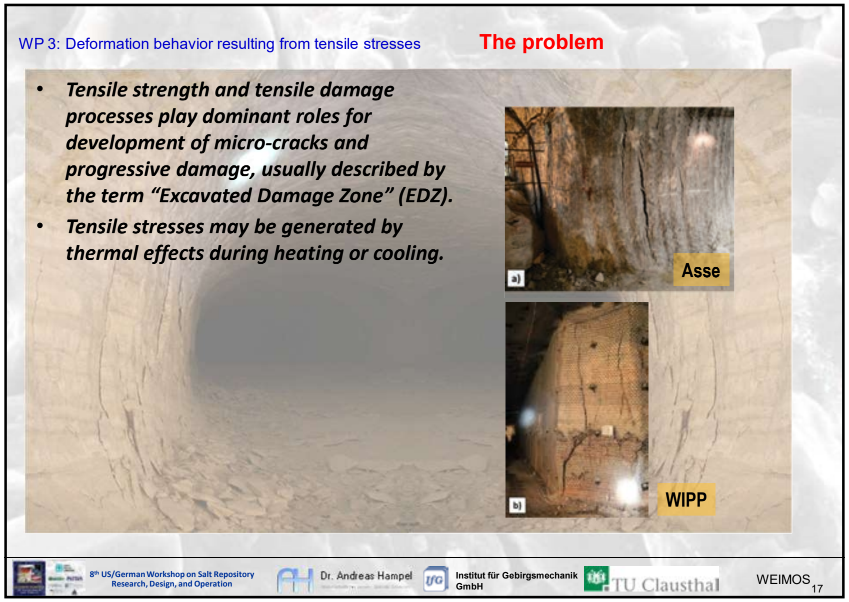
Vertical Velocity - after 1 Mio years



WP 1: Deformation behavior at small deviatoric stresses **Outcome with the IfG-GS Model**

Recent Uplift Rate
Target Value:
0.01….0.05 mm/a

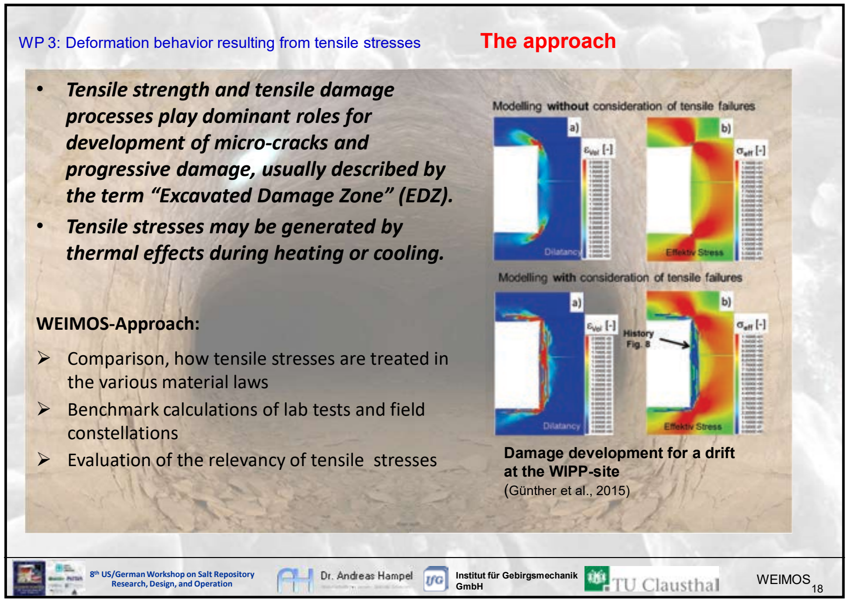
Vertical Velocity - after 1 Mio years



WP 3: Deformation behavior resulting from tensile stresses

The problem

- ***Tensile strength and tensile damage processes play dominant roles for development of micro-cracks and progressive damage, usually described by the term "Excavated Damage Zone" (EDZ).***
- ***Tensile stresses may be generated by thermal effects during heating or cooling.***



WP 3: Deformation behavior resulting from tensile stresses

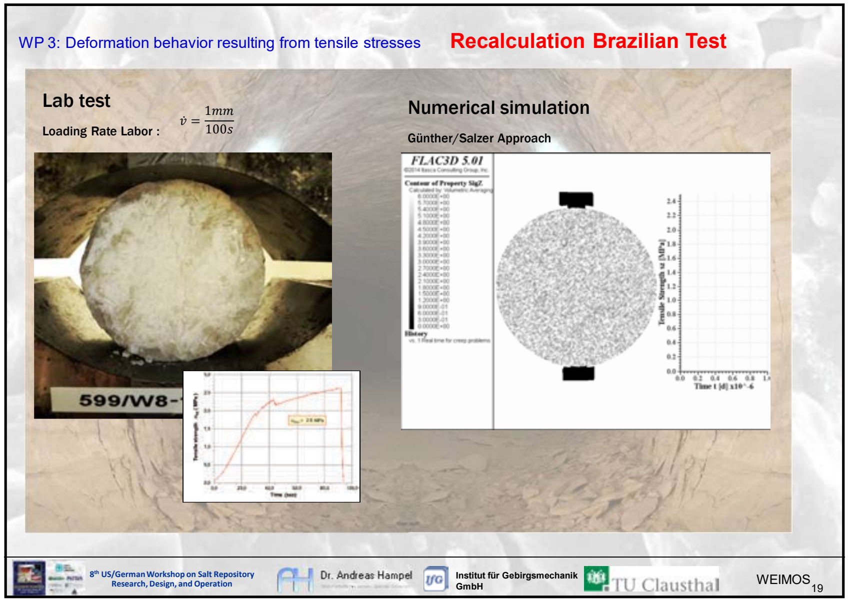
The approach

- ***Tensile strength and tensile damage processes play dominant roles for development of micro-cracks and progressive damage, usually described by the term "Excavated Damage Zone" (EDZ).***
- ***Tensile stresses may be generated by thermal effects during heating or cooling.***

WEIMOS-Approach:

- Comparison, how tensile stresses are treated in the various material laws
- Benchmark calculations of lab tests and field constellations
- Evaluation of the relevancy of tensile stresses

Damage development for a drift at the WIPP-site
(Günther et al., 2015)



WP 3: Deformation behavior resulting from tensile stresses

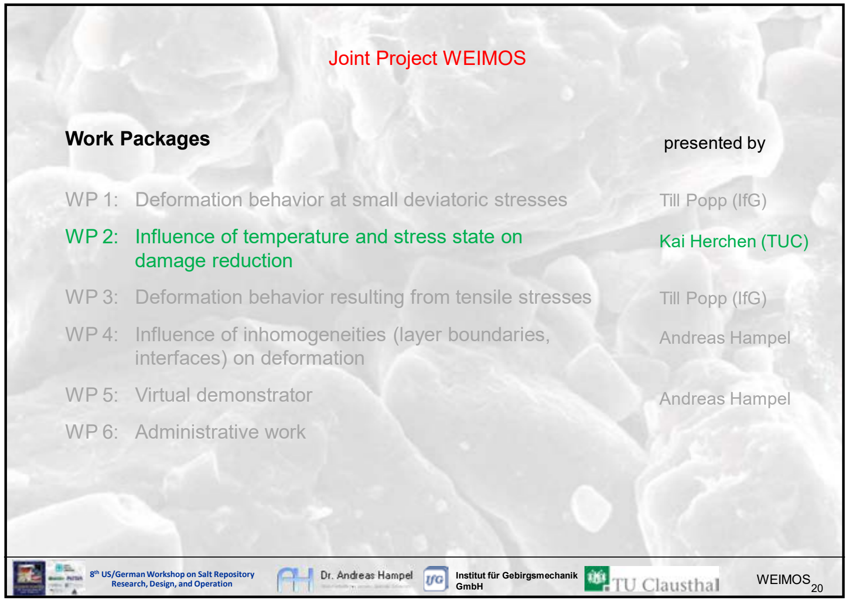
Recalculation Brazilian Test

Lab test

Loading Rate Labor : $\dot{v} = \frac{1mm}{100s}$

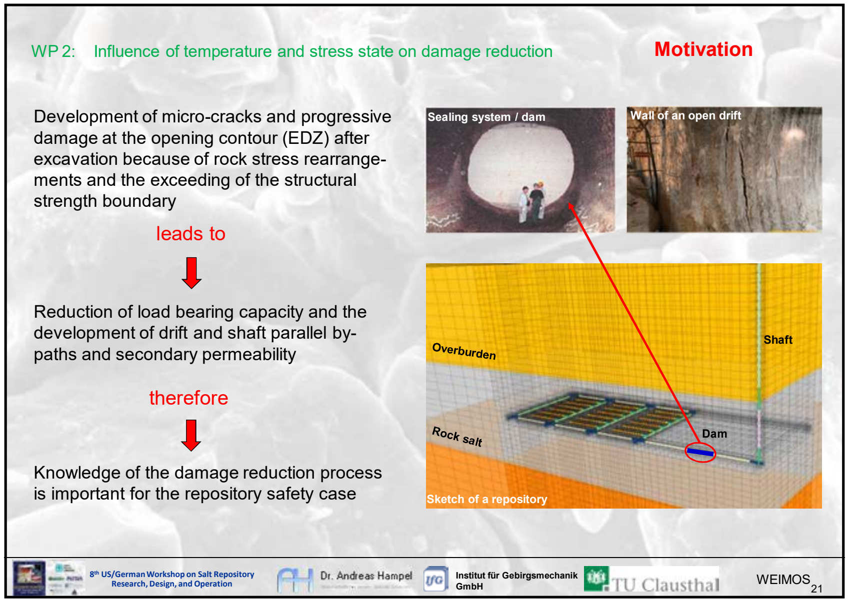
Numerical simulation

Günther/Salzer Approach



Joint Project WEIMOS

Work Packages		presented by
WP 1:	Deformation behavior at small deviatoric stresses	Till Popp (IfG)
WP 2:	Influence of temperature and stress state on damage reduction	Kai Herchen (TUC)
WP 3:	Deformation behavior resulting from tensile stresses	Till Popp (IfG)
WP 4:	Influence of inhomogeneities (layer boundaries, interfaces) on deformation	Andreas Hampel
WP 5:	Virtual demonstrator	Andreas Hampel
WP 6:	Administrative work	



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

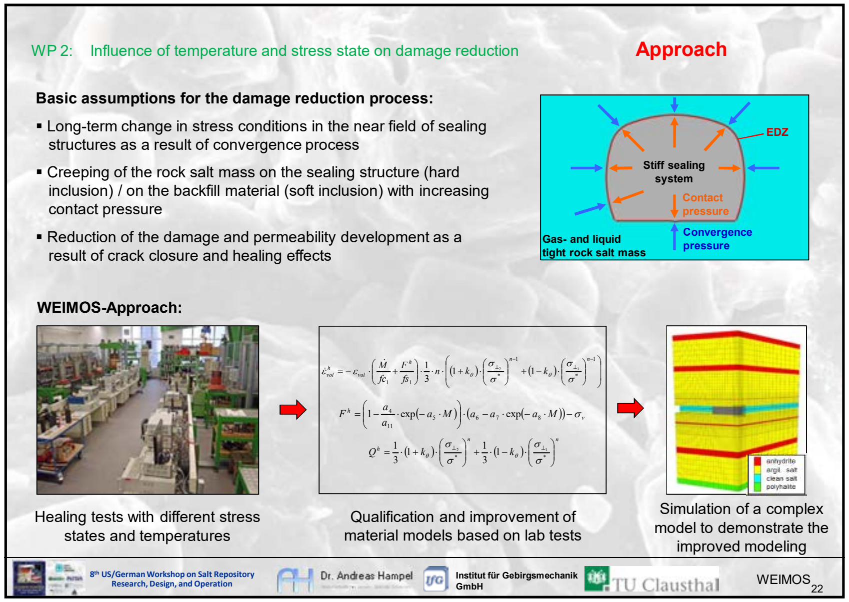
Development of micro-cracks and progressive damage at the opening contour (EDZ) after excavation because of rock stress rearrangements and the exceeding of the structural strength boundary

leads to

Reduction of load bearing capacity and the development of drift and shaft parallel by-paths and secondary permeability

therefore

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



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

Basic assumptions for the damage reduction process:

- Long-term change in stress conditions in the near field of sealing structures as a result of convergence process
- Creeping of the rock salt mass on the sealing structure (hard inclusion) / on the backfill material (soft inclusion) with increasing contact pressure
- Reduction of the damage and permeability development as a result of crack closure and healing effects

WEIMOS-Approach:

$$\dot{\varepsilon}_{vol}^{h} = -\varepsilon_{vol} \cdot \left(\frac{\dot{M}}{fc_1} + \frac{F^h}{fs_1} \right) \cdot \frac{1}{3} \cdot n \cdot \left((1+k_\theta) \cdot \left(\frac{\sigma_{\perp_2}}{\sigma^*} \right)^{n-1} + (1-k_\theta) \cdot \left(\frac{\sigma_{\perp_1}}{\sigma^*} \right)^{n-1} \right)$$

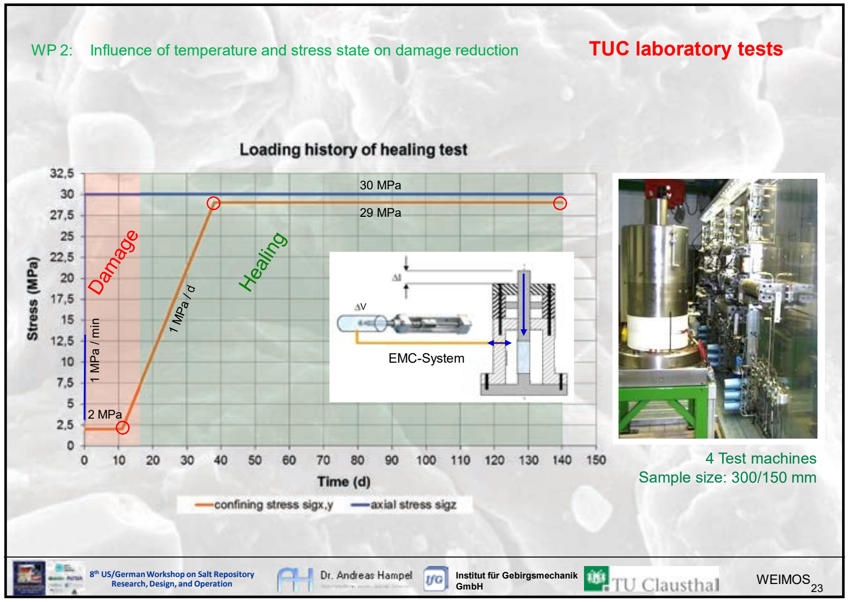
$$F^h = \left(1 - \frac{a_4}{a_{11}} \cdot \exp(-a_5 \cdot M) \right) \cdot (a_6 - a_7 \cdot \exp(-a_8 \cdot M)) - \sigma_v$$

$$Q^h = \frac{1}{3} \cdot (1+k_\theta) \cdot \left(\frac{\sigma_{\perp_2}}{\sigma^*} \right)^n + \frac{1}{3} \cdot (1-k_\theta) \cdot \left(\frac{\sigma_{\perp_1}}{\sigma^*} \right)^n$$

Healing tests with different stress states and temperatures

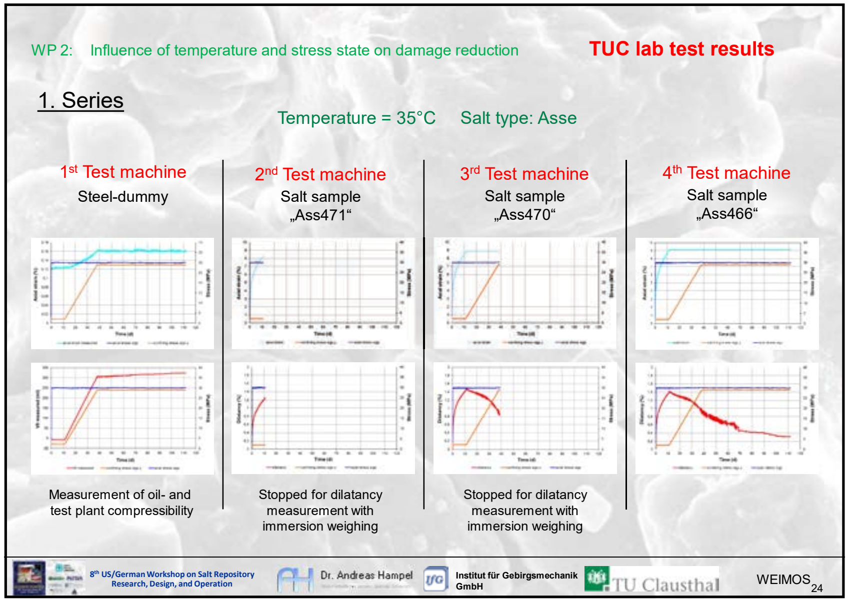
Qualification and improvement of material models based on lab tests

Simulation of a complex model to demonstrate the improved modeling



WP 2: Influence of temperature and stress state on damage reduction **TUC laboratory tests**

4 Test machines
Sample size: 300/150 mm

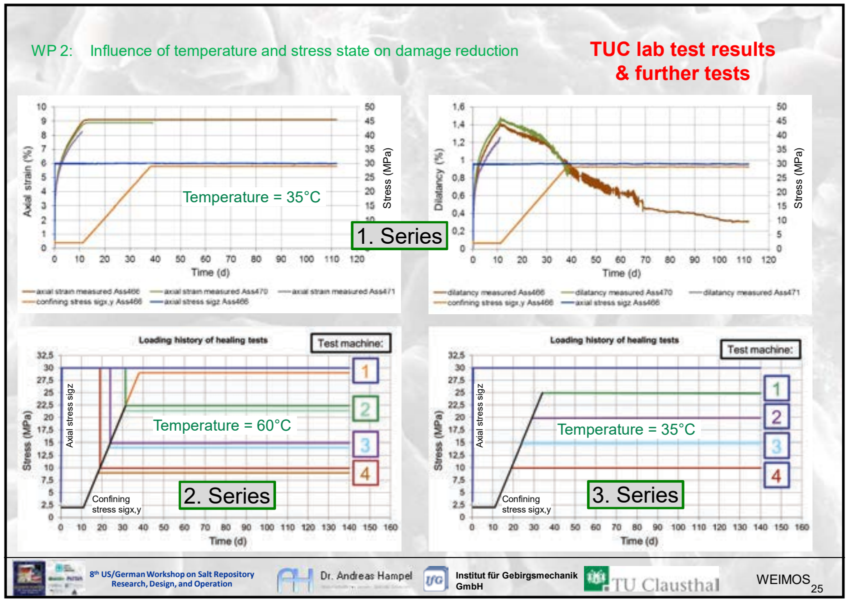


WP 2: Influence of temperature and stress state on damage reduction **TUC lab test results**

1. Series

Temperature = 35°C Salt type: Asse

1st Test machine	2nd Test machine	3rd Test machine	4th Test machine
Steel-dummy	Salt sample „Ass471“	Salt sample „Ass470“	Salt sample „Ass466“
Measurement of oil- and test plant compressibility	Stopped for dilatancy measurement with immersion weighing	Stopped for dilatancy measurement with immersion weighing	



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

TUC lab test results & further tests

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Dr. Andreas Hampel
Institut für Gebirgsmechanik GmbH
TU Clausthal
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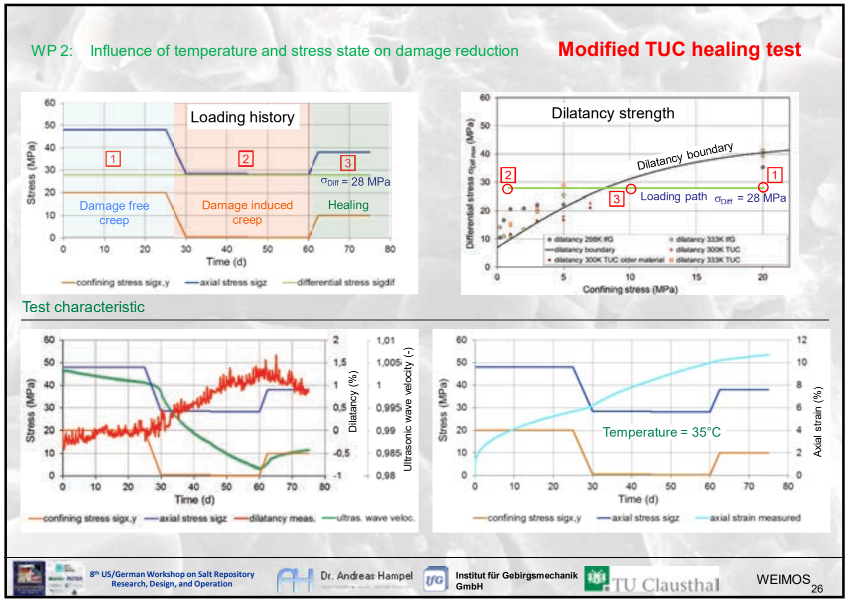

WP 2: Influence of temperature and stress state on damage reduction

Modified TUC healing test

Test characteristic

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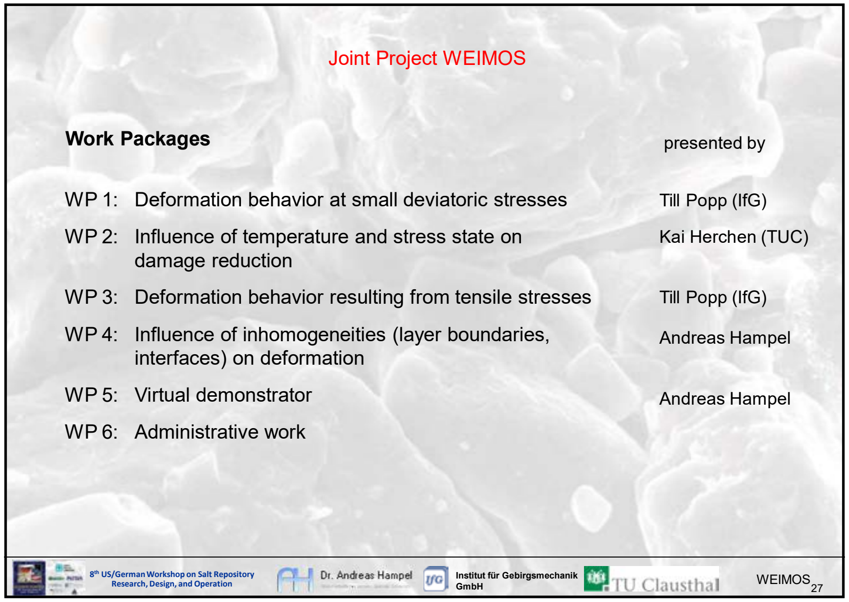

Joint Project WEIMOS

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Institut für Gebirgsmechanik GmbH
TU Clausthal
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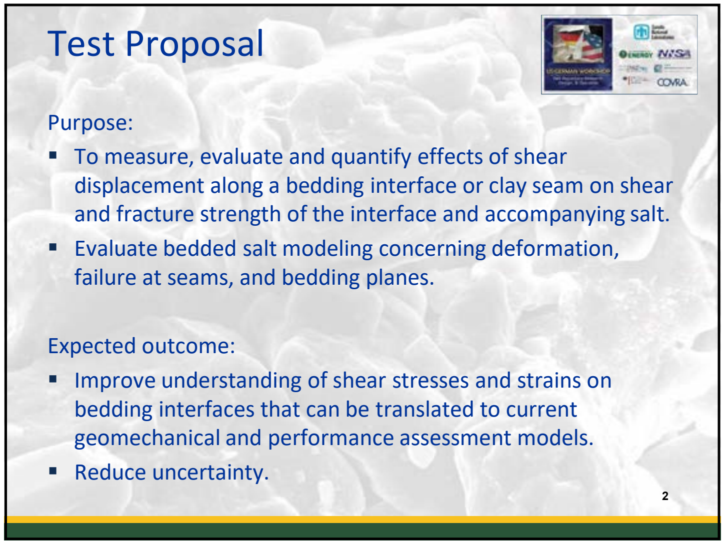
Testing Shear Strength and Deformation along Discontinuities in Salt

8th US/German Workshop on Salt Repository Research, Design, and Operation

Steven R. Sobolik, Sandia National Laboratories,
Albuquerque, New Mexico, USA
Stuart Buchholz, RESPEC, Rapid City, South Dakota, USA

Middelburg, The Netherlands
September 5-7, 2017

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. SAND2017-9197C



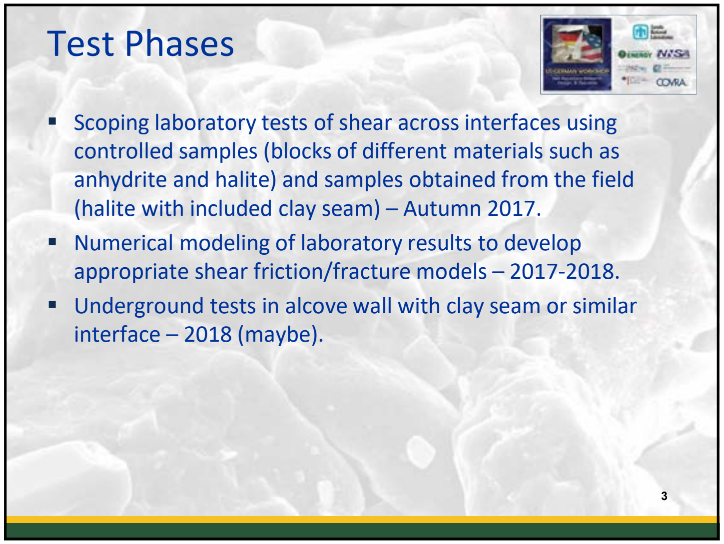
Test Proposal

Purpose:

- To measure, evaluate and quantify effects of shear displacement along a bedding interface or clay seam on shear and fracture strength of the interface and accompanying salt.
- Evaluate bedded salt modeling concerning deformation, failure at seams, and bedding planes.

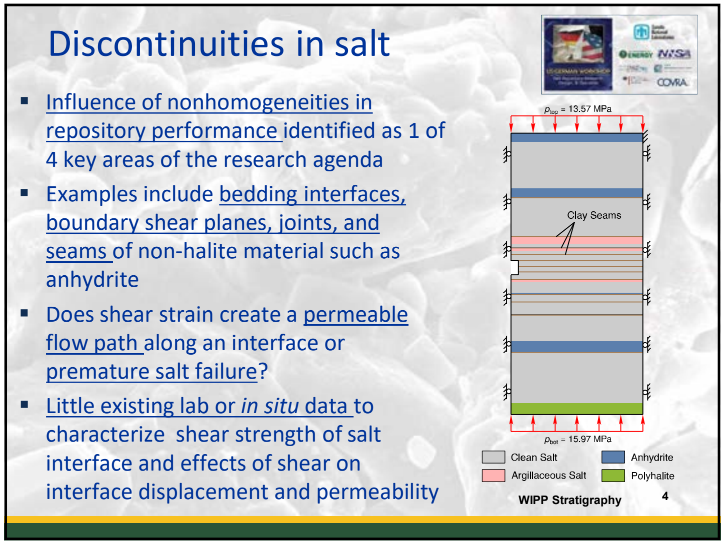
Expected outcome:

- Improve understanding of shear stresses and strains on bedding interfaces that can be translated to current geomechanical and performance assessment models.
- Reduce uncertainty.



Test Phases

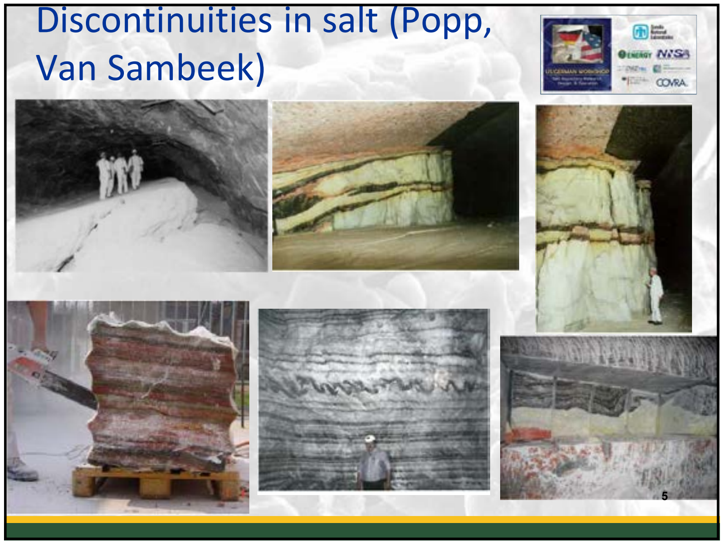
- Scoping laboratory tests of shear across interfaces using controlled samples (blocks of different materials such as anhydrite and halite) and samples obtained from the field (halite with included clay seam) – Autumn 2017.
- Numerical modeling of laboratory results to develop appropriate shear friction/fracture models – 2017-2018.
- Underground tests in alcove wall with clay seam or similar interface – 2018 (maybe).



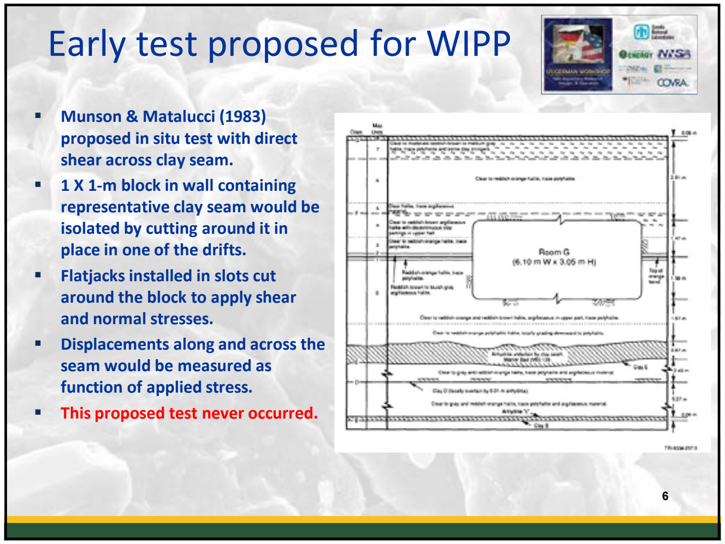
Discontinuities in salt

- Influence of nonhomogeneities in repository performance identified as 1 of 4 key areas of the research agenda
- Examples include bedding interfaces, boundary shear planes, joints, and seams of non-halite material such as anhydrite
- Does shear strain create a permeable flow path along an interface or premature salt failure?
- Little existing lab or *in situ* data to characterize shear strength of salt interface and effects of shear on interface displacement and permeability

WIPP Stratigraphy



Discontinuities in salt (Popp, Van Sambeek)



Early test proposed for WIPP

- **Munson & Matalucci (1983) proposed in situ test with direct shear across clay seam.**
- **1 X 1-m block in wall containing representative clay seam would be isolated by cutting around it in place in one of the drifts.**
- **Flatjacks installed in slots cut around the block to apply shear and normal stresses.**
- **Displacements along and across the seam would be measured as function of applied stress.**
- **This proposed test never occurred.**

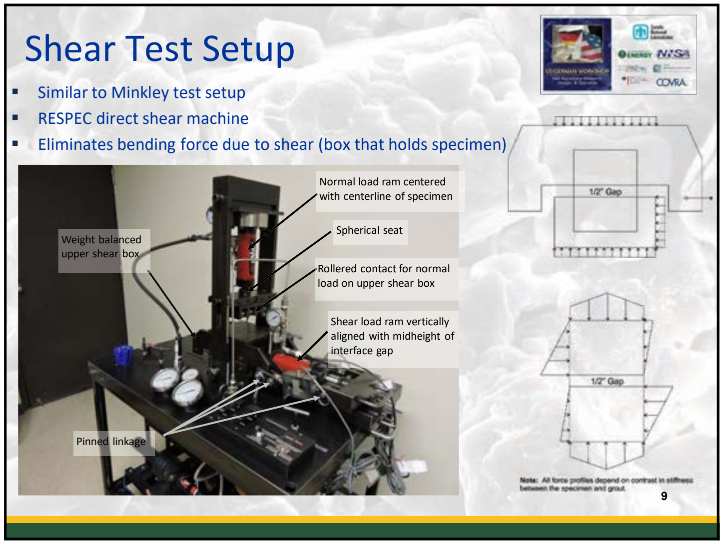
Laboratory testing in 2017

Test description: Series of laboratory tests to begin in late 2017 to be used in conjunction with WIPP, WEIMOS modeling exercises.

- Test plan written, completed WIPP QA reviews 7/27/2017.
- Contract modification between SNL, RESPEC in process, pending DOE requirements for WIPP; NEPA checklist completed 8/7/2017
- Plan to obtain cores for up to 33 test samples from New Mexico potash/salt mines:
  - 30 cm diameter, 56 cm length cores cut vertically from floor
  - Cores to contain clay seam identified from further uphill in drift
  - Test samples cut from cores will be 10-cm cylinders or square blocks
  - Seam size no greater than 2.5 cm; or interface between distinct layers
  - Material next to seam/interface – halite, polyhalite, anhydrite
  - Asperity characteristics?

Laboratory testing goals

- Laboratory shear tests similar to those on carnalite and salt performed in 2007 (Minkley & Mühlbauer); test results were used for model development.
- 2017 laboratory tests require following:
  - 10-cm samples, with existing or fabricated interface
  - 6.9-20.7 MPa stress capacity both in axial (compression) and shear loading
  - Fixed normal stress for most tests; fixed normal displacement another option
  - Variable shear velocity to evaluate onset of fracture/slip
  - RESPEC direct shear machine (Capacity for up to 15-cm cube samples, 130 kN capacity, shear velocities 0.25-5 mm/min.)
- Analysis plan in process (Reedlunn) to develop constitutive, numerical model for shear slip in seams from results of 2017 lab tests.



Shear Test Setup

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

Weight balanced upper shear box

Normal load ram centered with centerline of specimen

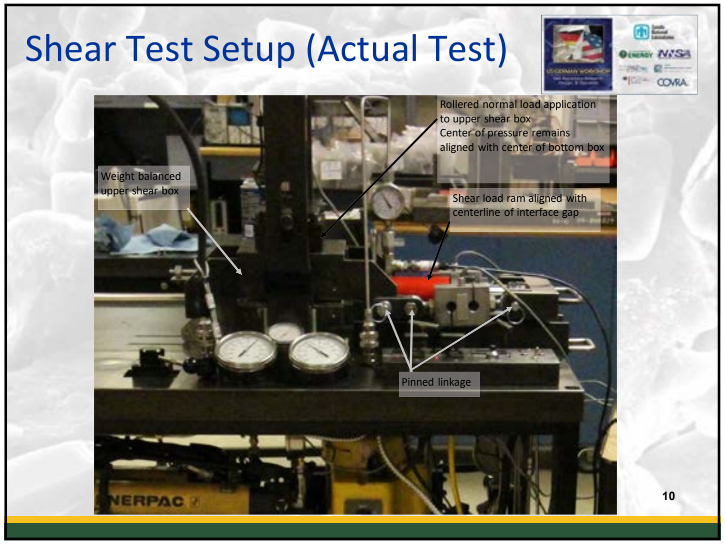
Spherical seat

Rollered contact for normal load on upper shear box

Shear load ram vertically aligned with midheight of interface gap

Pinned linkage

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



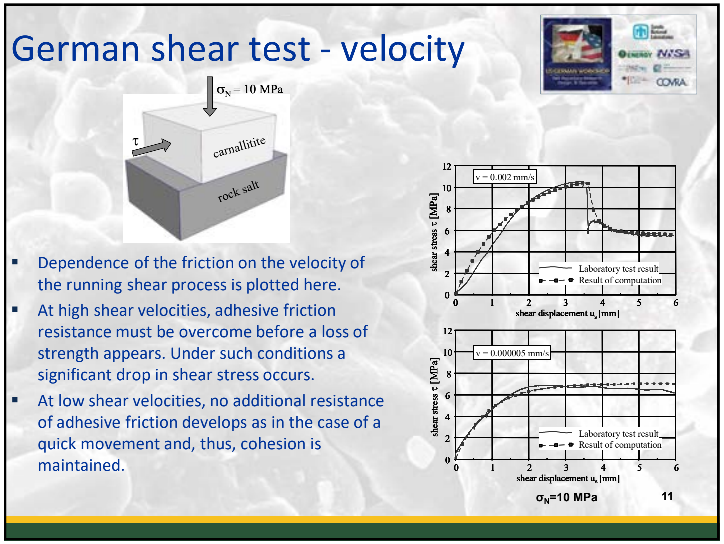
Shear Test Setup (Actual Test)

Rollered normal load application to upper shear box
Center of pressure remains aligned with center of bottom box

Weight balanced upper shear box

Shear load ram aligned with centerline of interface gap

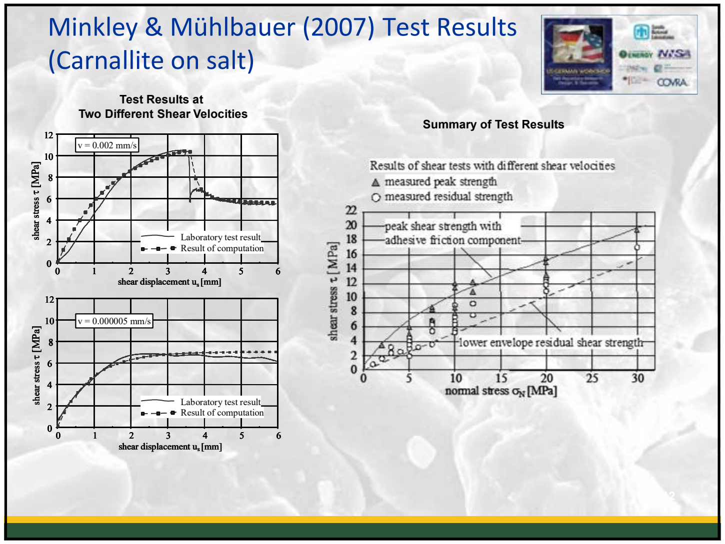
Pinned linkage



German shear test - velocity

- Dependence of the friction on the velocity of the running shear process is plotted here.
- At high shear velocities, adhesive friction resistance must be overcome before a loss of strength appears. Under such conditions a significant drop in shear stress occurs.
- At low shear velocities, no additional resistance of adhesive friction develops as in the case of a quick movement and, thus, cohesion is maintained.

σ_N=10 MPa

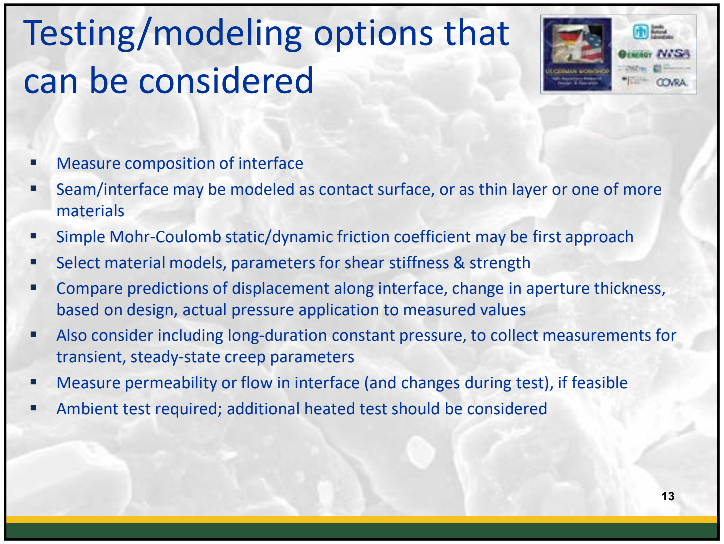


Minkley & Mühlbauer (2007) Test Results (Carnallite on salt)

Test Results at
Two Different Shear Velocities

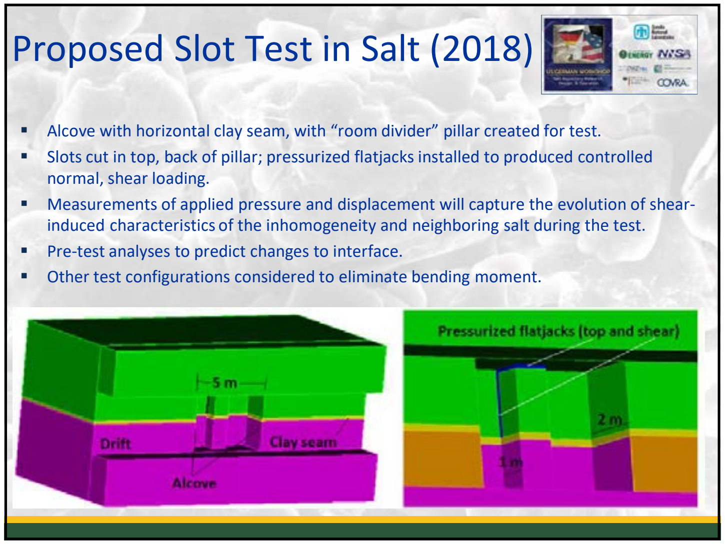
Summary of Test Results

Results of shear tests with different shear velocities
▲ measured peak strength
○ measured residual strength



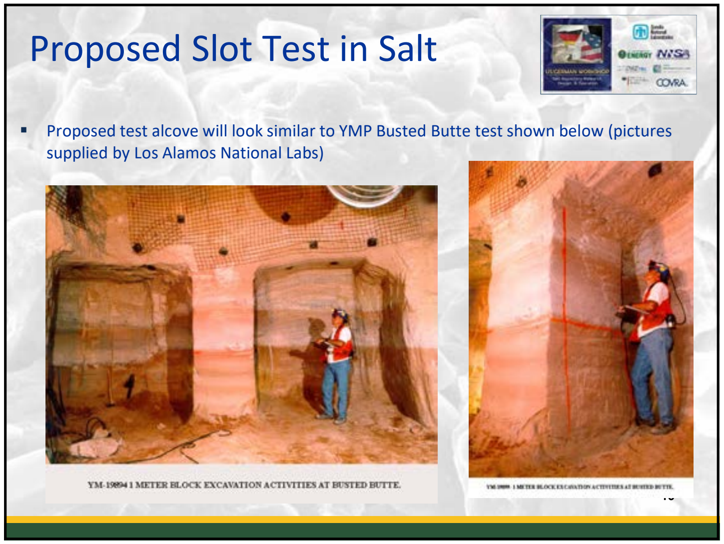
Testing/modeling options that can be considered

- Measure composition of interface
- Seam/interface may be modeled as contact surface, or as thin layer or one of more materials
- Simple Mohr-Coulomb static/dynamic friction coefficient may be first approach
- Select material models, parameters for shear stiffness & strength
- Compare predictions of displacement along interface, change in aperture thickness, based on design, actual pressure application to measured values
- Also consider including long-duration constant pressure, to collect measurements for transient, steady-state creep parameters
- Measure permeability or flow in interface (and changes during test), if feasible
- Ambient test required; additional heated test should be considered



Proposed Slot Test in Salt (2018)

- Alcove with horizontal clay seam, with "room divider" pillar created for test.
- Slots cut in top, back of pillar; pressurized flatjacks installed to produced controlled normal, shear loading.
- Measurements of applied pressure and displacement will capture the evolution of shear-induced characteristics of the inhomogeneity and neighboring salt during the test.
- Pre-test analyses to predict changes to interface.
- Other test configurations considered to eliminate bending moment.

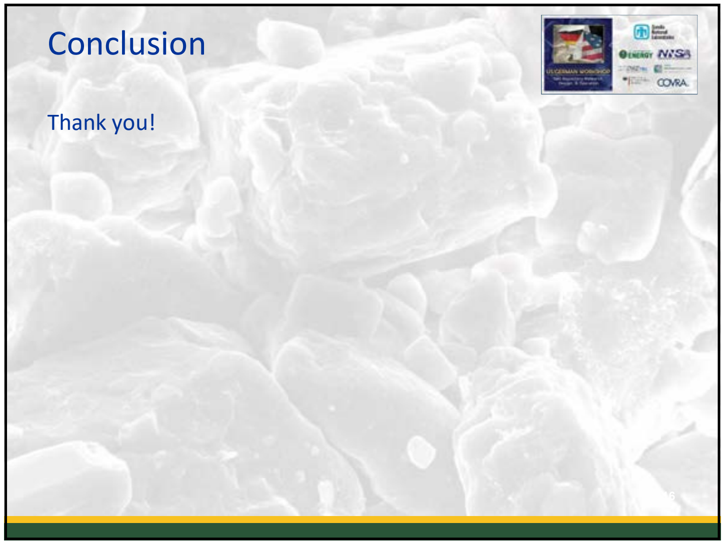


Proposed Slot Test in Salt

- Proposed test alcove will look similar to YMP Busted Butte test shown below (pictures supplied by Los Alamos National Labs)

YM-19894 1 METER BLOCK EXCAVATION ACTIVITIES AT BUSTED BUTTE.

YM-[illegible] 1 METER BLOCK EXCAVATION ACTIVITIES AT BUSTED BUTTE.



Conclusion

Thank you!

8th US/German Workshop on Salt Repository Research, Design, and Operation

Middelburg, The Netherlands
September 5-7, 2017

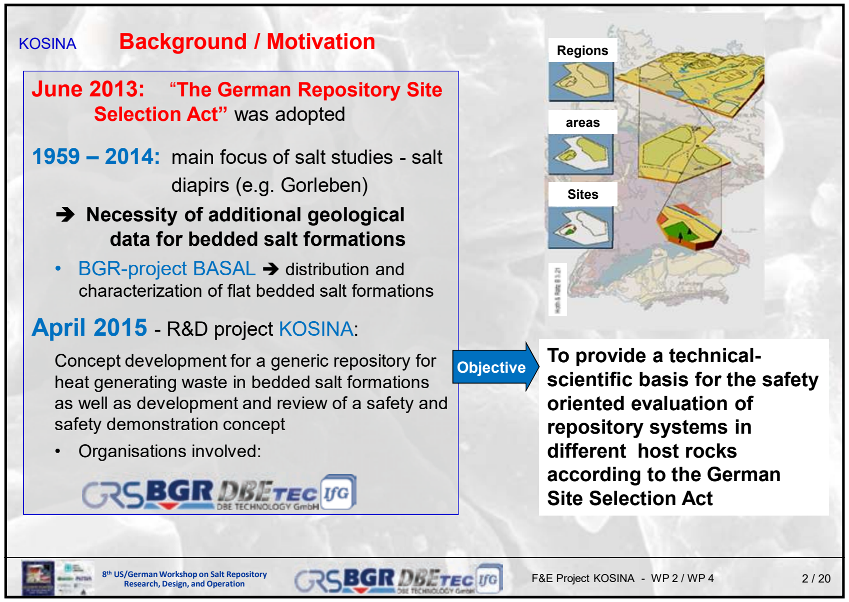
New results of the KOSINA project - Generic geological models / Integrity analysis

Till Popp (IfG), Tatjana Kühnlenz (BGR) & KOSINA-Team

KOSINA:

FuE-Projekt: **Ko**nzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines **Si**cherheits- und **Na**chweiskonzeptes

R&D Project: **Concept development for a generic repository for heat generating waste in bedded salt formations as well as development and review of a safety and safety demonstration concept (KOSINA)**



KOSINA

Background / Motivation

June 2013: "The German Repository Site Selection Act" was adopted

1959 – 2014: main focus of salt studies - salt diapirs (e.g. Gorleben)

➔ **Necessity of additional geological data for bedded salt formations**

- BGR-project BASAL ➔ distribution and characterization of flat bedded salt formations

April 2015 - R&D project KOSINA:

Concept development for a generic repository for heat generating waste in bedded salt formations as well as development and review of a safety and safety demonstration concept

- Organisations involved:

Objective

To provide a technical-scientific basis for the safety oriented evaluation of repository systems in different host rocks according to the German Site Selection Act

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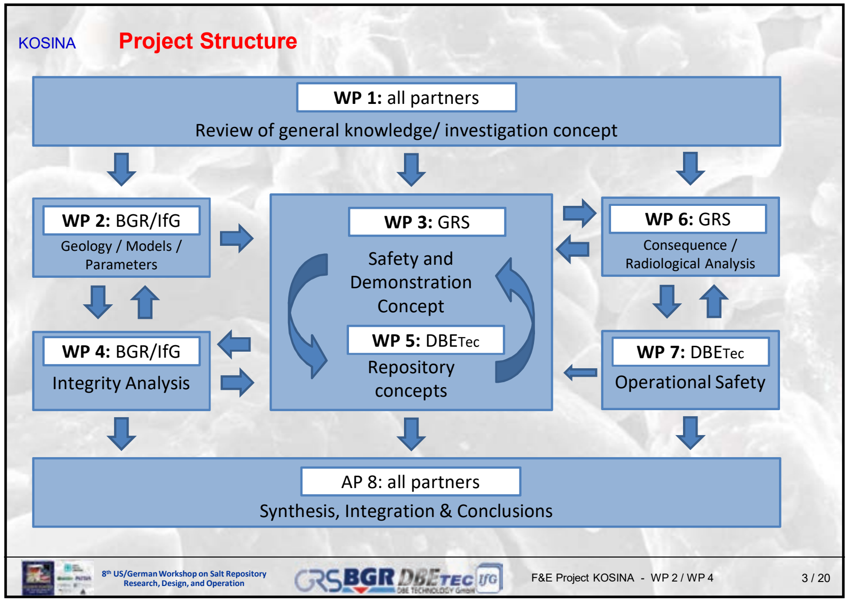
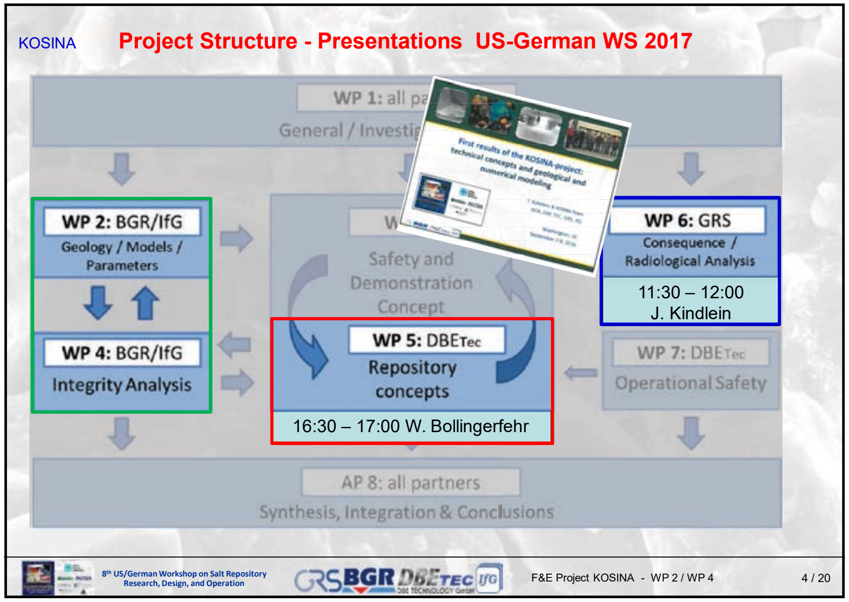


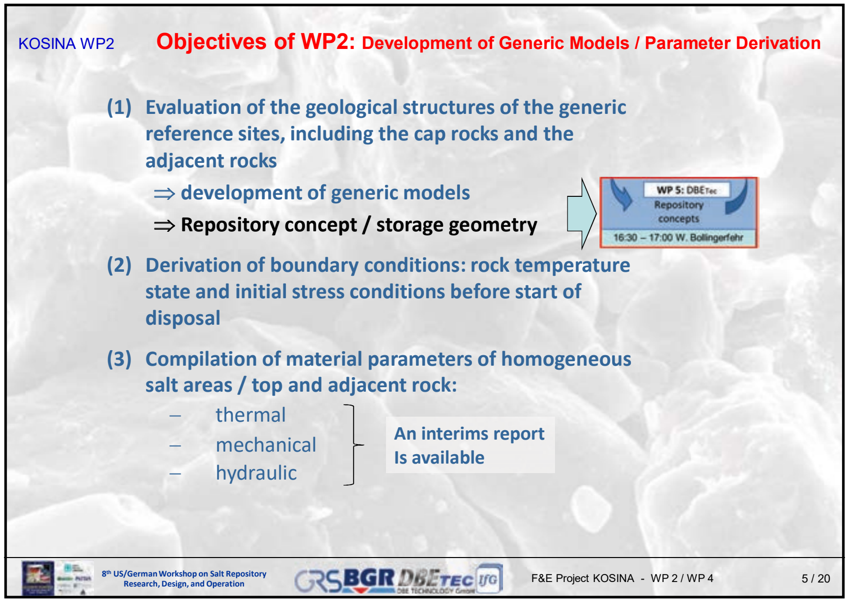
KOSINA

Project Structure



KOSINA

Project Structure - Presentations US-German WS 2017



KOSINA WP2

Objectives of WP2: Development of Generic Models / Parameter Derivation

(1) Evaluation of the geological structures of the generic reference sites, including the cap rocks and the adjacent rocks

⇒ development of generic models

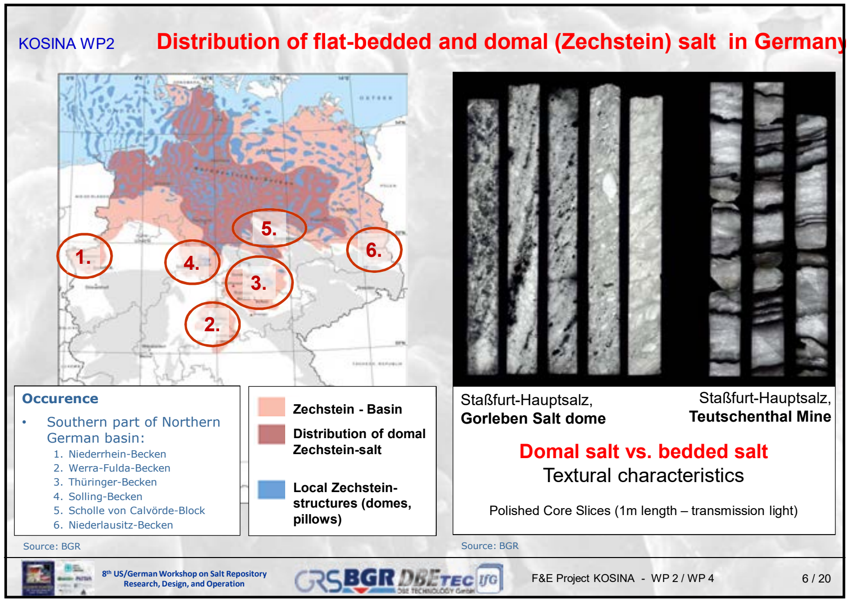
⇒ **Repository concept / storage geometry**

(2) Derivation of boundary conditions: rock temperature state and initial stress conditions before start of disposal

(3) Compilation of material parameters of homogeneous salt areas / top and adjacent rock:

- thermal
- mechanical
- hydraulic

An interims report Is available



KOSINA WP2

Distribution of flat-bedded and domal (Zechstein) salt in Germany

Occurence

- Southern part of Northern German basin:
  1. Niederrhein-Becken
  2. Werra-Fulda-Becken
  3. Thüringer-Becken
  4. Solling-Becken
  5. Scholle von Calvörde-Block
  6. Niederlausitz-Becken

🟥	**Zechstein - Basin**
🟥	**Distribution of domal Zechstein-salt**
🟦	**Local Zechstein-structures (domes, pillows)**

Source: BGR

Staßfurt-Hauptsalz, **Gorleben Salt dome**

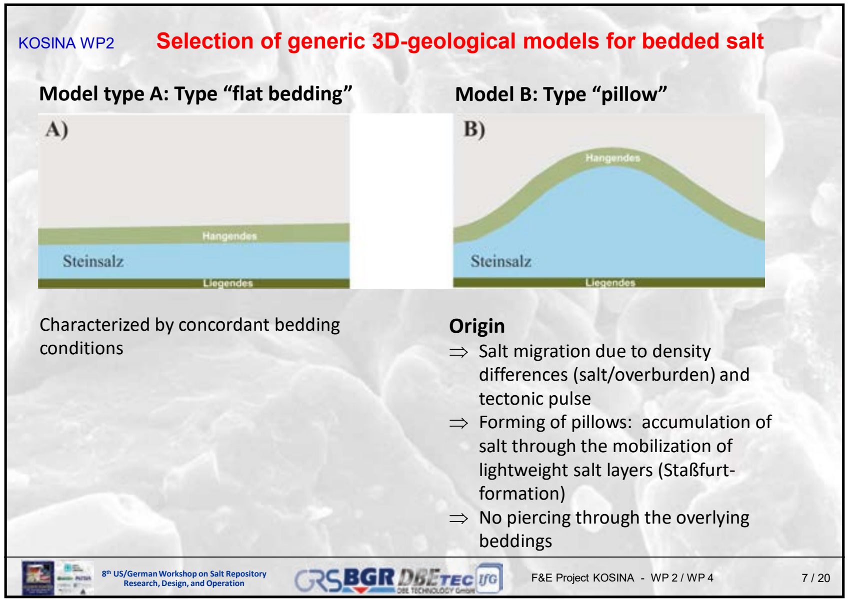
Staßfurt-Hauptsalz, **Teutschenthal Mine**

Domal salt vs. bedded salt

Textural characteristics

Polished Core Slices (1m length – transmission light)

Source: BGR



KOSINA WP2

Selection of generic 3D-geological models for bedded salt

Model type A: Type "flat bedding"

Model B: Type "pillow"

Characterized by concordant bedding conditions

Origin

⇒ Salt migration due to density differences (salt/overburden) and tectonic pulse

⇒ Forming of pillows: accumulation of salt through the mobilization of lightweight salt layers (Staßfurt-formation)

⇒ No piercing through the overlying beddings

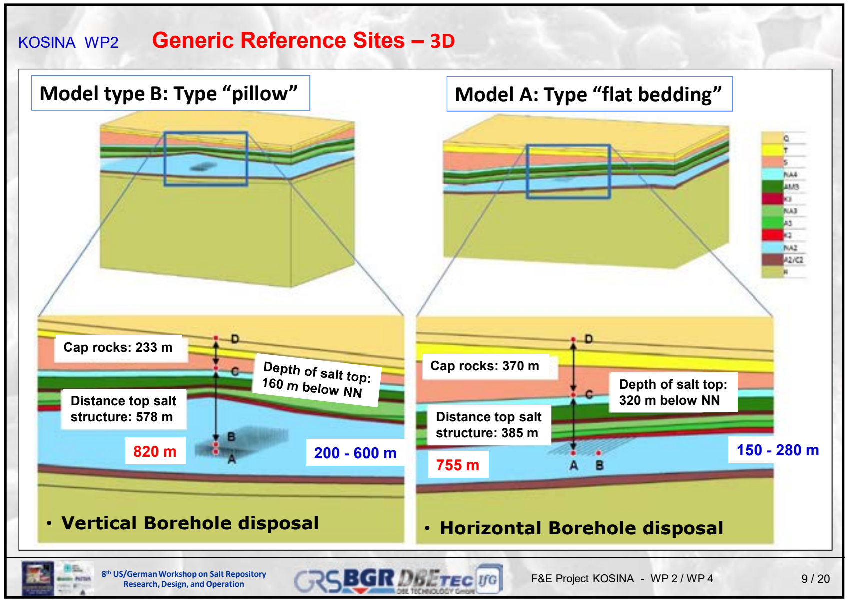
KOSINA WP2

Bedded salt, but not always flat …

Salt mine Teutschenthal

"Neue Werkstatt" – Staßfurt Potash layer z2SF

Source: IfG



KOSINA WP2 **Generic Reference Sites – 3D**

Model type B: Type "pillow"

Model A: Type "flat bedding"

Cap rocks: 233 m

Depth of salt top: 160 m below NN

Distance top salt structure: 578 m

820 m

200 - 600 m

Cap rocks: 370 m

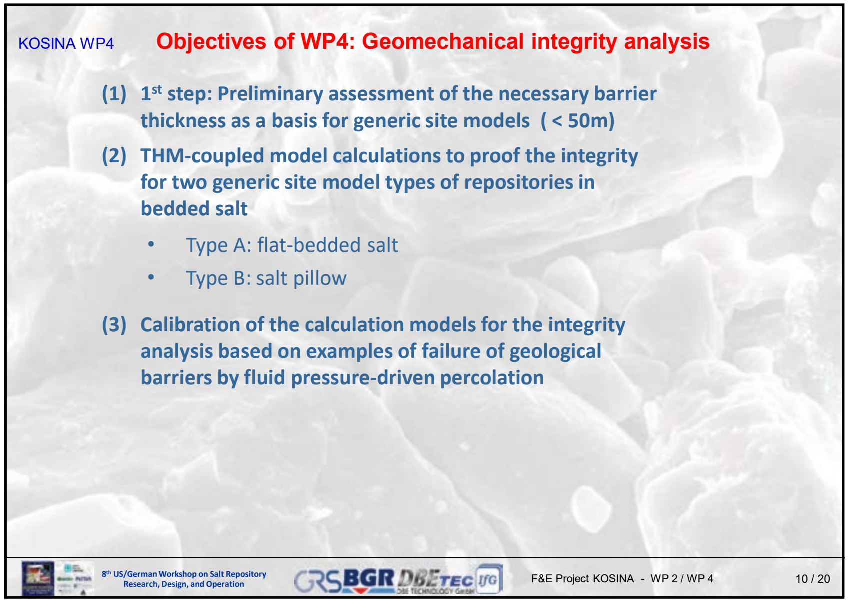
Depth of salt top: 320 m below NN

Distance top salt structure: 385 m

755 m

150 - 280 m

- **Vertical Borehole disposal**
- **Horizontal Borehole disposal**



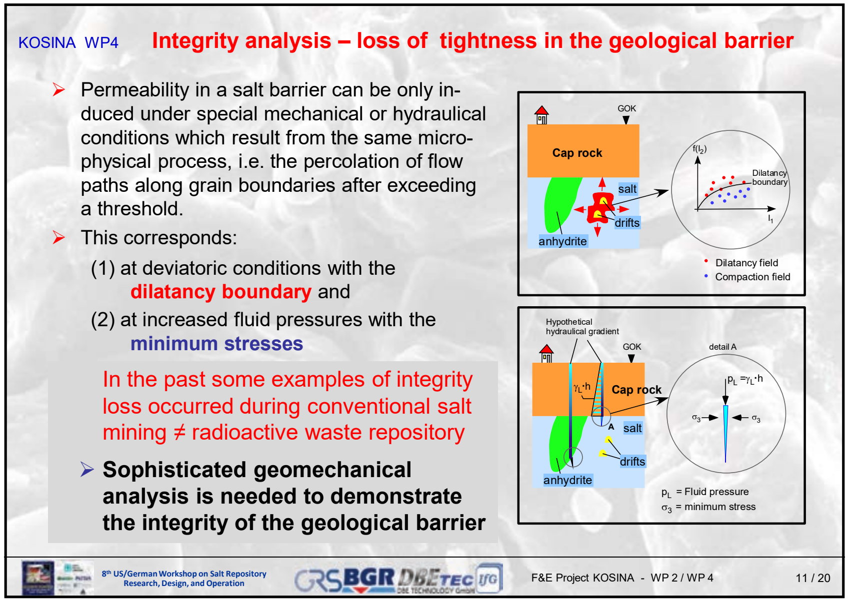
KOSINA WP4 **Objectives of WP4: Geomechanical integrity analysis**

(1) 1st step: Preliminary assessment of the necessary barrier thickness as a basis for generic site models (< 50m)

(2) THM-coupled model calculations to proof the integrity for two generic site model types of repositories in bedded salt

- Type A: flat-bedded salt
- Type B: salt pillow

(3) Calibration of the calculation models for the integrity analysis based on examples of failure of geological barriers by fluid pressure-driven percolation



KOSINA WP4 **Integrity analysis – loss of tightness in the geological barrier**

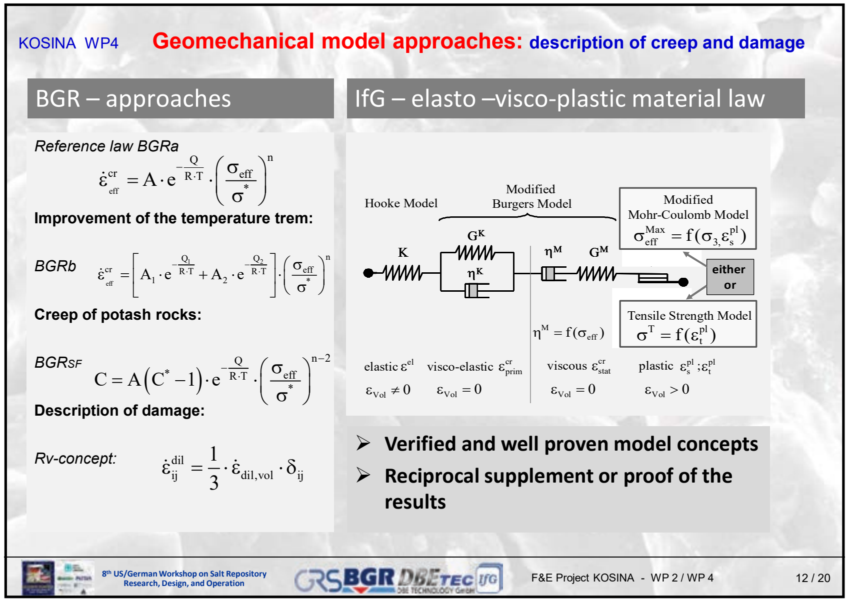
- Permeability in a salt barrier can be only induced under special mechanical or hydraulical conditions which result from the same microphysical process, i.e. the percolation of flow paths along grain boundaries after exceeding a threshold.
- This corresponds:

  (1) at deviatoric conditions with the **dilatancy boundary** and

  (2) at increased fluid pressures with the **minimum stresses**

In the past some examples of integrity loss occurred during conventional salt mining ≠ radioactive waste repository

- **Sophisticated geomechanical analysis is needed to demonstrate the integrity of the geological barrier**



KOSINA WP4 **Geomechanical model approaches: description of creep and damage**

BGR – approaches

Reference law BGRa

$$\dot{\varepsilon}^{cr}_{eff} = A \cdot e^{-\frac{Q}{R \cdot T}} \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^n$$

Improvement of the temperature trem:

BGRb

$$\dot{\varepsilon}^{cr}_{eff} = \left[A_1 \cdot e^{-\frac{Q_1}{R \cdot T}} + A_2 \cdot e^{-\frac{Q_2}{R \cdot T}}\right] \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^n$$

Creep of potash rocks:

BGRSF

$$C = A\left(C^* - 1\right) \cdot e^{-\frac{Q}{R \cdot T}} \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^{n-2}$$

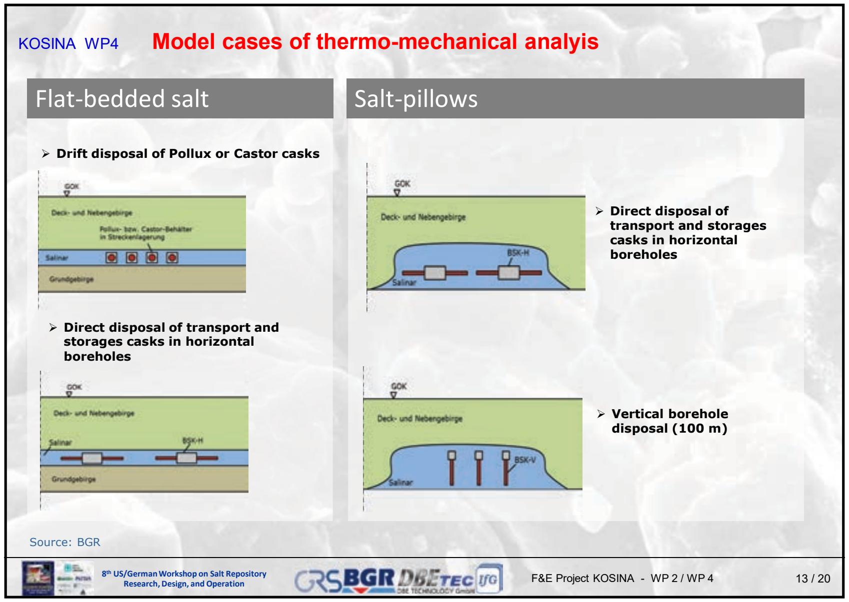
Description of damage:

Rv-concept:

$$\dot{\varepsilon}^{dil}_{ij} = \frac{1}{3} \cdot \dot{\varepsilon}_{dil,vol} \cdot \delta_{ij}$$

IfG – elasto –visco-plastic material law

- **Verified and well proven model concepts**
- **Reciprocal supplement or proof of the results**



KOSINA WP4 **Model cases of thermo-mechanical analyis**

Flat-bedded salt

- **Drift disposal of Pollux or Castor casks**

- **Direct disposal of transport and storages casks in horizontal boreholes**

Salt-pillows

- **Direct disposal of transport and storages casks in horizontal boreholes**

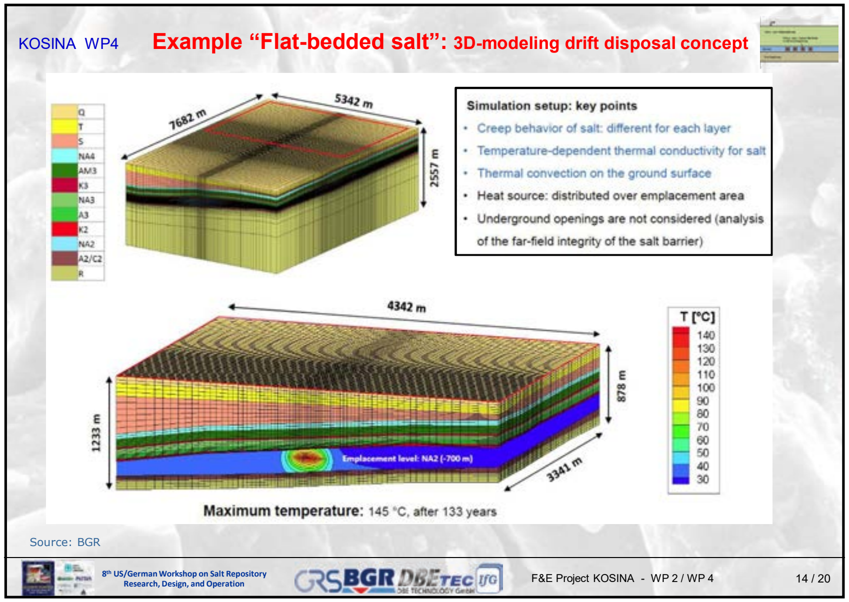
- **Vertical borehole disposal (100 m)**

Source: BGR

8th US/German Workshop on Salt Repository Research, Design, and Operation

F&E Project KOSINA - WP 2 / WP 4

13 / 20



KOSINA WP4 **Example "Flat-bedded salt": 3D-modeling drift disposal concept**

Simulation setup: key points

- Creep behavior of salt: different for each layer
- Temperature-dependent thermal conductivity for salt
- Thermal convection on the ground surface
- Heat source: distributed over emplacement area
- Underground openings are not considered (analysis of the far-field integrity of the salt barrier)

Maximum temperature: 145 °C, after 133 years

Source: BGR

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F&E Project KOSINA - WP 2 / WP 4

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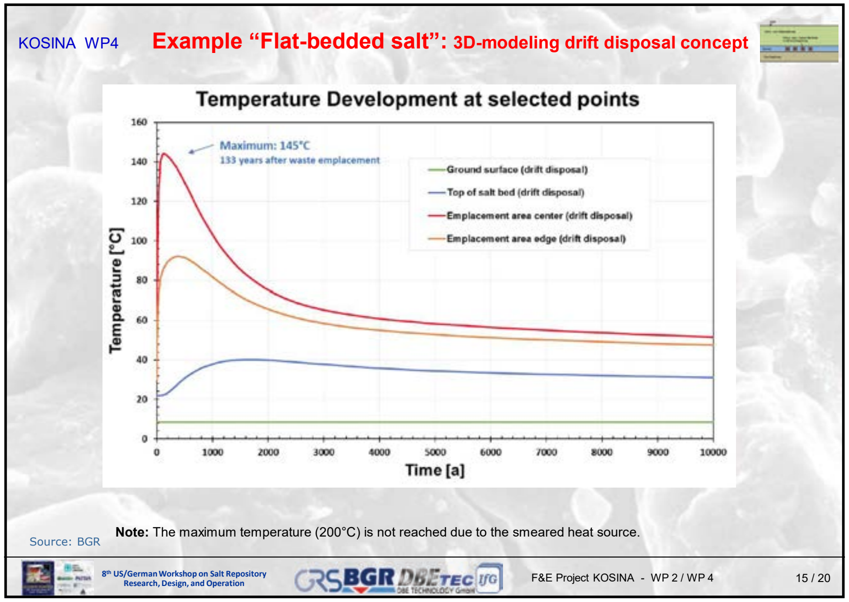

KOSINA WP4 **Example "Flat-bedded salt": 3D-modeling drift disposal concept**

Temperature Development at selected points

Note: The maximum temperature (200°C) is not reached due to the smeared heat source.

Source: BGR

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F&E Project KOSINA - WP 2 / WP 4

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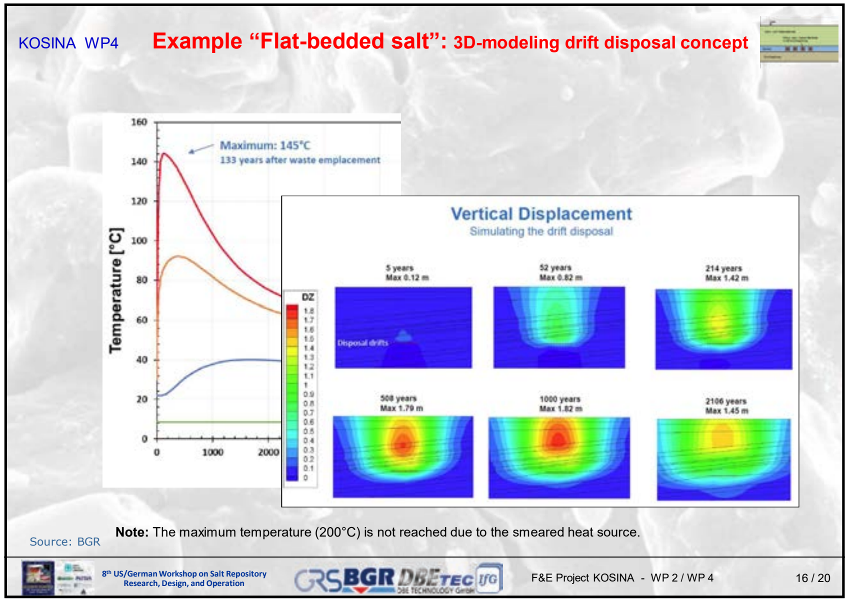

KOSINA WP4 **Example "Flat-bedded salt": 3D-modeling drift disposal concept**

Note: The maximum temperature (200°C) is not reached due to the smeared heat source.

Source: BGR

8th US/German Workshop on Salt Repository Research, Design, and Operation

F&E Project KOSINA - WP 2 / WP 4

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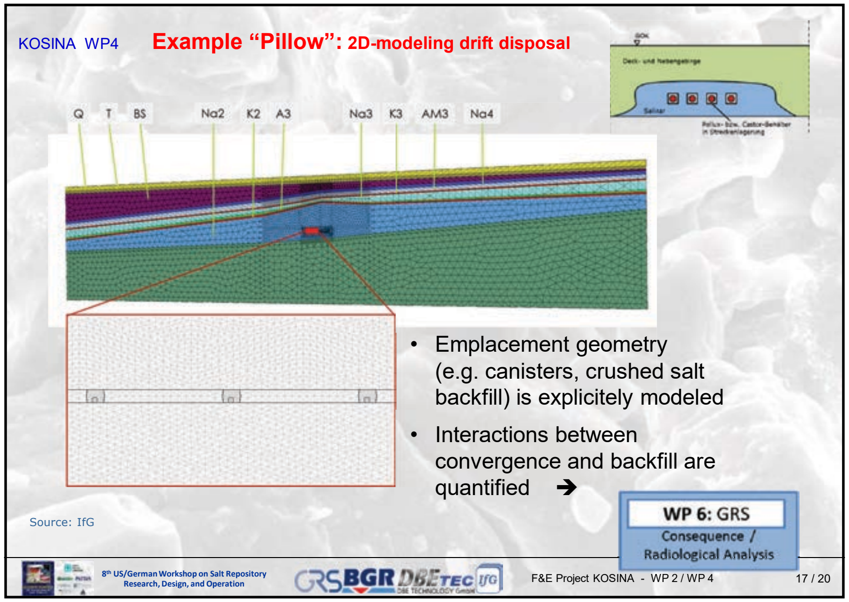
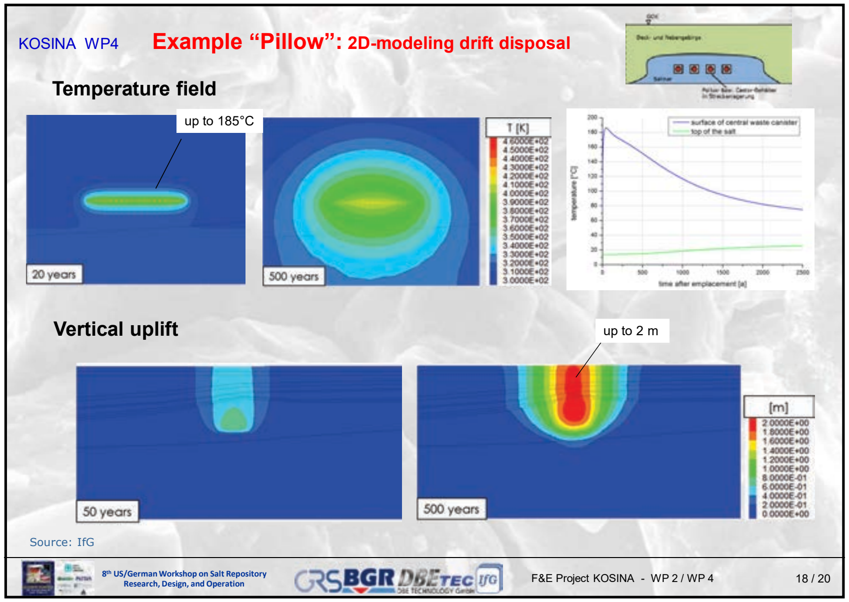


KOSINA WP4 **Example “Pillow”: 2D-modeling drift disposal**

- Emplacement geometry (e.g. canisters, crushed salt backfill) is explicitely modeled
- Interactions between convergence and backfill are quantified ➔

WP 6: GRS
Consequence / Radiological Analysis

Source: IfG

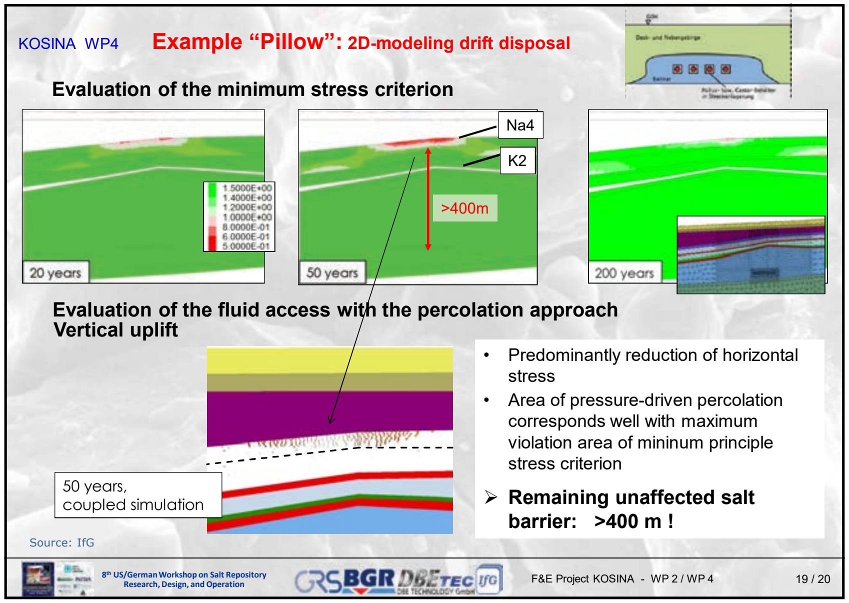


KOSINA WP4 **Example “Pillow”: 2D-modeling drift disposal**

Temperature field

Vertical uplift

Source: IfG



KOSINA WP4 **Example “Pillow”: 2D-modeling drift disposal**

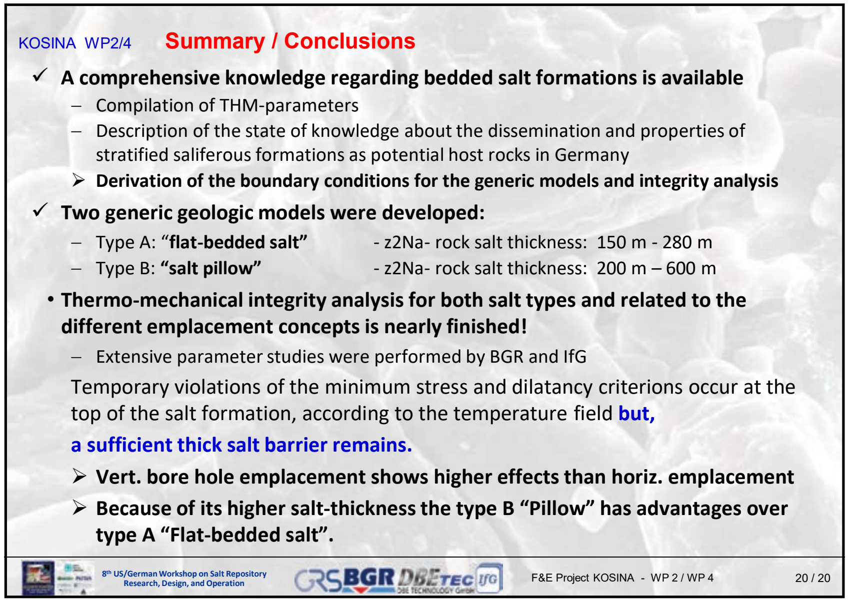
Evaluation of the minimum stress criterion

Evaluation of the fluid access with the percolation approach
Vertical uplift

- Predominantly reduction of horizontal stress
- Area of pressure-driven percolation corresponds well with maximum violation area of mininum principle stress criterion

➢ **Remaining unaffected salt barrier: >400 m !**

Source: IfG



KOSINA WP2/4 **Summary / Conclusions**

✓ **A comprehensive knowledge regarding bedded salt formations is available**
- Compilation of THM-parameters
- Description of the state of knowledge about the dissemination and properties of stratified saliferous formations as potential host rocks in Germany

➢ **Derivation of the boundary conditions for the generic models and integrity analysis**

✓ **Two generic geologic models were developed:**
- Type A: **“flat-bedded salt”** - z2Na- rock salt thickness: 150 m - 280 m
- Type B: **“salt pillow”** - z2Na- rock salt thickness: 200 m – 600 m

- **Thermo-mechanical integrity analysis for both salt types and related to the different emplacement concepts is nearly finished!**
  - Extensive parameter studies were performed by BGR and IfG

Temporary violations of the minimum stress and dilatancy criterions occur at the top of the salt formation, according to the temperature field **but,**

a sufficient thick salt barrier remains.

➢ **Vert. bore hole emplacement shows higher effects than horiz. emplacement**

➢ **Because of its higher salt-thickness the type B “Pillow” has advantages over type A “Flat-bedded salt”.**

Radiological Consequences Analysis for a HLW Repository in Bedded Salt in Germany (Project KOSINA)

Jonathan Kindlein
GRS gGmbH

Middelburg, The Netherlands
September 5-7, 2017

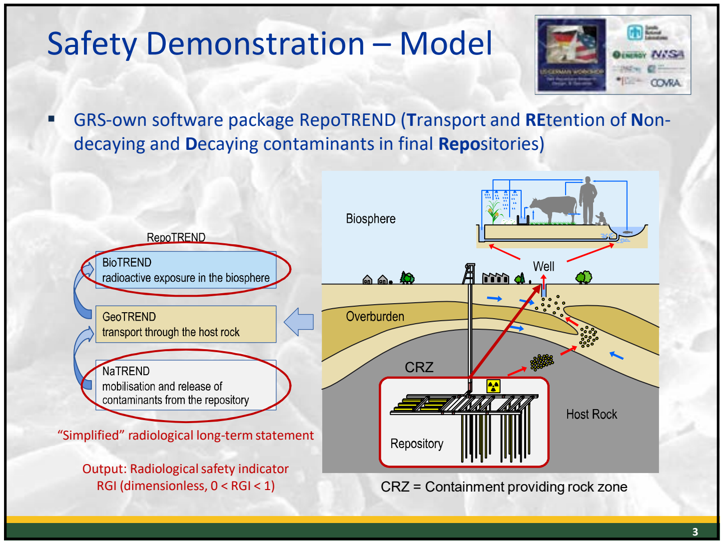
Introduction – Project Tasks

WP3: Development of a safety concept and safety demonstration concept

- Development of a safety concept for a repository for heat-generating radioactive waste and spent fuel in bedded rock salt formations
- Development of a safety demonstration concept based on the safety concept
- Dealing with uncertainties

WP6: Analysis of radiological consequences

- Derivation of test cases for radiological consequences analysis, verification of the applicability of existing radiological indicators (RGI, etc.)
- Verification of the applicability of existing instruments for radiological consequences analysis on the basis of the specified test cases and indicators



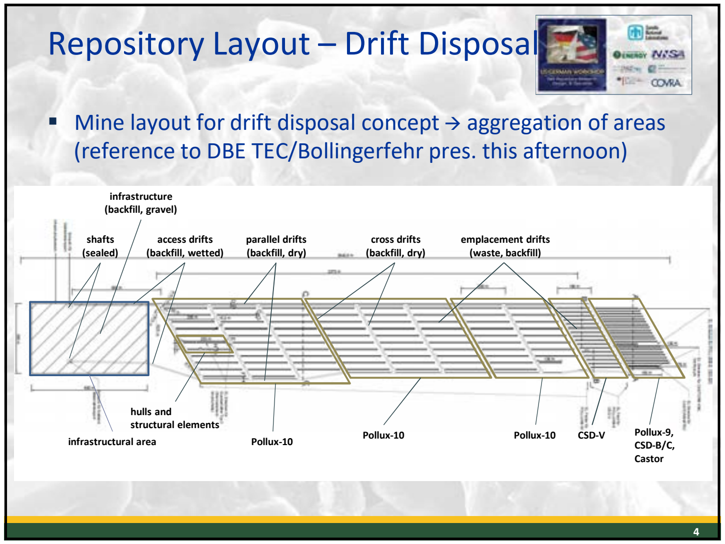
Safety Demonstration – Model

- GRS-own software package RepoTREND (**T**ransport and **RE**tention of **N**on-decaying and **D**ecaying contaminants in final **Repo**sitories)

"Simplified" radiological long-term statement

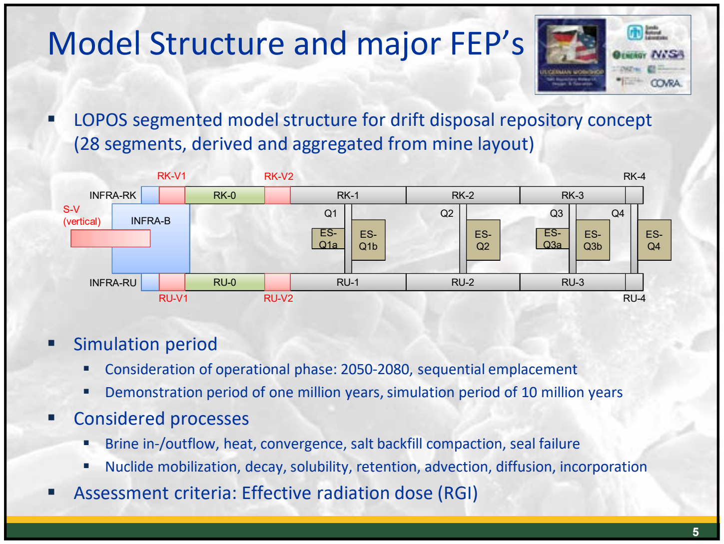
Output: Radiological safety indicator RGI (dimensionless, 0 < RGI < 1)

CRZ = Containment providing rock zone



Repository Layout – Drift Disposal

- Mine layout for drift disposal concept → aggregation of areas (reference to DBE TEC/Bollingerfehr pres. this afternoon)



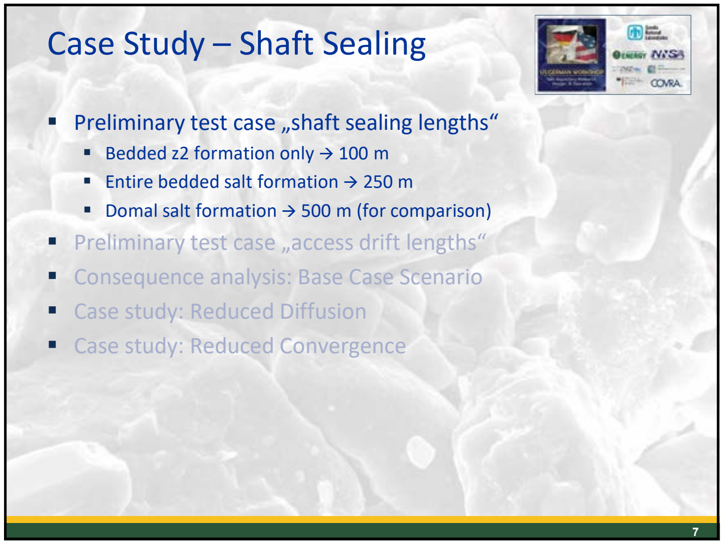
Model Structure and major FEP's

- LOPOS segmented model structure for drift disposal repository concept (28 segments, derived and aggregated from mine layout)

- Simulation period
  - Consideration of operational phase: 2050-2080, sequential emplacement
  - Demonstration period of one million years, simulation period of 10 million years
- Considered processes
  - Brine in-/outflow, heat, convergence, salt backfill compaction, seal failure
  - Nuclide mobilization, decay, solubility, retention, advection, diffusion, incorporation
- Assessment criteria: Effective radiation dose (RGI)

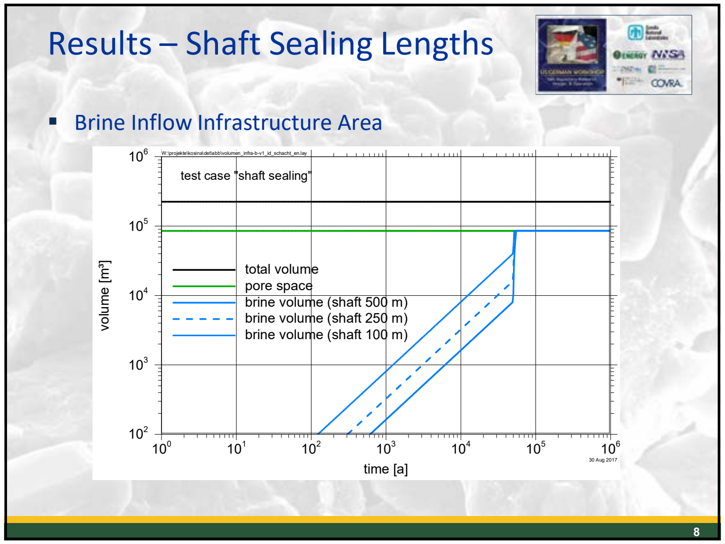
Case Studies - Overview

- Preliminary test case „shaft sealing lengths“
- Preliminary test case „access drift lengths“
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
- Case study: Reduced Convergence



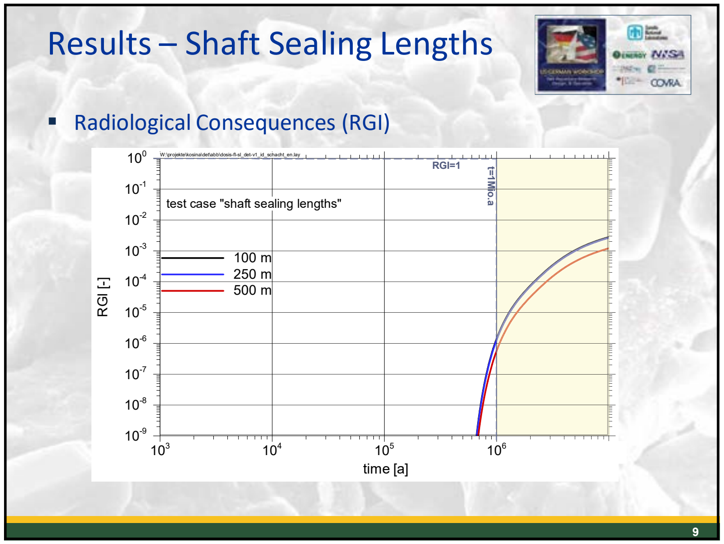
Case Study – Shaft Sealing

- Preliminary test case „shaft sealing lengths“
  - Bedded z2 formation only → 100 m
  - Entire bedded salt formation → 250 m
  - Domal salt formation → 500 m (for comparison)
- Preliminary test case „access drift lengths“
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
- Case study: Reduced Convergence



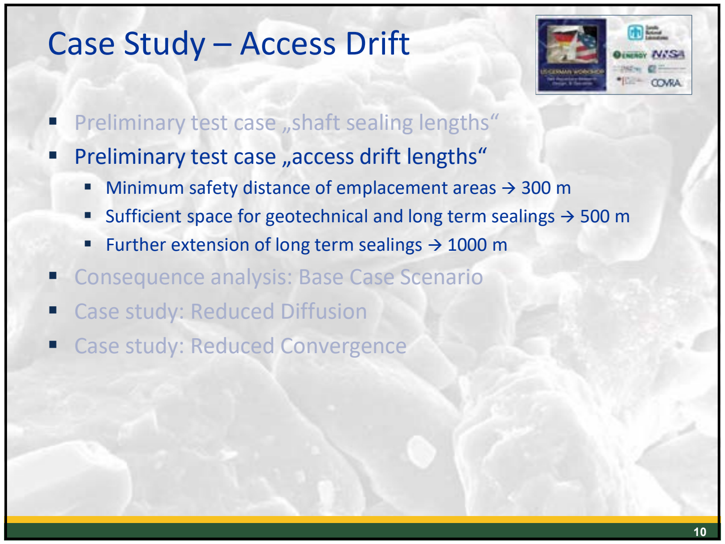
Results – Shaft Sealing Lengths

- Brine Inflow Infrastructure Area



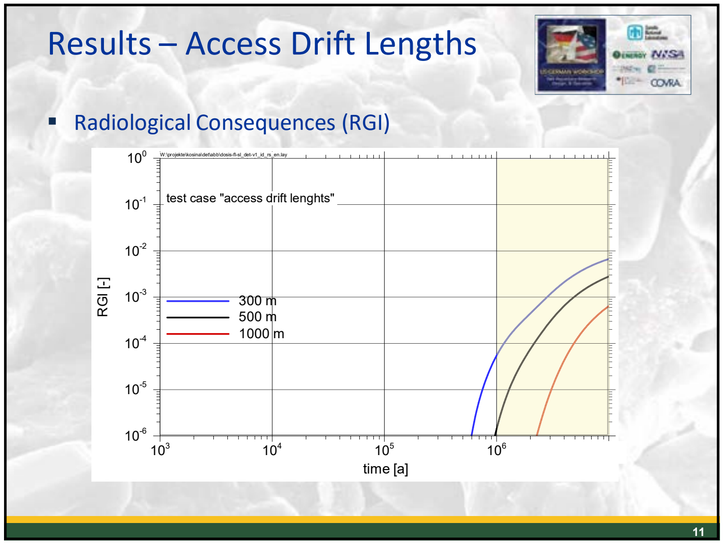
Results – Shaft Sealing Lengths

- Radiological Consequences (RGI)



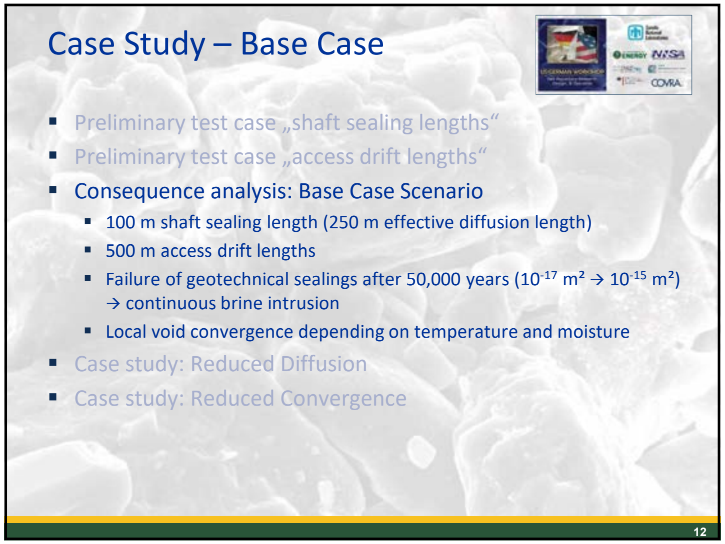
Case Study – Access Drift

- Preliminary test case „shaft sealing lengths“
- Preliminary test case „access drift lengths“
  - Minimum safety distance of emplacement areas → 300 m
  - Sufficient space for geotechnical and long term sealings → 500 m
  - Further extension of long term sealings → 1000 m
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
- Case study: Reduced Convergence



Results – Access Drift Lengths

- Radiological Consequences (RGI)

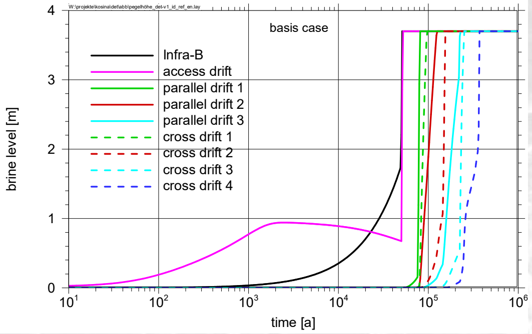


Case Study – Base Case

- Preliminary test case „shaft sealing lengths“
- Preliminary test case „access drift lengths“
- Consequence analysis: Base Case Scenario
  - 100 m shaft sealing length (250 m effective diffusion length)
  - 500 m access drift lengths
  - Failure of geotechnical sealings after 50,000 years (10^{-17} m² → 10^{-15} m²) → continuous brine intrusion
  - Local void convergence depending on temperature and moisture
- Case study: Reduced Diffusion
- Case study: Reduced Convergence

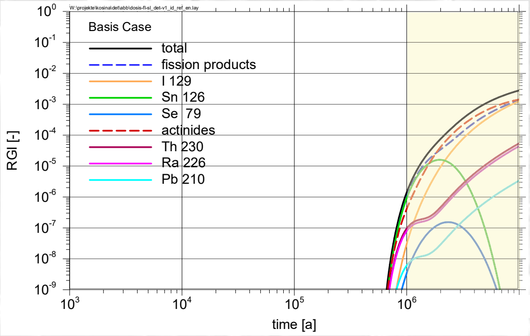
Results – Base Case

- Brine level in mine



Results – Base Case

- Radiological Consequences (RGI)

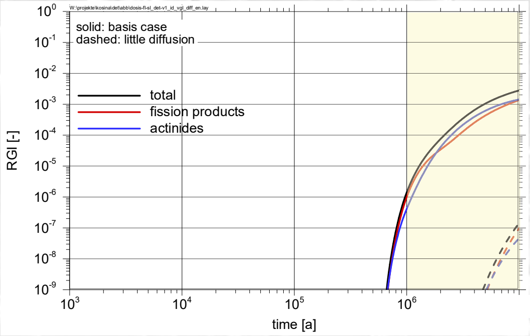


Case Study – Diffusion

- Preliminary test case „shaft sealing lengths“
- Preliminary test case „access drift lengths“
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
  - Reference value: average diffusion coefficient in water (overestimating)
  - Neglecting: accessible pore space, nuclear/molecular size
  - Reduction by one magnitude: $1.5 \cdot 10^{-9}$ m²/s → $1.5 \cdot 10^{-10}$ m²/s
- Case study: Reduced Convergence

Results – Reduced Diffusion

- Radiological Consequences (RGI) compared to Base case

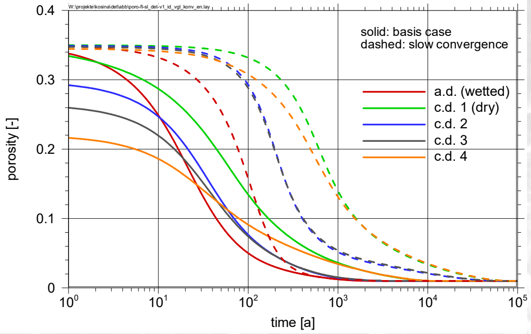


Case Study – Convergence

- Preliminary test case „shaft sealing lengths"
- Preliminary test case „access drift lengths"
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
- Case study: Reduced Convergence
  - Slower salt rock creep properties, low end of margin → convergence approx. 10 times slower

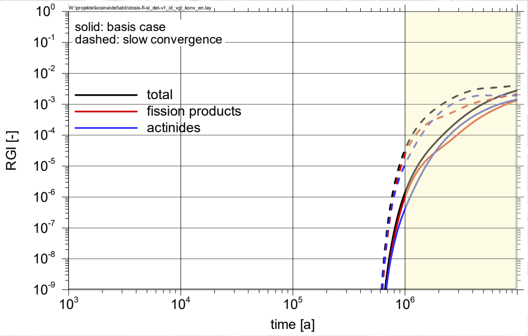
Results – Reduced Convergence

- Porosity evolution of backfilled drifts



Results – Reduced Convergence

- Radiological Consequences (RGI) compared to Base case



Interpretation and Conclusion

- Results
  - Geotechnical barriers along with long-term drift sealings of compacting salt backfill reduce radiological consequences to negligible values
  - RN release from repository is mainly controlled by diffusion
  - RN releases from CRZ only occur at very late times
  - Reduced convergence rates may increase/add advective portion
- Conclusions
  - Optimization of repository layout and design based on numerical consequences analysis is possible and necessary
  - Computational case studies are useful and necessary for process analysis as well as further identification of sensitive parameters
- Outlook
  - Different disposal concepts; Probabilistic Analysis; Report

Thanks and Acknowledgements

Thanks to GRS **colleagues** D. Buhmann, J. Mönig, J. Wolf.

Thanks to project **partners** BGR DBETEC IfG.
project management

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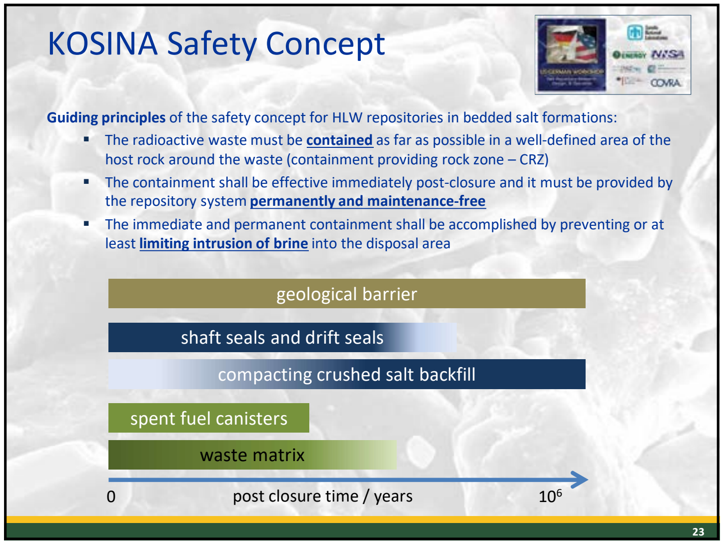
on the basis of a decision by the German Bundestag

FKZ 02E11405B
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

Thank you for your attention!

Backup Slides



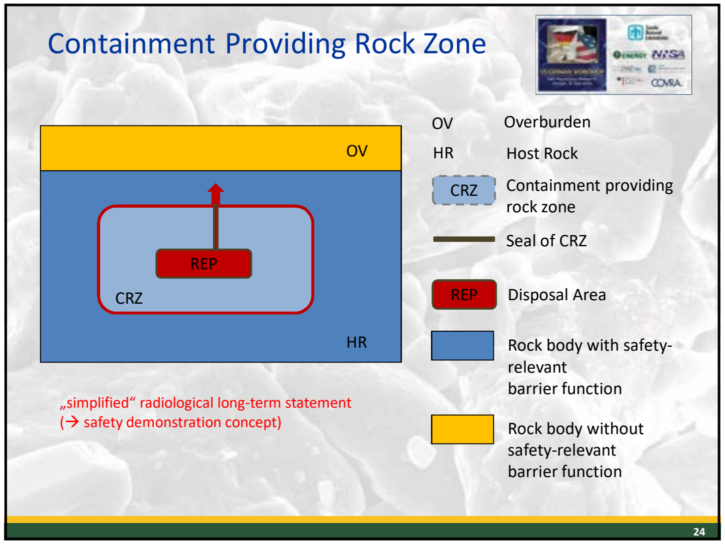
KOSINA Safety Concept

Guiding principles of the safety concept for HLW repositories in bedded salt formations:

- The radioactive waste must be **contained** as far as possible in a well-defined area of the host rock around the waste (containment providing rock zone – CRZ)
- The containment shall be effective immediately post-closure and it must be provided by the repository system **permanently and maintenance-free**
- The immediate and permanent containment shall be accomplished by preventing or at least **limiting intrusion of brine** into the disposal area

geological barrier
shaft seals and drift seals
compacting crushed salt backfill
spent fuel canisters
waste matrix

0 post closure time / years 10^6



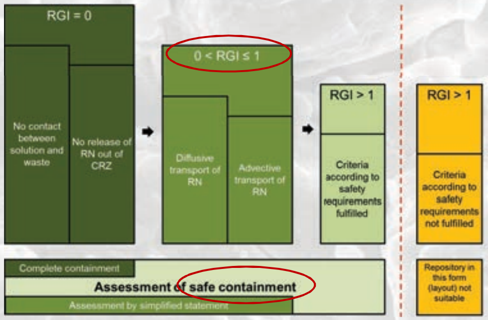
Containment Providing Rock Zone

OV	Overburden
HR	Host Rock
CRZ	Containment providing rock zone
▬	Seal of CRZ
REP	Disposal Area
🟦	Rock body with safety-relevant barrier function
🟨	Rock body without safety-relevant barrier function

„simplified" radiological long-term statement
(→ safety demonstration concept)

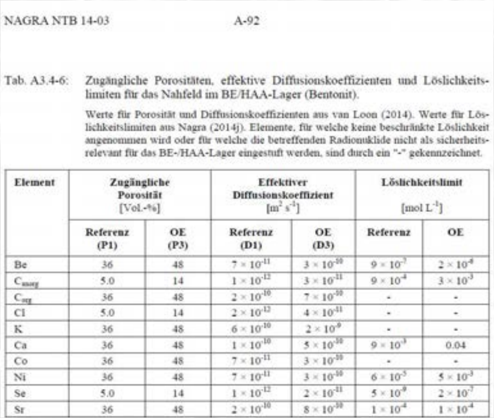
Demonstration of Long-Term Safety

- Proof of radiological negligibility of radionuclide releases from the CRZ
- Indicator: index of marginal radiological impact (RGI, dimensionless number)
- Staged approach for long-term safety assessment


RGI = 0
No contact between solution and waste
No release of RN out of CRZ
0 < RGI ≤ 1
Diffusive transport of RN
Advective transport of RN
RGI > 1
Criteria according to safety requirements fulfilled
RGI > 1
Criteria according to safety requirements not fulfilled
Complete containment
Assessment of safe containment
Assessment by simplified statement
Repository in this form (layout) not suitable

$$RGI = \frac{10 \cdot \frac{\sum_i S_i \cdot DKF_i}{W}}{K_{RGI}}$$

Diffusion Coefficients from Literature



NAGRA NTB 14-03 A-92

Tab. A3.4-6: Zugängliche Porositäten, effektive Diffusionskoeffizienten und Löslichkeitslimiten für das Nahfeld im BE/HAA-Lager (Bentonit).

Werte für Porosität und Diffusionskoeffizienten aus van Loon (2014). Werte für Löslichkeitslimiten aus Nagra (2014j). Elemente, für welche keine beschränkte Löslichkeit angenommen wird oder für welche die betreffenden Radionuklide nicht als sicherheitsrelevant für das BE-/HAA-Lager eingestuft werden, sind durch ein "-" gekennzeichnet.

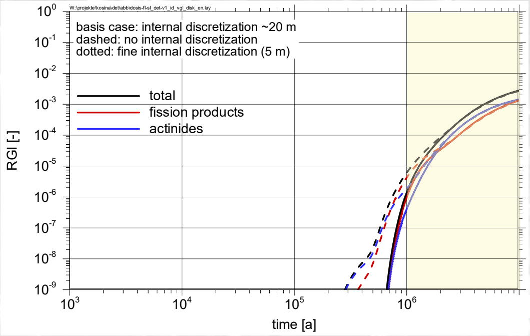
Element	Zugängliche Porosität [Vol.-%]		Effektiver Diffusionskoeffizient [$m^2 s^{-1}$]		Löslichkeitslimit [$mol L^{-1}$]	
	Referenz (P1)	OE (P3)	Referenz (D1)	OE (D3)	Referenz	OE
Be	36	48	7×10^{-11}	3×10^{-10}	9×10^{-7}	2×10^{-6}
C_{anorg}	5.0	14	1×10^{-12}	3×10^{-11}	9×10^{-4}	3×10^{-3}
C_{org}	36	48	2×10^{-10}	7×10^{-10}	-	-
Cl	5.0	14	2×10^{-12}	4×10^{-11}	-	-
K	36	48	6×10^{-10}	2×10^{-9}	-	-
Ca	36	48	1×10^{-10}	5×10^{-10}	9×10^{-3}	0.04
Co	36	48	7×10^{-11}	3×10^{-10}	-	-
Ni	36	48	7×10^{-11}	3×10^{-10}	6×10^{-5}	5×10^{-3}
Se	5.0	14	1×10^{-12}	2×10^{-11}	5×10^{-9}	2×10^{-7}
Sr	36	48	2×10^{-10}	8×10^{-10}	1×10^{-4}	1×10^{-4}

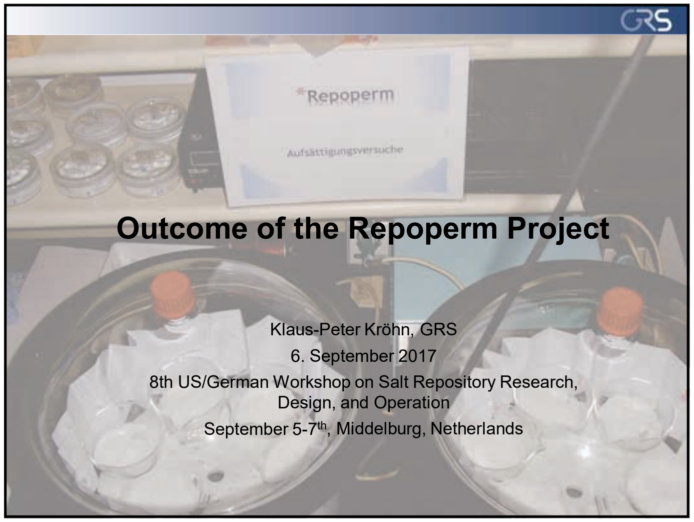
Case Study – Discretization

- Preliminary test case „shaft sealing lengths"
- Preliminary test case „access drift lengths"
- Consequence analysis: Base Case Scenario
- Case study: Reduced Diffusion
- Case study: Reduced Convergence
- Case study: Discretization
  - Base case: internal discretization of model segments (~20m block lengths)
  - **coarse** discretization of model segments (no internal blocks)
  - **refined** discretization of model segments (~5m block lengths)

Results – Different Discretization

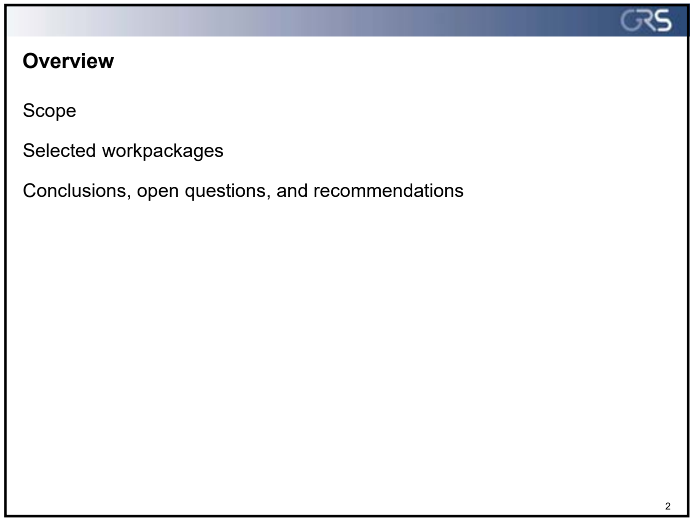
- Radiological Consequences (RGI) compared to Base case





Outcome of the Repoperm Project

Klaus-Peter Kröhn, GRS
6. September 2017
8th US/German Workshop on Salt Repository Research, Design, and Operation
September 5-7th, Middelburg, Netherlands



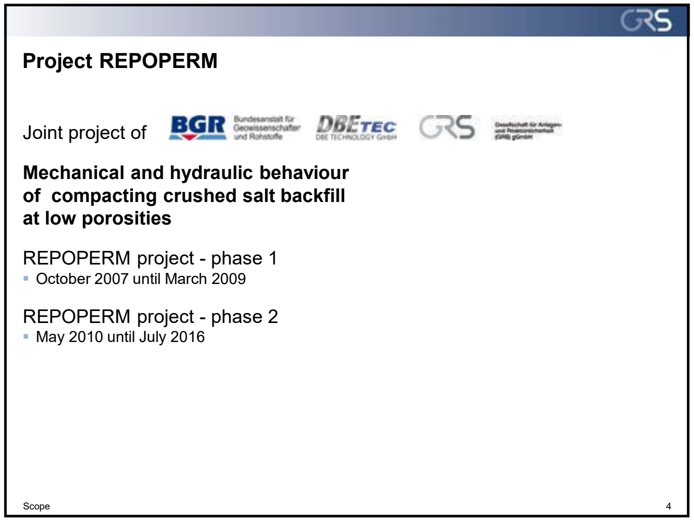
Overview

Scope

Selected workpackages

Conclusions, open questions, and recommendations

Scope



Project REPOPERM

Joint project of BGR Bundesanstalt für Geowissenschaften und Rohstoffe, DBE TEC DBE TECHNOLOGY GmbH, GRS Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

Mechanical and hydraulic behaviour of compacting crushed salt backfill at low porosities

REPOPERM project - phase 1
- October 2007 until March 2009

REPOPERM project - phase 2
- May 2010 until July 2016

Objectives

Key question for Phase 1

- Threshold porosity $\Phi_0 \rightarrow$ permeability $k_0 = 0$ m² ?

Main result of Phase 1

- A possible Φ_0 lies in a range where measurement of porosity is of inherent high uncertainty

Key question for Phase 2

- Relevance of Φ_0
  $\rightarrow$ reliable prediction of crushed salt behaviour under repository conditions
- Mechanical and hydraulic data for compaction especially of wet material

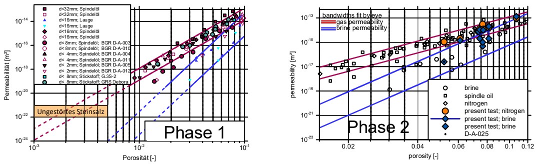
REPOPERM project - phase 1

Tasks

- Data review
- Compaction test

Results

- Criteria for in-situ relevant laboratory test conditions
- Porosity-permeability relation for gas and brine



- High inherent uncertainties in determination of a porosity < 1-2%
- No reliable constitutive equations for two-phase flow

REPOPERM project - phase 2

Experimental investigations

- Examining the porosity in relevant, past experiments
- Influence of the sieve line on compaction behaviour
- Triaxial compaction test with dry material at low porosities
- Influence of humidity on compaction
- Permeability associated with low porosity
- Constitutive relations for two-phase flow
- Microstructural Investigations

Basics for numerical modelling of compacting crushed salt

- Phenomenology and physics related to crushed salt compaction
- Development/definition and comparison of material models
- Benchmark calculations and parameter improvement
- Scaling-rules for capillary pressure
- Application of Discrete Element Codes

THM-coupled model calculations

- Relevant scenarios and boundary conditions
- Inflow into the drift backfill at the drift seal

REPOPERM project - phase 2

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THM-coupled model calculations
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Selected workpackages

Long-term multi-step load-controlled compaction test

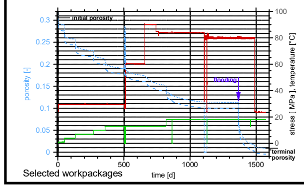
Uniaxial test running for 1654 days

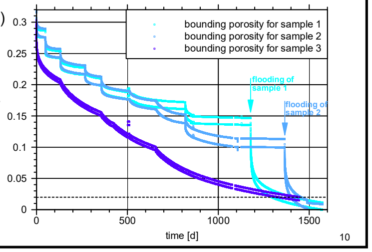
Sample data

Sample	Initial moisture content	Terminal porosity
1	0.0 %	1.11 %
2	0.1 %	0.88 %
3	1.0 %	2.00 %

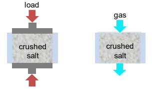
Load

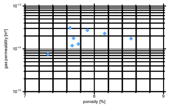
- Increasing mechanical load (up to 18 MPa)
- Varying temperature (up to 90 °C)
- Flooding with brine



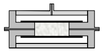


Test on constitutive relations for two-phase flow

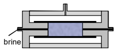




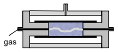
Compacting crushed salt;
Gas flow test
Sample selection
→ single-phase gas permeability



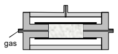
Installation of samples



Saturating with brine
→ single-phase brine permeability



Applying gas pressure;
observing outflow;
stepwise pressure increase
→ air entry pressure

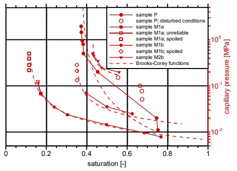


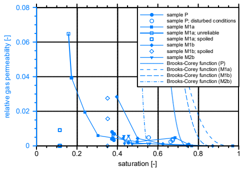
Measuring brine & gas outflow;
increasing gas pressure stepwise
→ capillary pressure
→ effective gas permeability
→ gas saturation

Constitutive relations for two-phase flow

Sample data

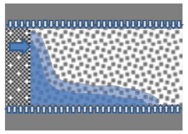
Sample	Porosity [%]	Gas permeability [m²]	Brine permeability [m²]
P1	7.33	$7.5 \cdot 10^{-15}$	$7.5 \cdot 10^{-15}$
P2a	8.13	$1.7 \cdot 10^{-14}$	$2.0 \cdot 10^{-15}$ - $2.0 \cdot 10^{-14}$
P2b	7.43	$1.3 \cdot 10^{-14}$	$2.0 \cdot 10^{-15}$ - $1.1 \cdot 10^{-14}$
M1a	10.70	$1.0 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
M1b	7.69	$1.2 \cdot 10^{-14}$	$1.0 \cdot 10^{-14}$
M2a	6.10	$2.0 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$
M2b	5.20	$1.1 \cdot 10^{-15}$	$2.5 \cdot 10^{-17}$





Applicability of modelling tools

First calibration of parameters for FADT



First generic THM-model for salt backfill
- compaction of crushed salt in a drift
- thermal gradient
- brine inflow at a certain point in time
- CODE_BRIGHT with repository-relevant material parameters

→plausible and coherent results

Validity of material models
- Three different tests (BAMBUS, BGR-test, REPOPERM)
- Calibration leads to three different parameter sets
- None of the sets could successfully be applied to one of the other two tests
- Same result with interpolated parameters

Three approaches were compared in detail (Hein, Heemann, Olivella)
- Qualitatively similar behaviour
- Agreement doubtful especially in case of low porosities

Some constitutive equations are not valid over the whole range of primary variables (stress, temperature, porosity, …)

Specific topics

Mechanics
- Uncertainty in the grain density → uncertainty of void ratio: Δe ≈ 0.0045 – 0.0065
- The fractions of the smaller grain sizes dominate the compaction behaviour
- Results of triaxial and uniaxial compaction tests increasingly disagree towards low porosities

Hydromechanics
- Uniaxial and triaxial tests indicate a transition from dry to wet compaction between 0.3% and 0.6% moisture content
- No significant influence of high relative humidity in the pore air on compaction

Hydraulics
- Very little adsorption of water on crushed salt in a humid atmosphere
- Confirming the porosity-permeability relation from Phase 1
- Two-phase/unsaturated flow
  - Measurement of two-phase flow properties of crushed salt with a repository-relevant grain size distribution down to a gas permeability of 10^{-15} m² is possible
  - Application of the theory of Brooks and Corey
    - works for the capillary pressure
    - fails for relative permeability

Conclusions, open questions, and recommendations

Conclusions

✚ Considerable advance in knowledge and understanding

First experimental data → parameters for wet compaction (FADT)

First repository relevant THM-model for salt buffer

A row of specific questions answered

▬ Limits of presently used models

Hydro-mechanical behaviour of compacting crushed salt is not yet
- completely characterized (e.g. validity of constitutive equations)
- sufficiently understood (e.g. permeability under unsaturated conditons)

Water vapour will spread out through the backfill unimpeded

Material parameters are presently test dependent

Open questions

(Hydro-)Mechanical properties
- Effekt of flooding at high porosities on compaction
- Effect of entrapped air on expulsion of brine during compaction

Reason for disagreement of tri- and uniaxial tests

Dynamics of transition from dry to wet compaction

Impact of deviations in the grain size distribution
- Compaction of material exclusively with large grains
- Dependence of constitutive equations for two-phase flow on porosity

Relevance of threshold porosity

Recommendations

Enhance the predictive capability of the numerical models
- Catalogue
  - all constitutive equations
  - all supporting experimental evidence
  - range of validity
  - uncertainties
- Ensure validity constitutive equations of over the whole range of possible THM conditions
  - do supplemental experiments where necessary

Material parameters must not be allowed to be test dependent!
- Increase understanding of the tests
- e.g. reconcile results of uniaxial and triaxial tests
- Include additional effects and processes like wall friction and hardening

Investigate
- Relevance of threshold porosity with a well-founded numerical model
- Impact of deviations in the grain size distribution
- Transition between dry and wet compaction
- Impact of vapour transport on canister corrosion

Decide about two-phase flow parameters
- further measurements
- dependency on grain size distribution
- alternatives

Thank you for listening

Thanks to all the contributing collegues

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8th US/German Workshop on Salt Repository Research, Design, and Operation

Klaus Wieczorek
GRS

Middelburg, The Netherlands
September 5-7, 2017

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

Klaus Wieczorek (GRS), Ulrich Heemann, Dieter Stührenberg (BGR),
Christian Lerch, Nina Müller-Hoeppe (DBE TECHNOLOGY),
Christoph Lüdeling, Till Popp (IfG), Uwe Düsterloh, Ralf Wolters (TUC)

8th US/German Workshop on Salt Repository Research, Design, and Operation
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Background

- Change of paradigm to the concept of containment-providing rock zone
  - **safe containment** in cpz
  - proof of **host rock integrity** and of technical **seal effectiveness**
  - more attention on **backfill and seals**
- Crushed salt backfill takes the role of **long-term barrier against brine** after reconsolidation, requiring sufficiently low permeability
- Reliable prediction of porosity and permeability evolution:
  - sound **process understanding**
  - suitable **models** for process simulation
  - experimental **database** for model validation and calibration

---

Purpose and structure of the DAEF report

- Compilation and assessment of **existing** material models and experimental data
- Strategy for **future** work to enable reliable prediction and assessment
  - of thermomechanical behavior
  - and consequences for the hydraulic behavior

  of crushed salt backfill

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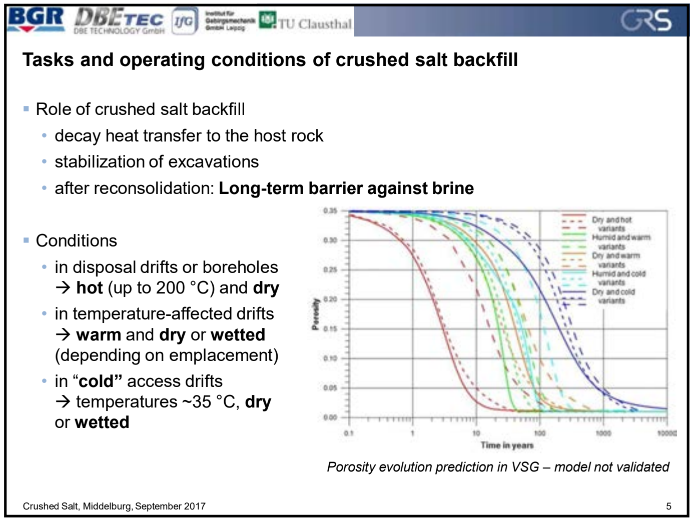
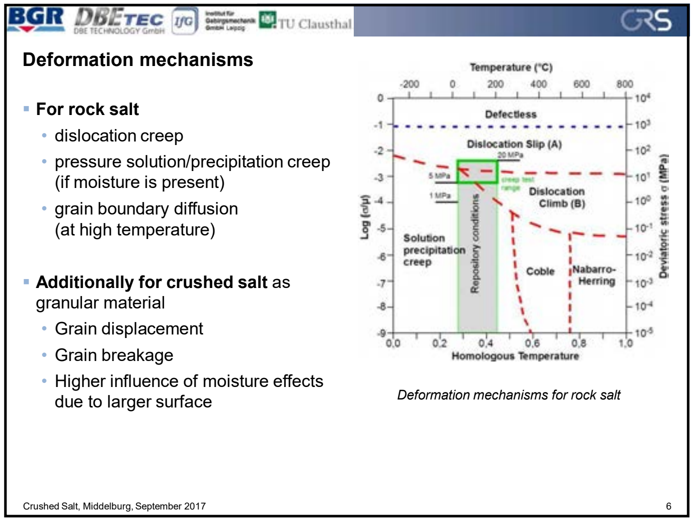


Tasks and operating conditions of crushed salt backfill

- Role of crushed salt backfill
  - decay heat transfer to the host rock
  - stabilization of excavations
  - after reconsolidation: **Long-term barrier against brine**
- Conditions
  - 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**

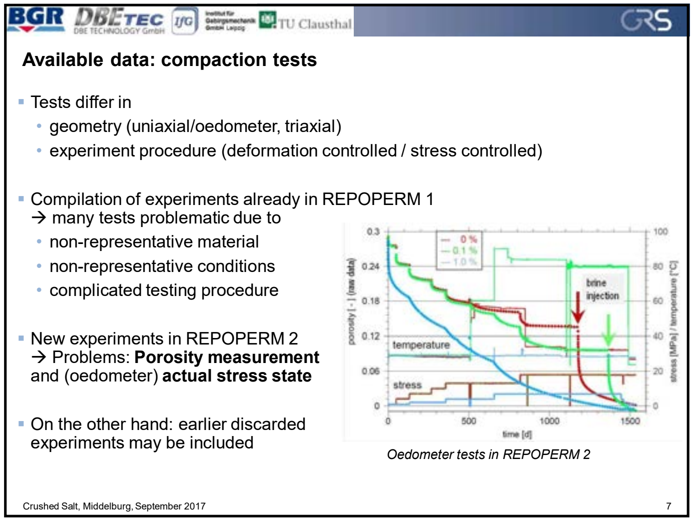
Porosity evolution prediction in VSG – model not validated



Deformation mechanisms

- **For rock salt**
  - dislocation creep
  - pressure solution/precipitation creep (if moisture is present)
  - grain boundary diffusion (at high temperature)
- **Additionally for crushed salt** as granular material
  - Grain displacement
  - Grain breakage
  - Higher influence of moisture effects due to larger surface

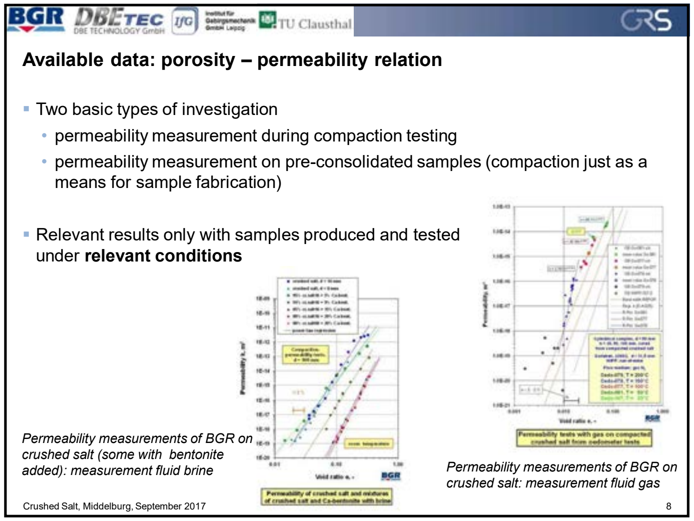
Deformation mechanisms for rock salt



Available data: compaction tests

- Tests differ in
  - geometry (uniaxial/oedometer, triaxial)
  - experiment procedure (deformation controlled / stress controlled)
- Compilation of experiments already in REPOPERM 1 → many tests problematic due to
  - non-representative material
  - non-representative conditions
  - complicated testing procedure
- New experiments in REPOPERM 2 → Problems: **Porosity measurement** and (oedometer) **actual stress state**
- On the other hand: earlier discarded experiments may be included

Oedometer tests in REPOPERM 2

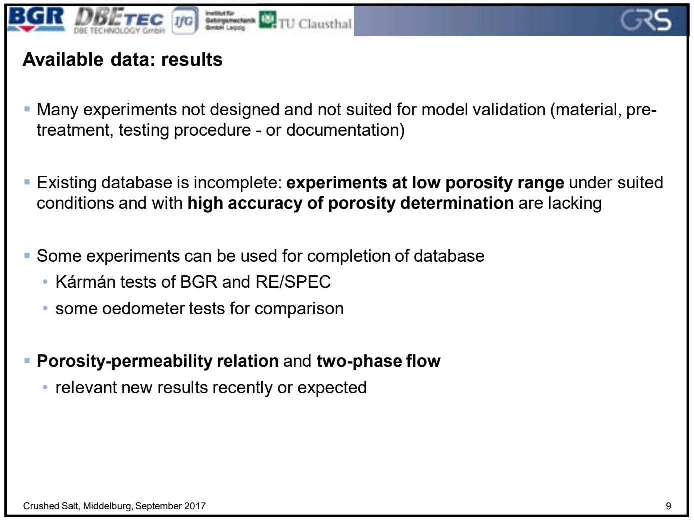


Available data: porosity – permeability relation

- Two basic types of investigation
  - permeability measurement during compaction testing
  - permeability measurement on pre-consolidated samples (compaction just as a means for sample fabrication)
- Relevant results only with samples produced and tested under **relevant conditions**

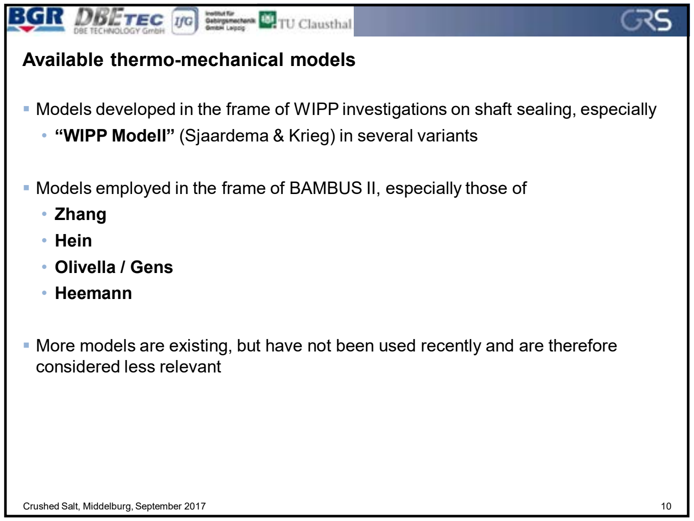
Permeability measurements of BGR on crushed salt (some with bentonite added): measurement fluid brine

Permeability measurements of BGR on crushed salt: measurement fluid gas



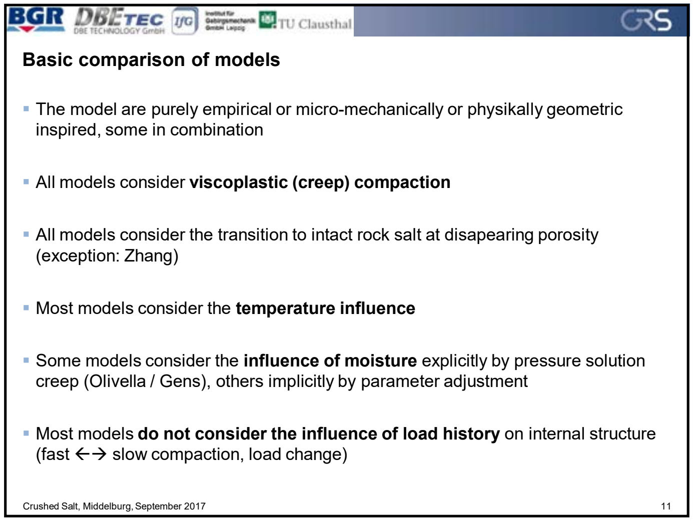
Available data: results

- Many experiments not designed and not suited for model validation (material, pre-treatment, testing procedure - or documentation)
- Existing database is incomplete: **experiments at low porosity range** under suited conditions and with **high accuracy of porosity determination** are lacking
- Some experiments can be used for completion of database
  - Kármán tests of BGR and RE/SPEC
  - some oedometer tests for comparison
- **Porosity-permeability relation** and **two-phase flow**
  - relevant new results recently or expected



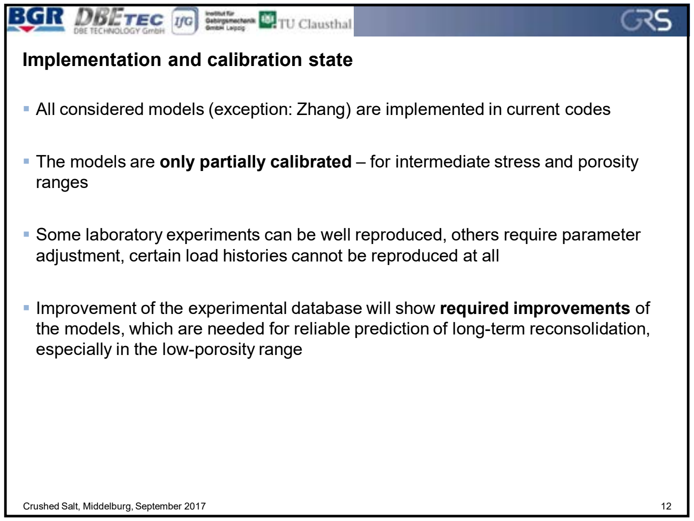
Available thermo-mechanical models

- Models developed in the frame of WIPP investigations on shaft sealing, especially
  - **“WIPP Modell”** (Sjaardema & Krieg) in several variants
- Models employed in the frame of BAMBUS II, especially those of
  - **Zhang**
  - **Hein**
  - **Olivella / Gens**
  - **Heemann**
- More models are existing, but have not been used recently and are therefore considered less relevant



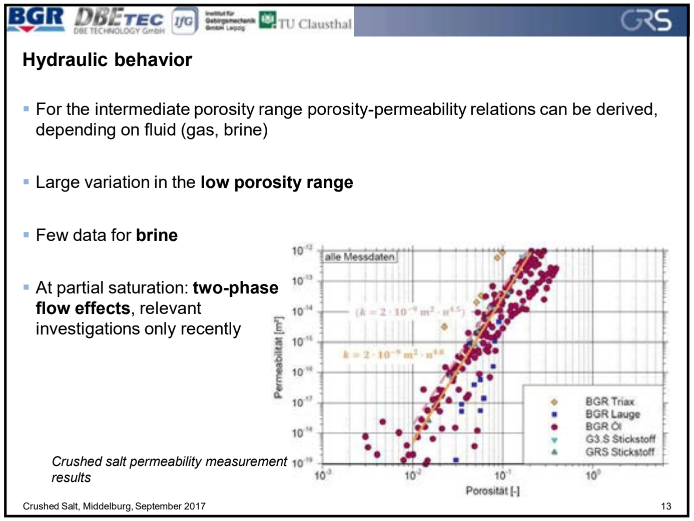
Basic comparison of models

- The model are purely empirical or micro-mechanically or physikally geometric inspired, some in combination
- All models consider **viscoplastic (creep) compaction**
- All models consider the transition to intact rock salt at disapearing porosity (exception: Zhang)
- Most models consider the **temperature influence**
- Some models consider the **influence of moisture** explicitly by pressure solution creep (Olivella / Gens), others implicitly by parameter adjustment
- Most models **do not consider the influence of load history** on internal structure (fast ←→ slow compaction, load change)



Implementation and calibration state

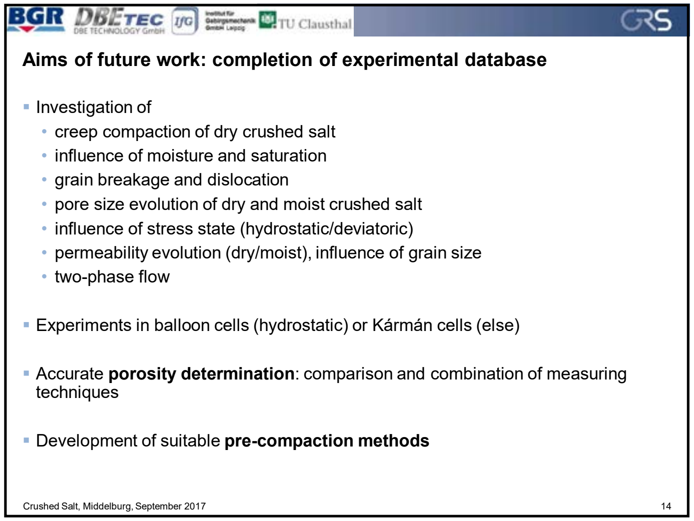
- All considered models (exception: Zhang) are implemented in current codes
- The models are **only partially calibrated** – for intermediate stress and porosity ranges
- Some laboratory experiments can be well reproduced, others require parameter adjustment, certain load histories cannot be reproduced at all
- Improvement of the experimental database will show **required improvements** of the models, which are needed for reliable prediction of long-term reconsolidation, especially in the low-porosity range



Hydraulic behavior

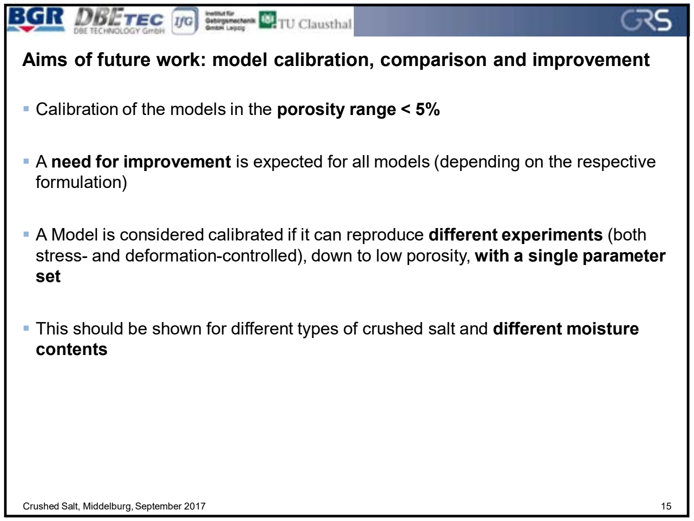
- For the intermediate porosity range porosity-permeability relations can be derived, depending on fluid (gas, brine)
- Large variation in the **low porosity range**
- Few data for **brine**
- At partial saturation: **two-phase flow effects**, relevant investigations only recently

Crushed salt permeability measurement results



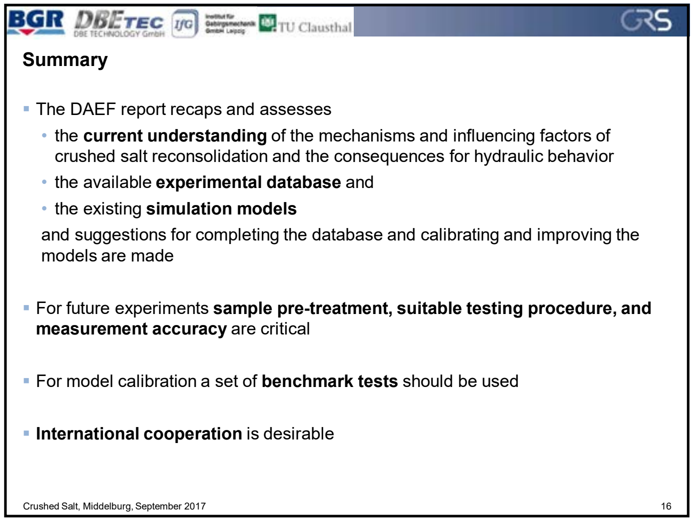
Aims of future work: completion of experimental database

- 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**



Aims of future work: model calibration, comparison and 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**



Summary

- 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

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K. Wieczorek, F. Hansen, N. Müller-Hoeppe

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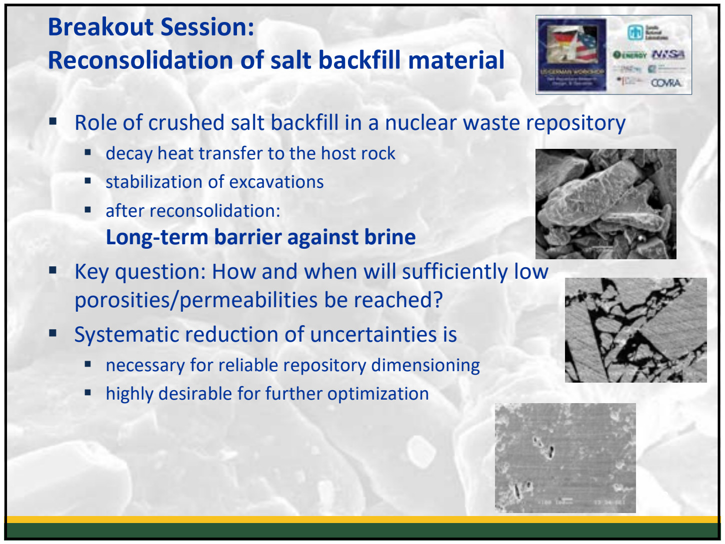
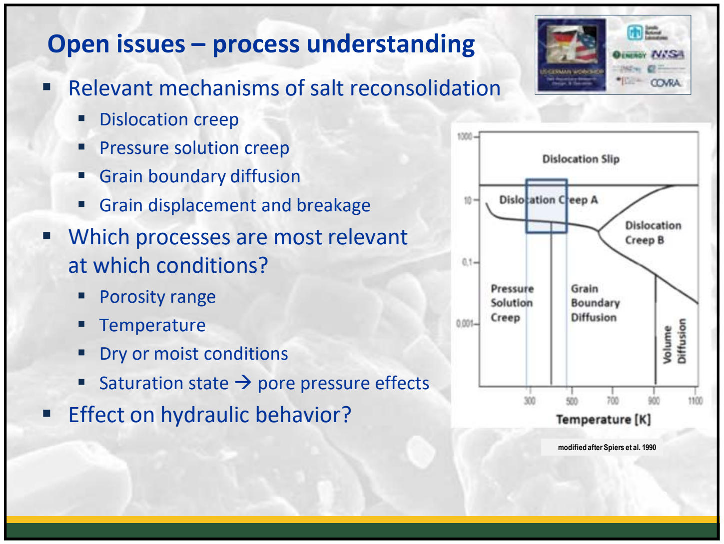


Breakout Session: Reconsolidation of salt backfill material

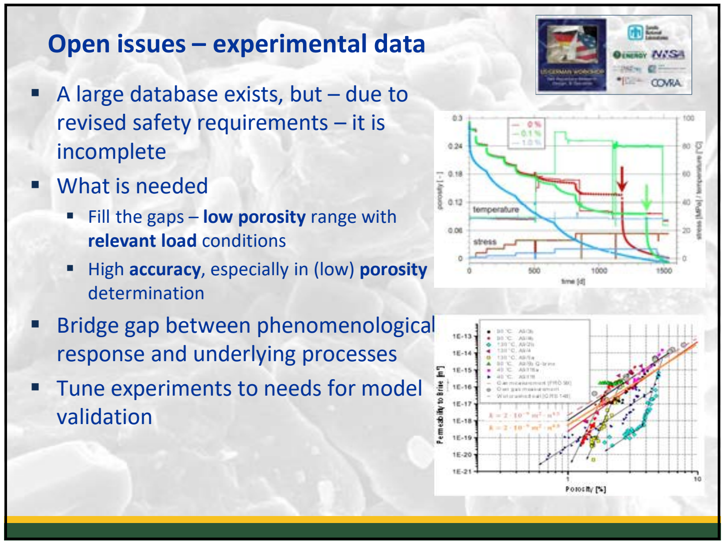
- Role of crushed salt backfill in a nuclear waste repository
  - decay heat transfer to the host rock
  - stabilization of excavations
  - after reconsolidation: **Long-term barrier against brine**
- Key question: How and when will sufficiently low porosities/permeabilities be reached?
- Systematic reduction of uncertainties is
  - necessary for reliable repository dimensioning
  - highly desirable for further optimization



Open issues – process understanding

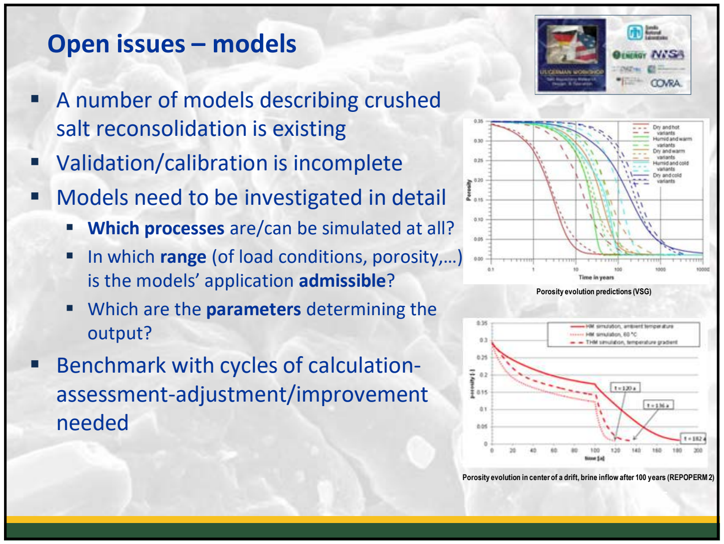
- Relevant mechanisms of salt reconsolidation
  - Dislocation creep
  - Pressure solution creep
  - Grain boundary diffusion
  - Grain displacement and breakage
- Which processes are most relevant at which conditions?
  - Porosity range
  - Temperature
  - Dry or moist conditions
  - Saturation state → pore pressure effects
- Effect on hydraulic behavior?

modified after Spiers et al. 1990



Open issues – experimental data

- A large database exists, but – due to revised safety requirements – it is incomplete
- What is needed
  - Fill the gaps – **low porosity** range with **relevant load** conditions
  - High **accuracy**, especially in (low) **porosity** determination
- Bridge gap between phenomenological response and underlying processes
- Tune experiments to needs for model validation



Open issues – models

- A number of models describing crushed salt reconsolidation is existing
- Validation/calibration is incomplete
- Models need to be investigated in detail
  - **Which processes** are/can be simulated at all?
  - In which **range** (of load conditions, porosity,…) is the models' application **admissible**?
  - Which are the **parameters** determining the output?
- Benchmark with cycles of calculation-assessment-adjustment/improvement needed

Porosity evolution predictions (VSG)

Porosity evolution in center of a drift, brine inflow after 100 years (REPOPERM 2)

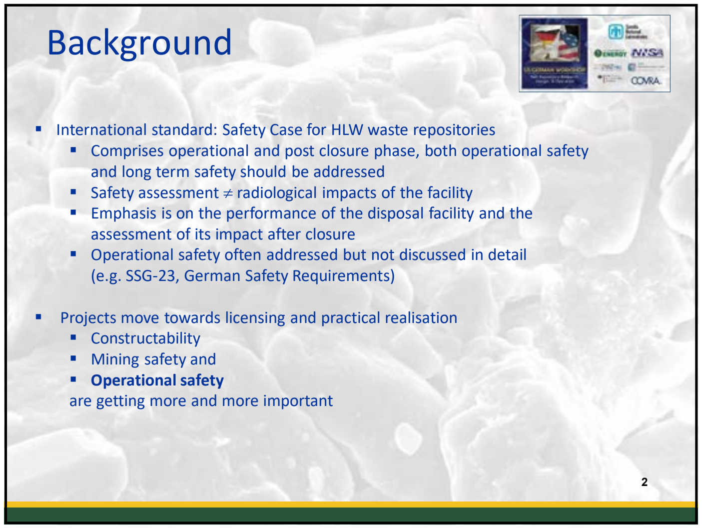
Ideas for a project (compiled by GRS, BGR, DBE TEC, IfG, TUC, SNL)

- A project aimed at clearing the deficits in prediction capability should include all three issues and their interrelation
  - **Modelling**
  - **Experimental investigations**
  - **Process understanding**
- Complementary idea: Tune backfill material to attain high performance characteristics early in a salt repository lifetime

Interaction between Operational Safety and Long-Term Safety (Project BASEL)

Wolf, J.[1], Bertrams, N.[2], Bollingerfehr, W.[2],
Buhmann, D.[1], Fahrenholz, C.[1], Filbert, W.[2],
Lommerzheim, A.[2], Noseck, U.[1], Prignitz, S.[2]
[1]GRS gGmbH, [2]DBE Technology GmbH

Middelburg, The Netherlands
September 5-7, 2017



Background

- International standard: Safety Case for HLW waste repositories
  - Comprises operational and post closure phase, both operational safety and long term safety should be addressed
  - Safety assessment ≠ radiological impacts of the facility
  - Emphasis is on the performance of the disposal facility and the assessment of its impact after closure
  - Operational safety often addressed but not discussed in detail (e.g. SSG-23, German Safety Requirements)

- Projects move towards licensing and practical realisation
  - Constructability
  - Mining safety and
  - **Operational safety**

  are getting more and more important

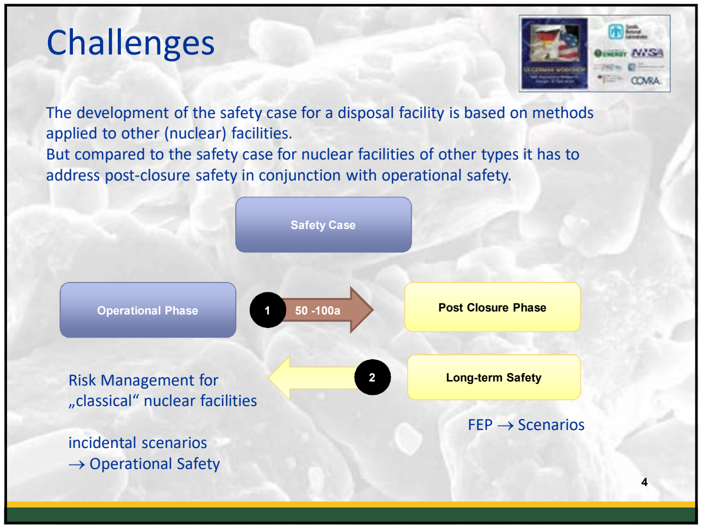
International Activities

- **OECD/NEA, IGSC**

  Expert Group on Operational Safety (since 2013)
  - share experience in operational safety
  - identify plausible hazards in a geological repository
  - share and improve know-how on the practical assessment of hazards
  - define technical solutions for risk prevention and mitigation

- **IAEA, GEOSAF projects**
  - WG dedicated on Operational Safety (since 2010), focus on hazards identification for the operational phase
  - Besides considerations on methodologies for hazards assessment, strong relationships between operational safety and post-closure safety were outlined:

    on the one hand, design and operational constraints are set by post-closure safety requirements, while on the other hand, operation has some impact on post-closure safety.
  - GEOSAF-III started in June 2017



Challenges

The development of the safety case for a disposal facility is based on methods applied to other (nuclear) facilities.
But compared to the safety case for nuclear facilities of other types it has to address post-closure safety in conjunction with operational safety.

Safety Case

Operational Phase

1 50 -100a

Post Closure Phase

2

Long-term Safety

Risk Management for
„classical“ nuclear facilities

FEP → Scenarios

incidental scenarios
→ Operational Safety

Tasks

Interaction between Operational Safety and Long-Term Safety:

① Identify and document impacts of operation, including construction, on post-closure safety (especially analysis of incidents and accidents during the operational phase)

② Identify and document impacts of post-closure constraints on the design and implementation of the geological disposal facility and for the operational phase.

Comprehensive analysis

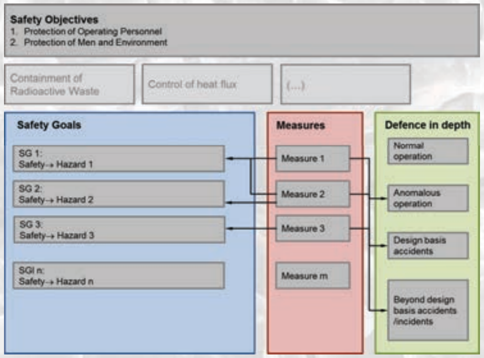
→ FEP analysis operational phase → Identification of Hazards

→ FEP analysis post-closure phase → Identification of Scenarios

Project BASEL

- Safety concept for the operational phase (basics, recommendations)
- FEP operational phase → Identification of hazards
- FEP operational phase → FEP post closure phase ① ← Focus of BASEL
- FEP post closure phase → FEP operational phase ②
- → Methods for illustrating (documenting) and balancing safety aspects
- Started in 2016 (two-year project)

Safety Concept Operational Phase: Basics



Safety Objectives
1. Protection of Operating Personnel
2. Protection of Men and Environment

Containment of Radioactive Waste

Control of heat flux

(...)

Safety Goals

SG 1: Safety → Hazard 1

SG 2: Safety → Hazard 2

SG 3: Safety → Hazard 3

SGl n: Safety → Hazard n

Measures

Measure 1

Measure 2

Measure 3

Measure m

Defence in depth

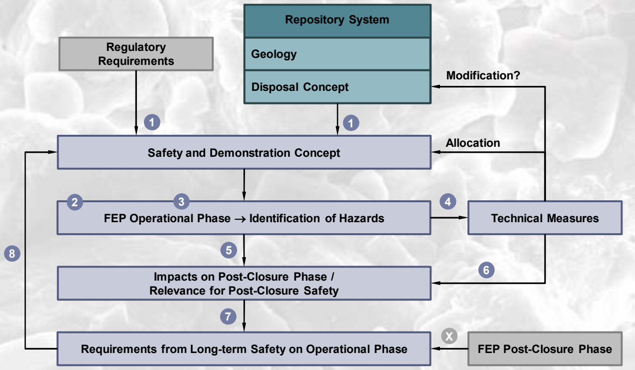
Normal operation

Anomalous operation

Design basis accidents

Beyond design basis accidents /incidents

Project BASEL: Approach



Repository System

Geology

Disposal Concept

Regulatory Requirements

Modification?

Allocation

Safety and Demonstration Concept

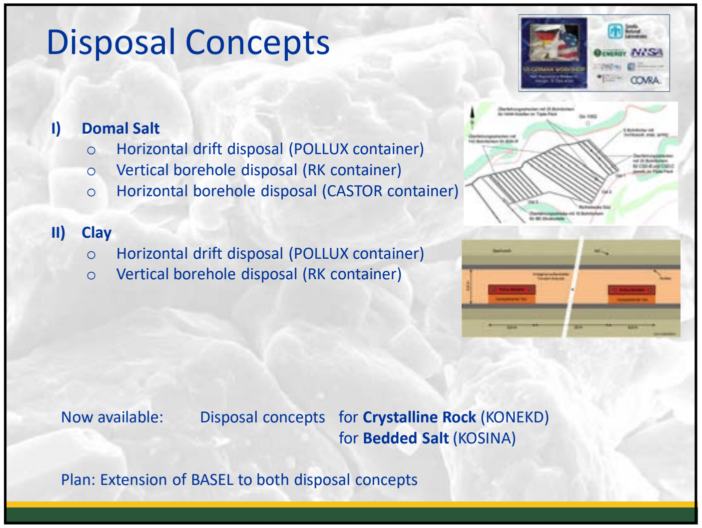
FEP Operational Phase → Identification of Hazards

Technical Measures

Impacts on Post-Closure Phase / Relevance for Post-Closure Safety

Requirements from Long-term Safety on Operational Phase

FEP Post-Closure Phase



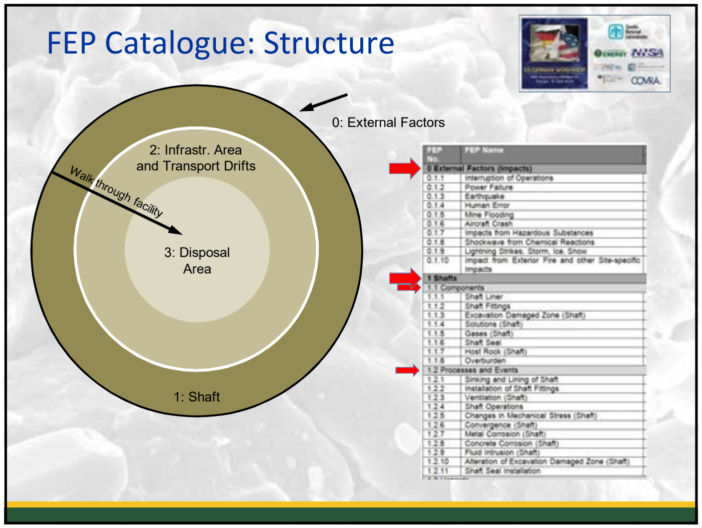
Disposal Concepts

I) Domal Salt
- Horizontal drift disposal (POLLUX container)
- Vertical borehole disposal (RK container)
- Horizontal borehole disposal (CASTOR container)

II) Clay
- Horizontal drift disposal (POLLUX container)
- Vertical borehole disposal (RK container)

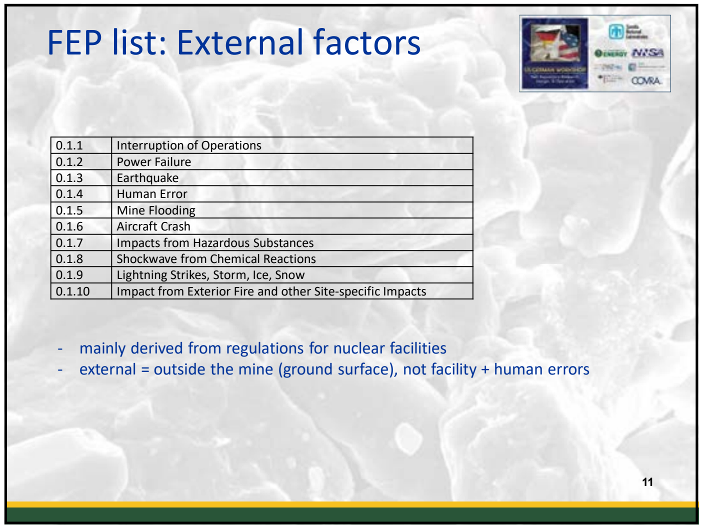
Now available: Disposal concepts for **Crystalline Rock** (KONEKD)
for **Bedded Salt** (KOSINA)

Plan: Extension of BASEL to both disposal concepts



FEP Catalogue: Structure

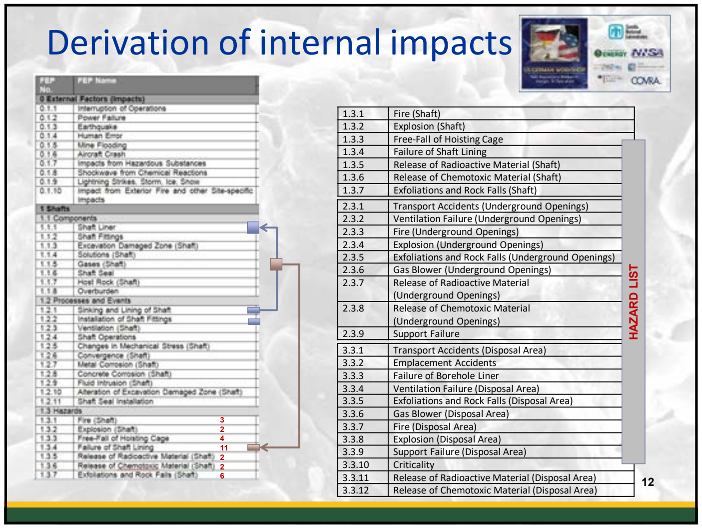
FEP No.	FEP Name
0 External Factors (Impacts)	
0.1.1	Interruption of Operations
0.1.2	Power Failure
0.1.3	Earthquake
0.1.4	Human Error
0.1.5	Mine Flooding
0.1.6	Aircraft Crash
0.1.7	Impacts from Hazardous Substances
0.1.8	Shockwave from Chemical Reactions
0.1.9	Lightning Strikes, Storm, Ice, Snow
0.1.10	Impact from Exterior Fire and other Site-specific Impacts
1 Shafts	
1.1 Components	
1.1.1	Shaft Liner
1.1.2	Shaft Fittings
1.1.3	Excavation Damaged Zone (Shaft)
1.1.4	Solutions (Shaft)
1.1.5	Gases (Shaft)
1.1.6	Shaft Seal
1.1.7	Host Rock (Shaft)
1.1.8	Overburden
1.2 Processes and Events	
1.2.1	Sinking and Lining of Shaft
1.2.2	Installation of Shaft Fittings
1.2.3	Ventilation (Shaft)
1.2.4	Shaft Operations
1.2.5	Changes in Mechanical Stress (Shaft)
1.2.6	Convergence (Shaft)
1.2.7	Metal Corrosion (Shaft)
1.2.8	Concrete Corrosion (Shaft)
1.2.9	Fluid Intrusion (Shaft)
1.2.10	Alteration of Excavation Damaged Zone (Shaft)
1.2.11	Shaft Seal Installation



FEP list: External factors

0.1.1	Interruption of Operations
0.1.2	Power Failure
0.1.3	Earthquake
0.1.4	Human Error
0.1.5	Mine Flooding
0.1.6	Aircraft Crash
0.1.7	Impacts from Hazardous Substances
0.1.8	Shockwave from Chemical Reactions
0.1.9	Lightning Strikes, Storm, Ice, Snow
0.1.10	Impact from Exterior Fire and other Site-specific Impacts

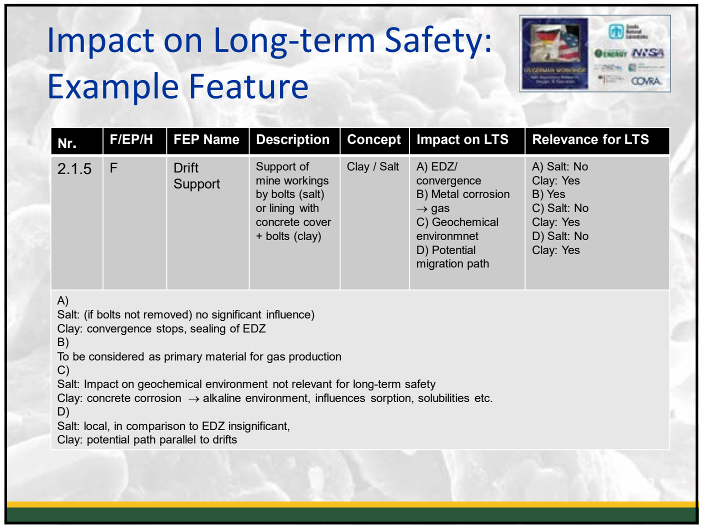
- mainly derived from regulations for nuclear facilities
- external = outside the mine (ground surface), not facility + human errors



Derivation of internal impacts

FEP No.	FEP Name	
0 External Factors (Impacts)		
0.1.1	Interruption of Operations	
0.1.2	Power Failure	
0.1.3	Earthquake	
0.1.4	Human Error	
0.1.5	Mine Flooding	
0.1.6	Aircraft Crash	
0.1.7	Impacts from Hazardous Substances	
0.1.8	Shockwave from Chemical Reactions	
0.1.9	Lightning Strikes, Storm, Ice, Snow	
0.1.10	Impact from Exterior Fire and other Site-specific Impacts	
1 Shafts		
1.1 Components		
1.1.1	Shaft Liner	
1.1.2	Shaft Fittings	
1.1.3	Excavation Damaged Zone (Shaft)	
1.1.4	Solutions (Shaft)	
1.1.5	Gases (Shaft)	
1.1.6	Shaft Seal	
1.1.7	Host Rock (Shaft)	
1.1.8	Overburden	
1.2 Processes and Events		
1.2.1	Sinking and Lining of Shaft	
1.2.2	Installation of Shaft Fittings	
1.2.3	Ventilation (Shaft)	
1.2.4	Shaft Operations	
1.2.5	Changes in Mechanical Stress (Shaft)	
1.2.6	Convergence (Shaft)	
1.2.7	Metal Corrosion (Shaft)	
1.2.8	Concrete Corrosion (Shaft)	
1.2.9	Fluid Intrusion (Shaft)	
1.2.10	Alteration of Excavation Damaged Zone (Shaft)	
1.2.11	Shaft Seal Installation	
1.3 Hazards		
1.3.1	Fire (Shaft)	3
1.3.2	Explosion (Shaft)	2
1.3.3	Free-Fall of Hoisting Cage	4
1.3.4	Failure of Shaft Lining	11
1.3.5	Release of Radioactive Material (Shaft)	2
1.3.6	Release of Chemotoxic Material (Shaft)	2
1.3.7	Exfoliations and Rock Falls (Shaft)	6

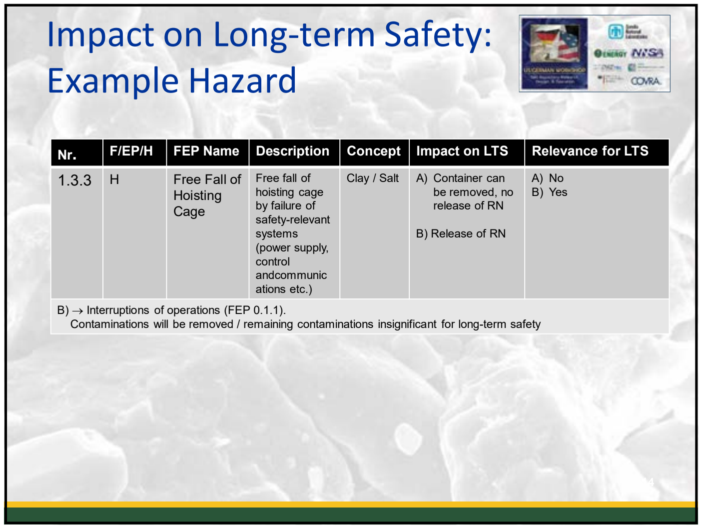
1.3.1	Fire (Shaft)
1.3.2	Explosion (Shaft)
1.3.3	Free-Fall of Hoisting Cage
1.3.4	Failure of Shaft Lining
1.3.5	Release of Radioactive Material (Shaft)
1.3.6	Release of Chemotoxic Material (Shaft)
1.3.7	Exfoliations and Rock Falls (Shaft)
2.3.1	Transport Accidents (Underground Openings)
2.3.2	Ventilation Failure (Underground Openings)
2.3.3	Fire (Underground Openings)
2.3.4	Explosion (Underground Openings)
2.3.5	Exfoliations and Rock Falls (Underground Openings)
2.3.6	Gas Blower (Underground Openings)
2.3.7	Release of Radioactive Material (Underground Openings)
2.3.8	Release of Chemotoxic Material (Underground Openings)
2.3.9	Support Failure
3.3.1	Transport Accidents (Disposal Area)
3.3.2	Emplacement Accidents
3.3.3	Failure of Borehole Liner
3.3.4	Ventilation Failure (Disposal Area)
3.3.5	Exfoliations and Rock Falls (Disposal Area)
3.3.6	Gas Blower (Disposal Area)
3.3.7	Fire (Disposal Area)
3.3.8	Explosion (Disposal Area)
3.3.9	Support Failure (Disposal Area)
3.3.10	Criticality
3.3.11	Release of Radioactive Material (Disposal Area)
3.3.12	Release of Chemotoxic Material (Disposal Area)



Impact on Long-term Safety: Example Feature

Nr.	F/EP/H	FEP Name	Description	Concept	Impact on LTS	Relevance for LTS
2.1.5	F	Drift Support	Support of mine workings by bolts (salt) or lining with concrete cover + bolts (clay)	Clay / Salt	A) EDZ/ convergence B) Metal corrosion → gas C) Geochemical environmnet D) Potential migration path	A) Salt: No Clay: Yes B) Yes C) Salt: No Clay: Yes D) Salt: No Clay: Yes

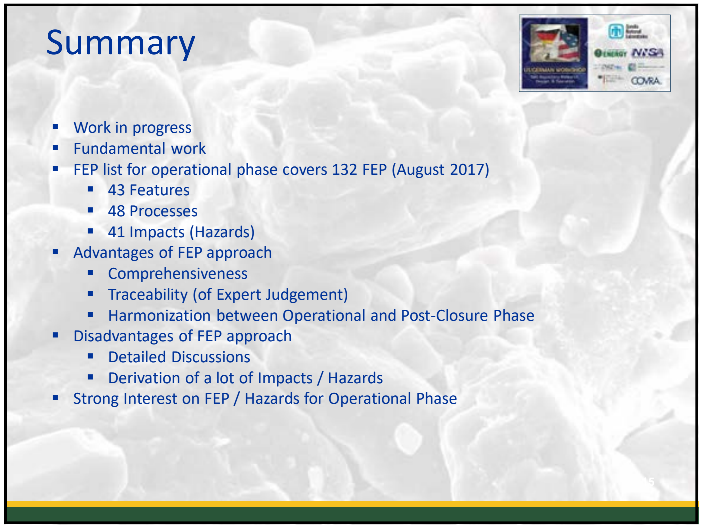
A)
Salt: (if bolts not removed) no significant influence)
Clay: convergence stops, sealing of EDZ
B)
To be considered as primary material for gas production
C)
Salt: Impact on geochemical environment not relevant for long-term safety
Clay: concrete corrosion → alkaline environment, influences sorption, solubilities etc.
D)
Salt: local, in comparison to EDZ insignificant,
Clay: potential path parallel to drifts



Impact on Long-term Safety: Example Hazard

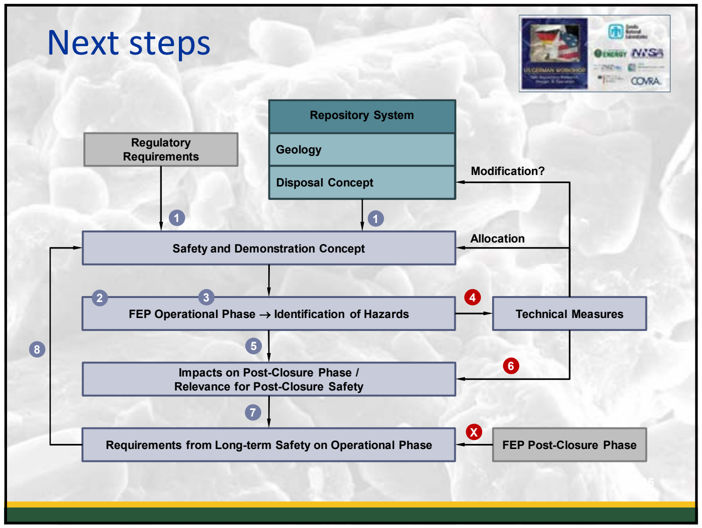
Nr.	F/EP/H	FEP Name	Description	Concept	Impact on LTS	Relevance for LTS
1.3.3	H	Free Fall of Hoisting Cage	Free fall of hoisting cage by failure of safety-relevant systems (power supply, control andcommunications etc.)	Clay / Salt	A) Container can be removed, no release of RN B) Release of RN	A) No B) Yes

B) → Interruptions of operations (FEP 0.1.1).
Contaminations will be removed / remaining contaminations insignificant for long-term safety



Summary

- Work in progress
- Fundamental work
- FEP list for operational phase covers 132 FEP (August 2017)
  - 43 Features
  - 48 Processes
  - 41 Impacts (Hazards)
- Advantages of FEP approach
  - Comprehensiveness
  - Traceability (of Expert Judgement)
  - Harmonization between Operational and Post-Closure Phase
- Disadvantages of FEP approach
  - Detailed Discussions
  - Derivation of a lot of Impacts / Hazards
- Strong Interest on FEP / Hazards for Operational Phase



Next steps

Repository System
Geology
Disposal Concept
Regulatory Requirements
Modification?
1
1
Safety and Demonstration Concept
Allocation
2
3
FEP Operational Phase → Identification of Hazards
4
Technical Measures
8
5
Impacts on Post-Closure Phase / Relevance for Post-Closure Safety
6
7
X
Requirements from Long-term Safety on Operational Phase
FEP Post-Closure Phase

Acknowledgement

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by the German Bundestag

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

Repository Designs in Bedded Salt, the KOSINA-Project

Wilhelm Bollingerfehr, Sabine Prignitz, Niklas Bertrams, Wolfgang Filbert, Eric Simo
DBE TECHNOLOGY GmbH

Middelburg, The Netherlands
September 5-7, 2017

Contents

❑ Context

❑ Objectives & Work Program

❑ Repository Designs

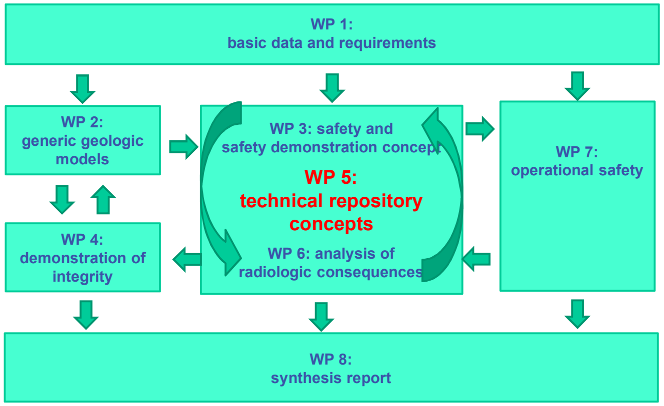
❑ Summary & Conclusions

Context

New Site Selection Act as of July, 2013: revised in May 2017

- ❑ Methodological approach: to compare safety of repository systems in different host rocks in Germany:
  - ➢ requires the existence of generic repository concepts and suitable safety and safety demonstration concepts for all potential host rock formations (salt, clay, and crystalline rock)
  - ➢ repository concepts, safety and safety demonstration concepts for domal salt and for clay exist, are in progress for crystalline rock, and have to be developed for flat bedded salt
- ❑ In summer 2015, BMWi/PTKA launched R&D-Project KOSINA to develop a generic repository concept for heat-generating waste in bedded salt as well as a suitable safety and safety demonstration concept
  - ❖ Project partners: BGR, GRS, IfG, and DBE TEC
  - ❖ Objectives: already presented by Till Popp (IfG)

Work Packages



WP 1:
basic data and requirements

WP 2:
generic geologic models

WP 3: safety and
safety demonstration concept

WP 5:
technical repository concepts

WP 6: analysis of
radiologic consequences

WP 4:
demonstration of integrity

WP 7:
operational safety

WP 8:
synthesis report

Fundamentals for Repository Design Work

1. **Knowledge about Types and Amounts of Waste**
2. **Clear Understanding of the Geologic Environment**
   (e.g. type and composition of geologic formation at site)
   - ➢ See presentation of BGR and IfG (Till Popp)
3. **Safety and Safety Demonstration Concept for Bedded Salt**
   - ➢ See presentation of GRS (Jonathan Kindlein)
4. **Design Temperature**
   - ➢ **max. 200°C**
5. **Regulatory Framework:**
   - ➢ (e.g. atomic energy act, mining act, safety requirements, etc.)

Repository Design for 4 Emplacement Alternatives

Type: flat bedded salt

1. **Drift disposal of POLLUX®Casks**
2. **borehole disposal (horizontal) of canisters (BSK-H)**

Type: salt pillow

3. **borehole disposal (vertical) of canisters (BSK-V)**
4. **Direct disposal of CASTOR® Casks**

Tasks:

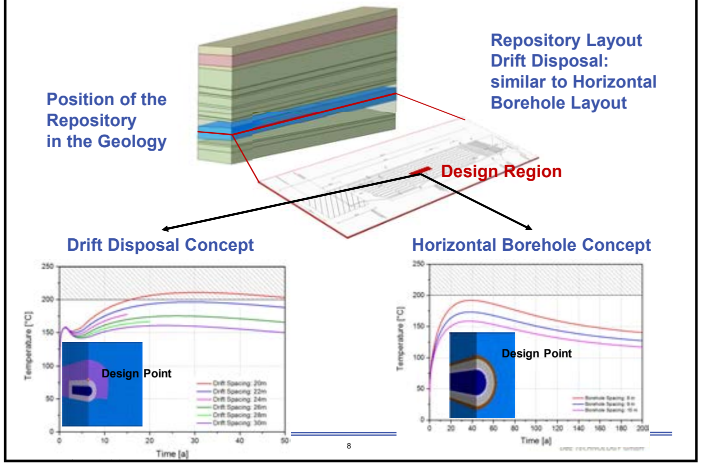
- **design temperature calculations (max. 200°C)**
- **design of the repository mine**
- **Transport and emplacement techniology and -systems**
- **backfilling and sealing concept**

Types and Amounts of Waste

Waste stream						Cask	
						Type	Number
Spent fuel elements from nuclear power plants		PWR	UO_2 MOX	12,450 FE 1,530 FE	6,415 tHM 765 tHM	POLLUX®-10	1,398
		BWR	UO_2 MOX	14,350 FE 1,250 FE	2,465 tHM 220 tHM		520
		WWER	UO_2	5,050 FE	580 tHM		202
		Total	**-**	**-**	**10,445 tHM**	**POLLUX®-10**	**2,120**
Waste from reprocessing	CSD-V	AREVA NC (F)	3,024			POLLUX®-9	336
		Sellafield Ltd. (UK)	565				63
		VEK (D)	140				16
	CSD-B	AREVA NC (F)	140			POLLUX®-9	16
	CSD-C	AREVA NC (F)	4,104			POLLUX®-9	456
		Total	**7,973**			**POLLUX®-9**	**887**
Spent fuel elements from prototype and research reactors		AVR	288,161 FE (spherical)			CASTOR® THTR/AVR	152
		THTR 300	617,606 FE (spherical)				305
		KNK II	2,484 fuel rods			CASTOR® KNK	4
		Otto-Hahn	52 fuel rods				
		FRM II	150 FE			CASTOR® MTR 2	30
		BER II	120 FE				20
		FRMZ	89 FE				1
		RFR	950 FE 1 fuel rod canister with 16 fuel rods				18
		Total	**-**			**-**	**530**
Compacted structural components of fuel elements		**Total**	**-**			**MOSAIK®**	**2,620**

(according to National Waste Management Program)

Bedded Salt Disposal Concepts



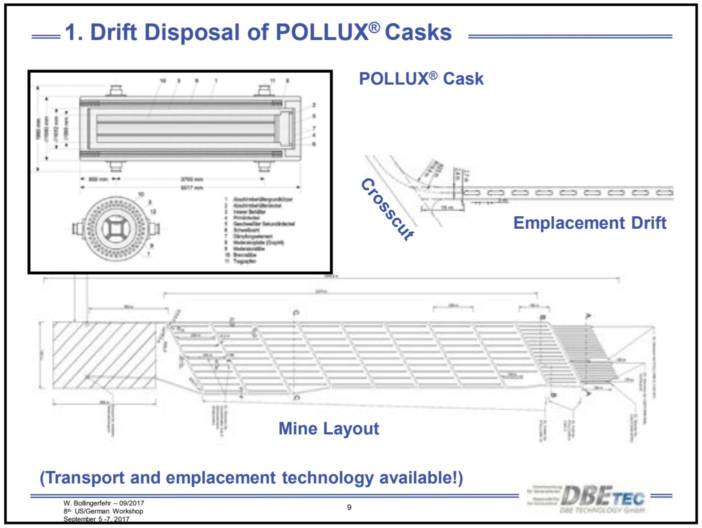
Position of the Repository in the Geology

Repository Layout Drift Disposal: similar to Horizontal Borehole Layout

Design Region

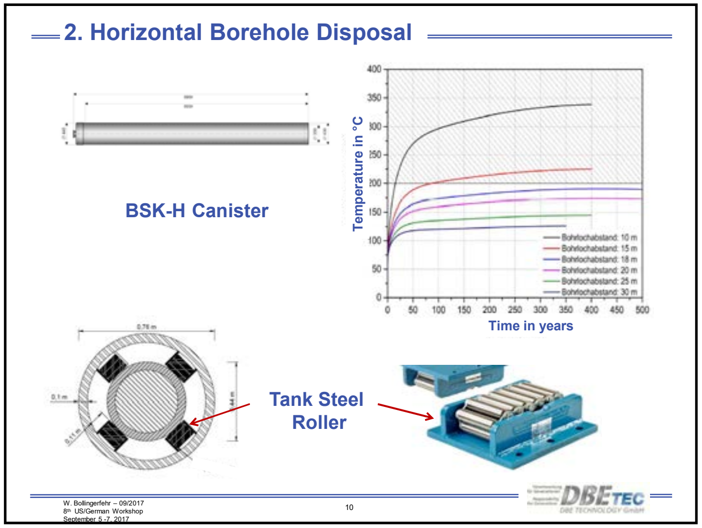
Drift Disposal Concept

Horizontal Borehole Concept



1. Drift Disposal of POLLUX® Casks

(Transport and emplacement technology available!)



2. Horizontal Borehole Disposal

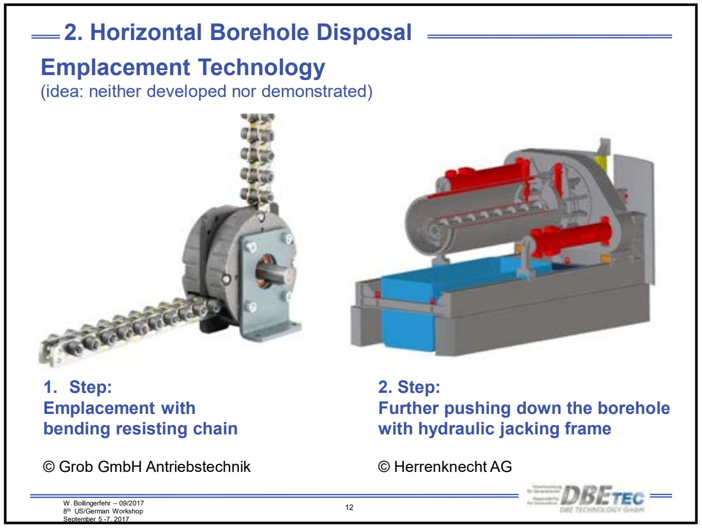
2. Horizontal Borehole Disposal

Microtunneling for Horizontal Boreholes

Machine data

Length incl. Cutting wheel	2 570 mm
Outer diameter	760 mm
Cutting diameter	785 mm
Steering cylinders	3 pcs (80/60-150)
Auger diameter	250 mm

© Herrenknecht AG



2. Horizontal Borehole Disposal

Emplacement Technology

(idea: neither developed nor demonstrated)

1. Step:
Emplacement with
bending resisting chain

© Grob GmbH Antriebstechnik

2. Step:
Further pushing down the borehole
with hydraulic jacking frame

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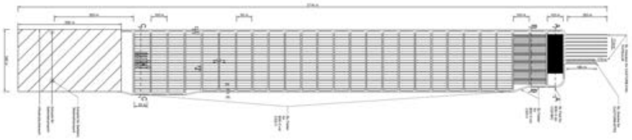
2. Horizontal Borehole Disposal

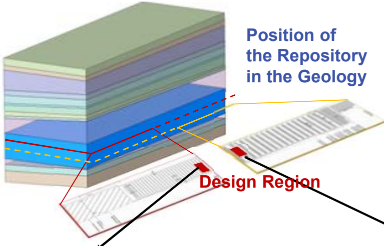
Design Parameters:

- Borehole Length: 100 m
- BSK-H per Borehole: 16



Mine Layout

Salt Pillow Concepts



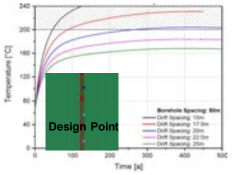
Position of the Repository in the Geology

Repository Layout for Vertical Borehole Disposal

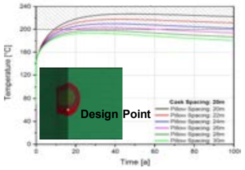
Repository Layout for Transport Cask Disposal

Design Region

Vertical Borehole Disposal Concept



Direct Disposal of Transport Casks



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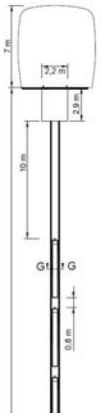
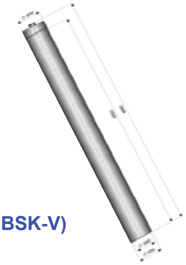
3. Vertical Borehole Disposal

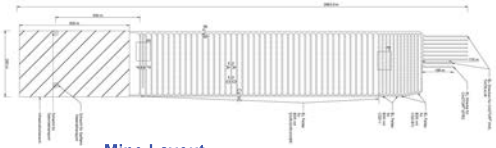


Design parameters:

- Borehole depth: 100 m
- BSK per borehole: 15



SF Canisters (BSK-V)



Mine Layout

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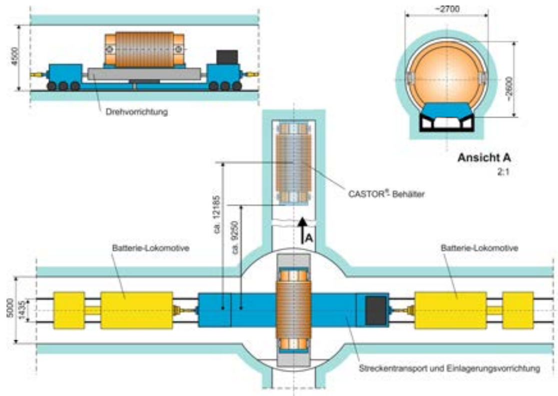
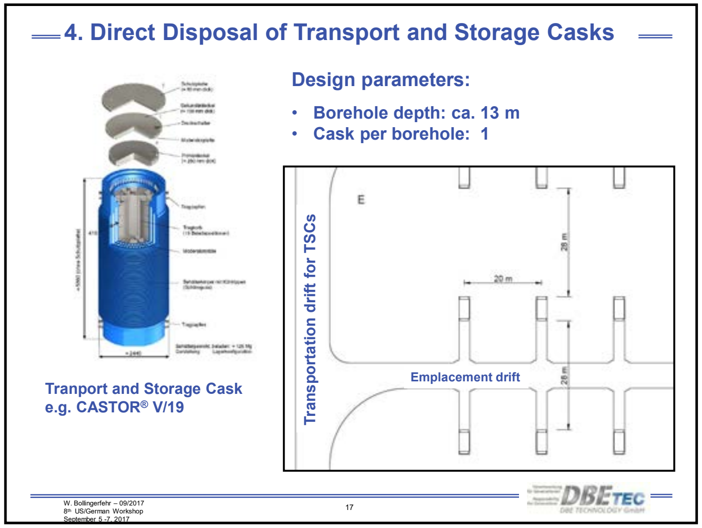
4. Direct Disposal of Transport- and Storage Casks



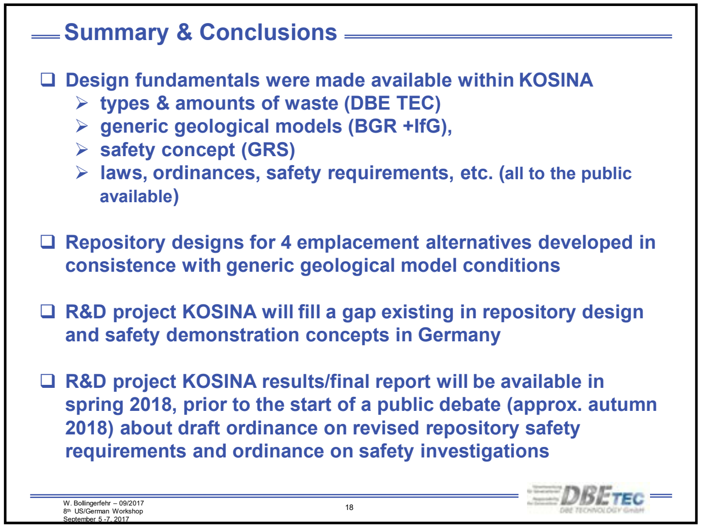


4. Direct Disposal of Transport and Storage Casks

Tranport and Storage Cask
e.g. CASTOR® V/19

Design parameters:

- Borehole depth: ca. 13 m
- Cask per borehole: 1



Summary & Conclusions

- ❑ Design fundamentals were made available within KOSINA
  - ➢ types & amounts of waste (DBE TEC)
  - ➢ generic geological models (BGR +IfG),
  - ➢ safety concept (GRS)
  - ➢ laws, ordinances, safety requirements, etc. (all to the public available)
- ❑ Repository designs for 4 emplacement alternatives developed in consistence with generic geological model conditions
- ❑ R&D project KOSINA will fill a gap existing in repository design and safety demonstration concepts in Germany
- ❑ R&D project KOSINA results/final report will be available in spring 2018, prior to the start of a public debate (approx. autumn 2018) about draft ordinance on revised repository safety requirements and ordinance on safety investigations

DBE TECHNOLOGY GmbH

Thank you for your attention.

EPA Review of DOE's 2014 Compliance Recertification Application for WIPP

Author: Kathleen Economy
Affiliation: US EPA

Middelburg, The Netherlands
September 5-7, 2017

Regulatory Steps to Recertify WIPP

Every 5 Years - DOE is required to submit to EPA a Compliance Recertification Application (CRA) with a Performance Assessment (PA) for WIPP

- March 26, 2014 - DOE submitted 3rd WIPP CRA PA to EPA for recertification
  - EPA responded to the February 14, 2014 radiological release incident, therefore the review was delayed
- July 13, 2017- EPA Issued the Recertification Decision

What are EPA activities during this review process?

Underpinning of Each CRA Review

- Focuses on what has been, or should have been, updated since the previous CRA
- Evaluates conceptual models and sub-models, asks…

  Do they adequately represent the system?

  Are they appropriately implemented?

  (e.g., suitable and updated input parameters)

Asks – Has DOE met the 'reasonable expectation' that they have demonstrated compliance with EPA's radioactive waste disposal regulations?

EPA's Review Process

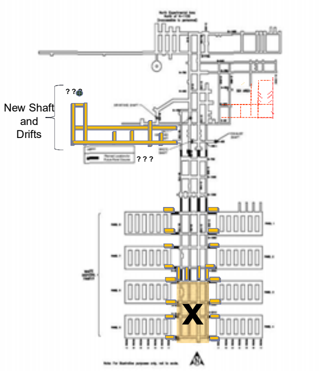
- Starts with a 'Completeness Review'
- Determines what changed since the previous CRA
  - Design changes?
  - Waste information (e.g., characterization, inventory)?
- Looks at parameter updates – are they aligned with current scientific information?
- Evaluates how updates are integrated into PA
  - Includes issues identified in previous recertifications
- Completeness review spawns clarifying questions to DOE
- May request additional calculations

After EPA's 1996 CCA, 2004 and 2009 CRA Reviews EPA Requests Additional Calculations

- Updated PA calculations were requested
  - Purpose –
    - Addresses EPA completeness questions
    - Evaluates movement of performance metrics
  - The updated PA is then considered the updated baseline
  - Labeled as Performance Assessment Baseline Calculations (PABC)
- During EPA's 2014 completeness review the possibility of a 2014 PABC was cancelled.....

  ...WHY?

Question: Why No 2014 PABC?.... Answer: Too Many Potential Design Changes



DOE proposing

- Installing new ventilation shaft and drifts
- Abandoning waste panel 9
- May not use run-of-mine panel closures in waste panels 3 thru 6

Therefore, a PABC using the 2014 configuration would not represent an expected future repository design

How to Address Issues Raised in EPA's 2014-CRA Completeness Review

Some of EPA's Top Issues

- DOE's revised probability of a borehole intersecting a waste panel and brine reservoir below

  - direct brine releases (DBR) are the dominant low-probability high consequence release mechanism
- Actinide chemistry modifications (e.g., solubility, oxidation states) – *determines availability of radionuclides for release*
- Long-term parameter values adopted for.....
  - Salt Aggregate (Run of Mine Salt - ROM)
  - Open Drifts
  - Disturbed Rock Zone (DRZ)

How to Resolve? EPA Requests DOE Perform **Four** Sensitivity Studies

Purpose: Addresses some of EPA's top concerns not directly affected by repository design changes

- Compare Results with 2014-CRA PA
- Determine Impact On Total Releases

SEN 1 and SEN 2 – Modify Parameter Values Affected by Creep Closure

- SEN 1– Non-waste areas: model time dependent reduction in permeability, porosity, invoke two-phase flow
  - Resulted in non-physical results – study abandoned
- SEN 2- Non-waste areas: instantly 'heal' non-waste areas
  - perm/porosity/two-phase same as intact halite for 10,000 years

SEN 3 – Modify Inputs for Non-waste Areas, ROM Salt in Panel Closures, Adjacent DRZ

- Instantly 'heal' both panel closures, non-waste areas, DRZ
  - perm/porosity/two-phase same as intact halite for 10,000 year

SEN 4 –Tested a subset of revised parameter values

- EPA's revised probability of encountering a Castile brine reservoir beneath the repository
- EPA's revised uncertainty distributions for actinide solubility
- Revise the iron sulfidation reaction – EPA supported assumption that iron passivated by H_2S
- Modified slightly lower limit for shear strength of degraded waste
- Used DOE corrected version for DRSPALL code
- Use corrected length of farthest north panel closure

How Will Modifications Affect Performance Metrics
Total Releases Must Be Below EPA Release Limits

Releases Composed of Four Primary Mechanisms

- **Releases to Culebra**

Minimally impacted by repository processes or design

- **Spallings Releases**

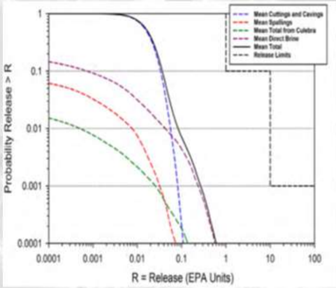
Impacted by repository processes, but effect on total releases small compared to direct brine releases

- **Cuttings and Cavings**

Not a function of repository processes

- **Direct Brine Releases**

Significantly impacted by repository processes and design



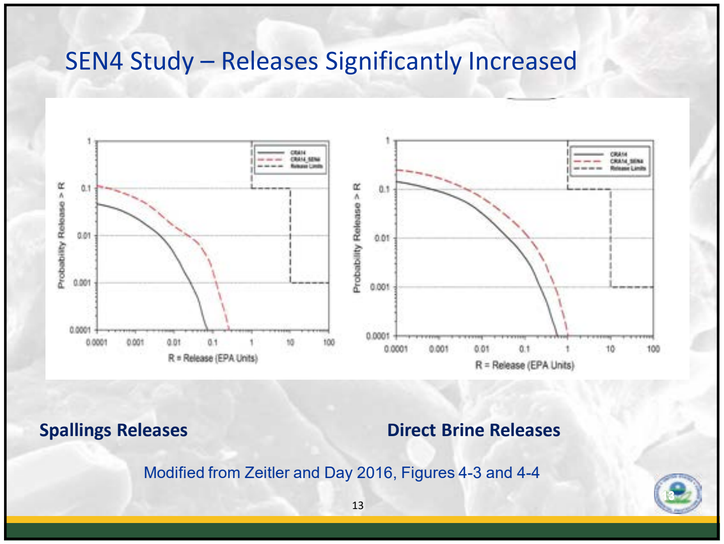
Mean of Four Main Release Components and Mean Total Releases
(SEN 2 Study from Day 2016, Figure 4-155)

SEN 2 Results – (non-waste areas instantly heal)

- Primarily Impacted Spallings Releases
  (due to increased waste panel pressures)
- Insignificantly Impacted Overall Releases

SEN 3 Results– (both the non-waste areas and ROM salt in panel closure drifts instantly heal)

- Primarily Impacted Spallings Releases
  (due to increased waste panel pressures)
- An increase in Direct Brine Releases seen
  (due to increased pressures in waste panel pressures and minor increase in saturation)
- Overall Releases - a slight increase seen

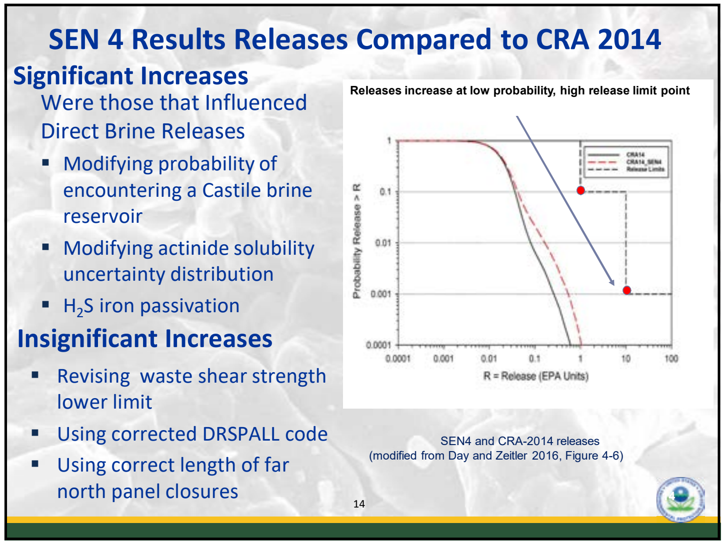


SEN4 Study – Releases Significantly Increased

Spallings Releases

Direct Brine Releases

Modified from Zeitler and Day 2016, Figures 4-3 and 4-4



SEN 4 Results Releases Compared to CRA 2014

Significant Increases

Were those that Influenced Direct Brine Releases

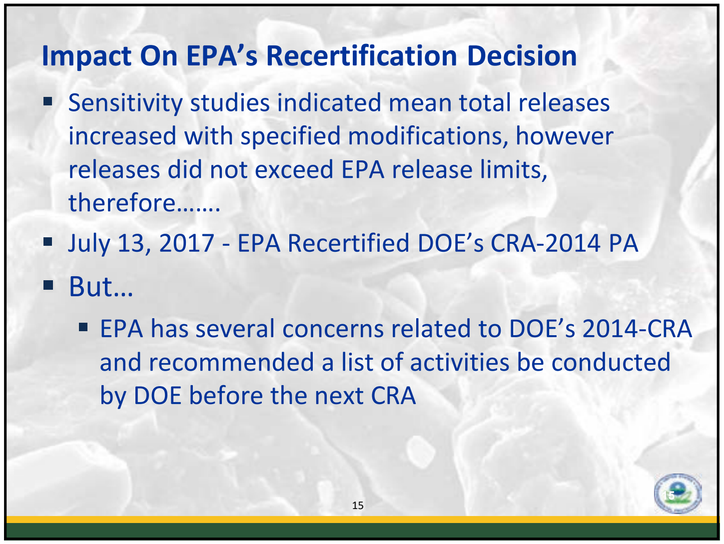
- Modifying probability of encountering a Castile brine reservoir
- Modifying actinide solubility uncertainty distribution
- H_2S iron passivation

Insignificant Increases

- Revising waste shear strength lower limit
- Using corrected DRSPALL code
- Using correct length of far north panel closures

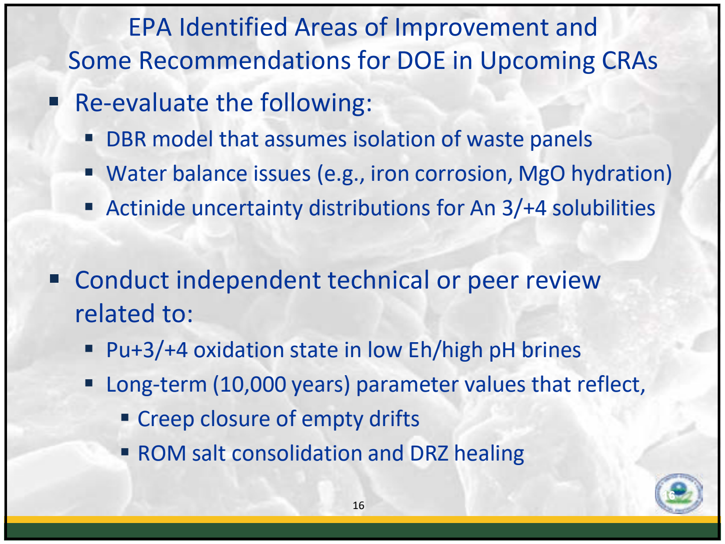
Releases increase at low probability, high release limit point

SEN4 and CRA-2014 releases
(modified from Day and Zeitler 2016, Figure 4-6)



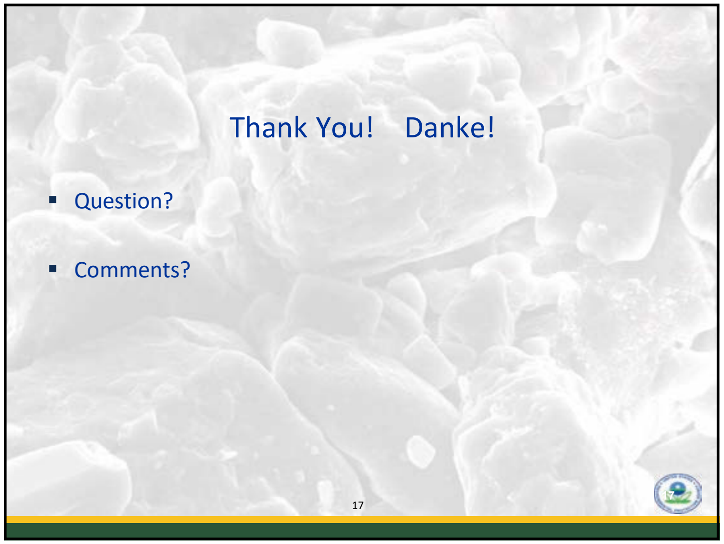
Impact On EPA's Recertification Decision

- Sensitivity studies indicated mean total releases increased with specified modifications, however releases did not exceed EPA release limits, therefore…….
- July 13, 2017 - EPA Recertified DOE's CRA-2014 PA
- But…
  - EPA has several concerns related to DOE's 2014-CRA and recommended a list of activities be conducted by DOE before the next CRA



EPA Identified Areas of Improvement and Some Recommendations for DOE in Upcoming CRAs

- Re-evaluate the following:
  - DBR model that assumes isolation of waste panels
  - Water balance issues (e.g., iron corrosion, MgO hydration)
  - Actinide uncertainty distributions for An 3/+4 solubilities
- Conduct independent technical or peer review related to:
  - Pu+3/+4 oxidation state in low Eh/high pH brines
  - Long-term (10,000 years) parameter values that reflect,
    - Creep closure of empty drifts
    - ROM salt consolidation and DRZ healing



Thank You!   Danke!

- Question?
- Comments?

References

EPA Radiation Protection Website:

https://www.epa.gov/radiation/waste-isolation-pilot-plant-wipp

EPA CRA-2014 Review Related Documents

http://www.regulations.gov, Docket ID No. EPA-HQ-OAR-2014-0609

Contains: EPA CRA-2014 Technical Support Documents, Compliance Application Requirement Documents, Completeness Comments and DOE Responses, Public Comments, Other EPA WIPP Review Documents

Day, Brad, and Todd Zeitler 2016. Panel Closure System Sensitivity Study, Revision 0. ERMS 566725. Sandia National Laboratories, Waste Isolation Pilot Plant. Carlsbad, New Mexico. August.

DOE (U.S. Department of Energy) 2014. Title 40 CFR 191 Subparts B and C Compliance Recertification Application 2014. U.S. Department of Energy, Carlsbad, New Mexico

(can be found DOE Website: http://www.wipp.energy.gov/Documents_All_Title.htm#C)

Zeitler, Todd, and Brad Day 2016. CRA14 SEN4 Sensitivity Study, Revision 1. ERMS 567505. Sandia National Laboratories, Waste Isolation Pilot Plant. Carlsbad, New Mexico. December.

WIPP Recovery and Operational Safety

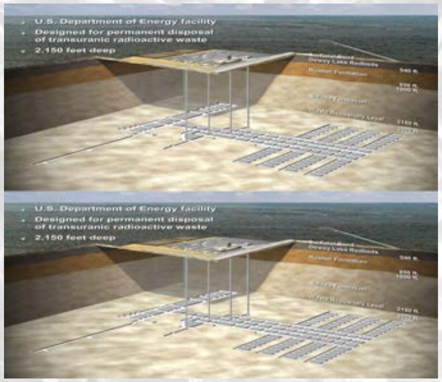
Sean Dunagan
Sandia National Laboratories

Middelburg, The Netherlands
September 5-7, 2017

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. SAND2017-8889C.

Outline

- Recovery
- Ground Control Challenges
- Waste Emplacement
- Resumption of Shipments
- Mining
- Future Planning



WIPP Incidents

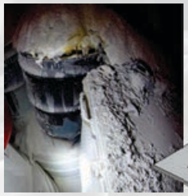
February 5, 2014 Truck Fire:

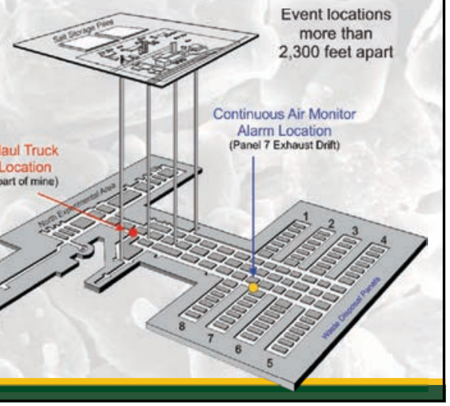
- All operations at the repository ceased following salt haul truck fire in the WIPP underground.
- An investigation team was deployed to determine the cause of the fire.

February 14, 2014 Radiological Incident:

- A continuous air monitor detected airborne radiation in the underground.
- WIPP's ventilation system automatically switched to high-efficiency particulate air (HEPA) filtration mode when airborne radiation was detected
- Underground and the WIPP mine remains in filtration mode at this time.
- Extensive sampling and monitoring conducted by DOE, New Mexico, and Carlsbad Environmental Monitoring Research Center
- Efforts by the DOE and Nuclear Waste Partnership are ensuring workers are fully protected during recovery and restart.

WIPP Incidents





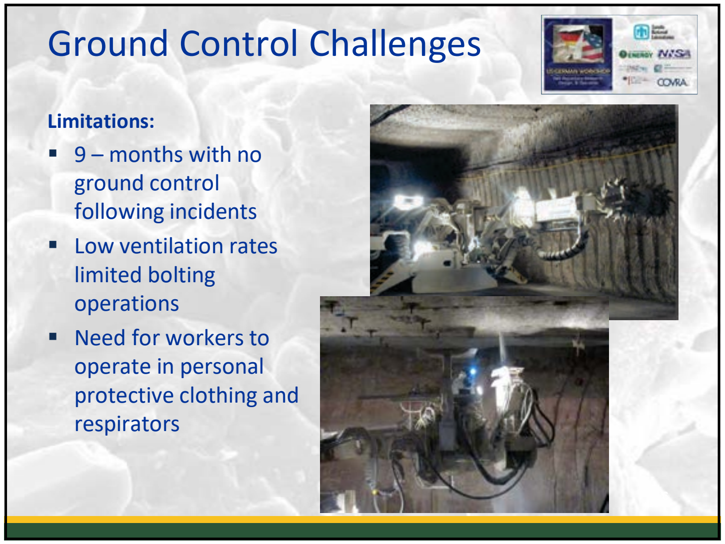
Event locations more than 2,300 feet apart

Continuous Air Monitor Alarm Location
(Panel 7 Exhaust Drift)

Salt Haul Truck Fire Location
(North part of mine)

Key Steps Toward Recovery

- Documented Safety Analysis Revisions
- Safety Management Program Revitalization
- Underground Restoration
  - Re-Establish Degraded Equipment
  - Fire Protection
  - Maintenance and Ground Control
  - Radiological Roll-back
  - Soot cleaning of electrical panels
- Expedite mine stability
- Initial Panel 6 and Panel 7, Room 7 Closure
- Interim Ventilation



Ground Control Challenges

Limitations:

- 9 – months with no ground control following incidents
- Low ventilation rates limited bolting operations
- Need for workers to operate in personal protective clothing and respirators

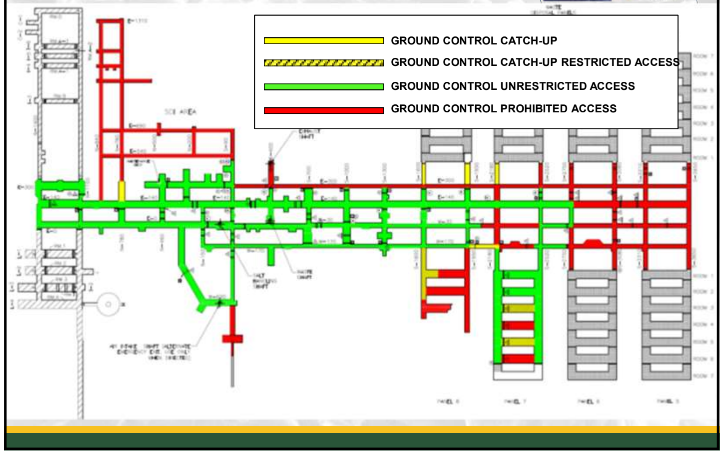
Ground Control Challenges

Ground Control Challenges

Ground Control Challenges

Ground Control Challenges

Ground Control Status



Reopening

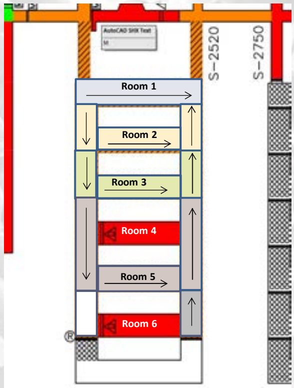
WIPP Officially Reopened with a ribbon cutting ceremony held on January 9, 2017

Waste Emplacement Resumes

- Waste emplacement operations resumed in Panel 7 – transition point between clean and contaminated area is necessary

Panel 7 Status

- Bulkhead were placed at both ends of Room 7 to isolate waste following events – remains closed
- Rock fall occurred in Room 4 on November 3, 2016 – fall was predicted and room was already prohibited
- Room 6 is prohibited due to ground control – also contains abandoned equipment
- Rooms 1, 2, 3 and 5 are safe and usable for waste emplacement
- Waste emplacement has started in S2520 moving west to east
- Currently available disposal capacity in Panel 7 should last approximately 3-4 years, depending on shipping rates



Shipments Resumed

- First shipment since incidents was received from Idaho on April 8
- Shipment rate started at 2/week, with goal of ramping up to 4/week by the end of 2017
- WIPP anticipates receipt of approximately 128 shipments between April of 2017 and the end of January 2018
- Currently receiving shipments from Idaho, Savanah River, Waste Control Specialist, and Oak Ridge.

Projected Shipping

Key considerations in the development of the shipping estimate and points of origin included:

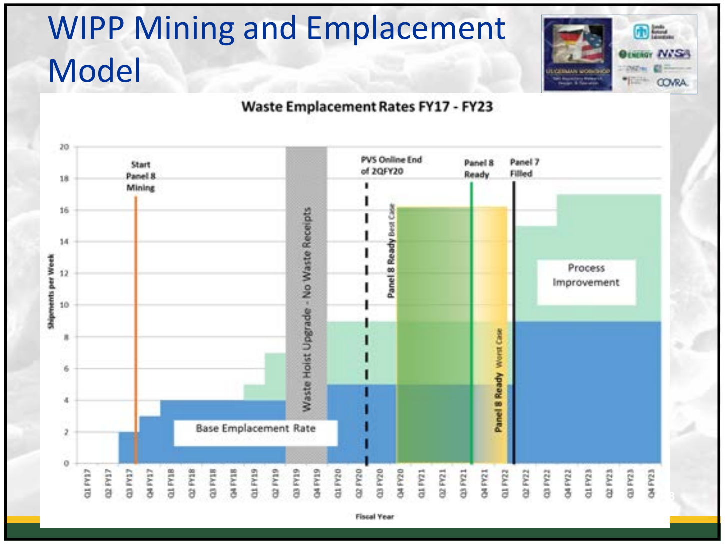
- WIPP waste emplacement rate;
- Available waste to ship;
- Regulatory commitments and agreements;
- WIPP transportation/waste acceptance capabilities;
- Flexibility for changing technical and policy constraints.

Site	Projected Shipments
Idaho	61
Los Alamos	24
Oak Ridge	24
Savannah River	8
Waste Control Specialists	11
TOTAL	128

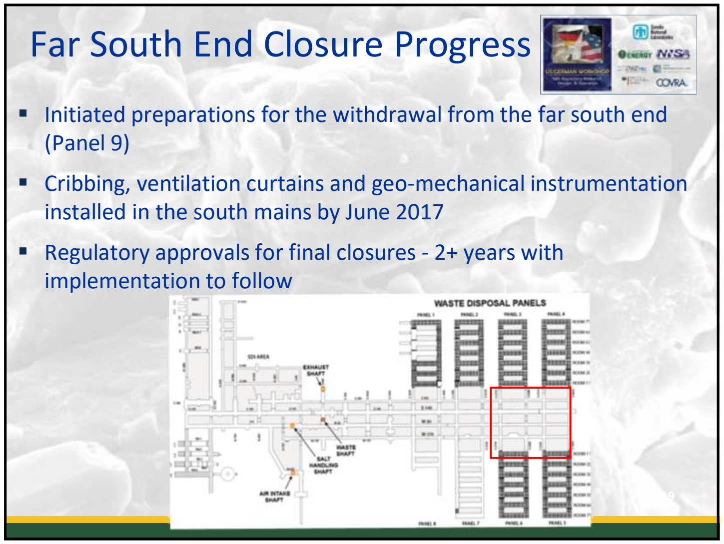
Mining Panel 8

Mining of Panel 8:

- Planned to begin in October 2017
- No contamination present
- Required to bolt our way into the panel to remove equipment that has remained there since events
- Mining operations are expected to take approximately 3 years

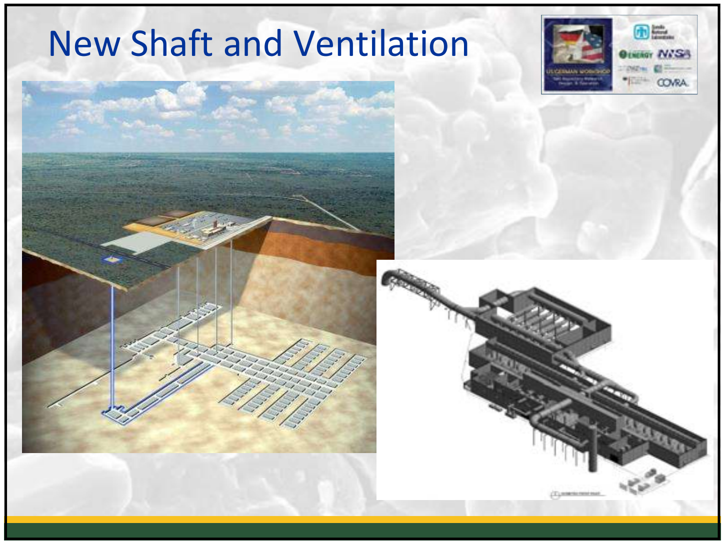


WIPP Mining and Emplacement Model



Far South End Closure Progress

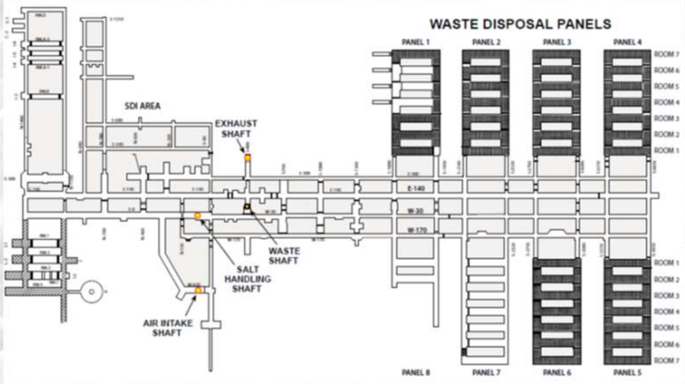
- Initiated preparations for the withdrawal from the far south end (Panel 9)
- Cribbing, ventilation curtains and geo-mechanical instrumentation installed in the south mains by June 2017
- Regulatory approvals for final closures - 2+ years with implementation to follow

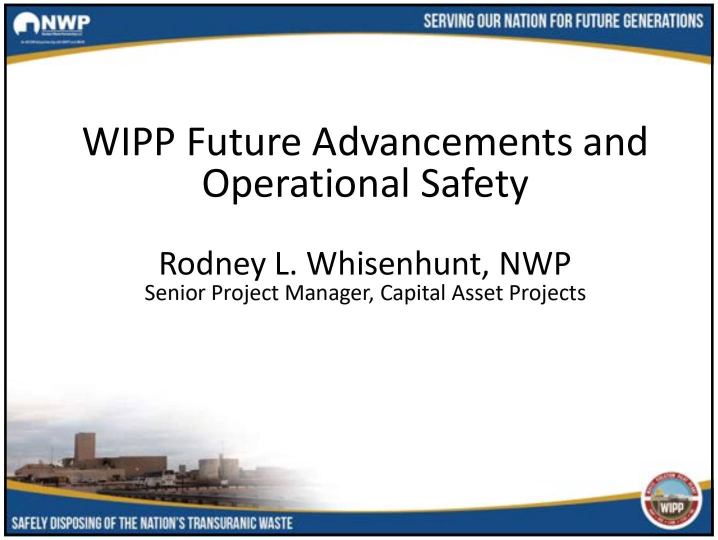


New Shaft and Ventilation

Questions

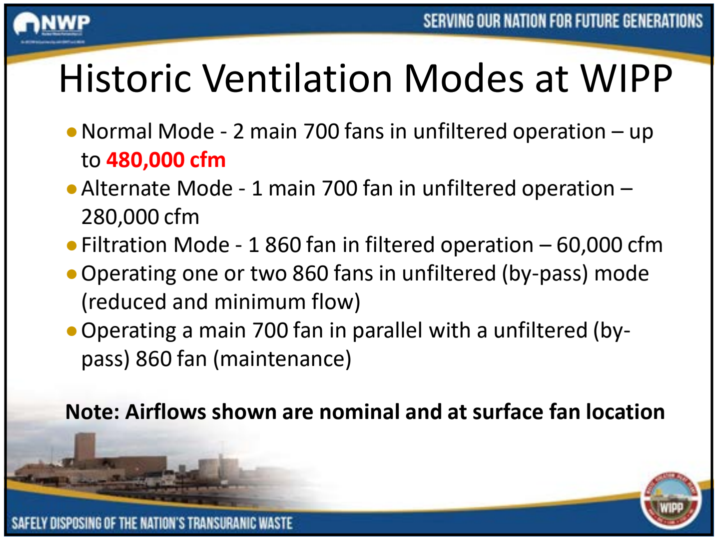
WIPP Underground Map





WIPP Future Advancements and Operational Safety

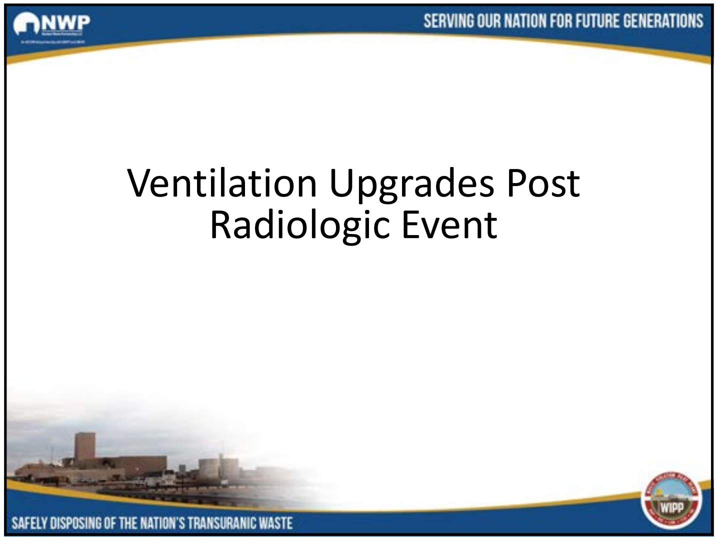
Rodney L. Whisenhunt, NWP
Senior Project Manager, Capital Asset Projects



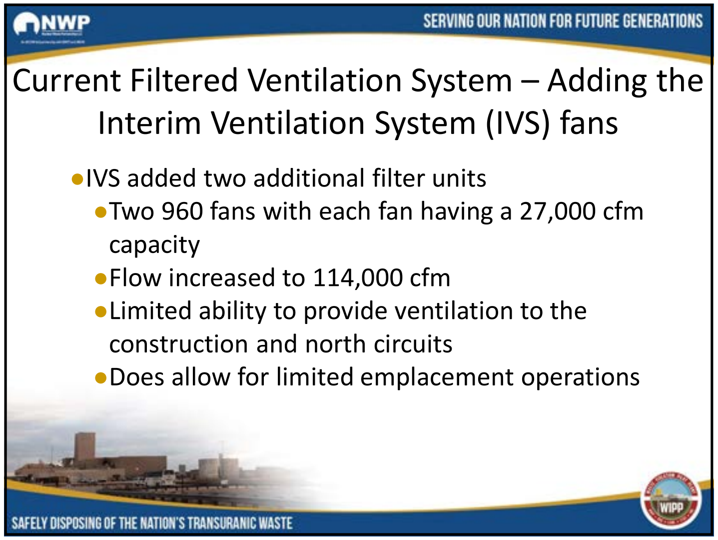
Historic Ventilation Modes at WIPP

- Normal Mode - 2 main 700 fans in unfiltered operation – up to **480,000 cfm**
- Alternate Mode - 1 main 700 fan in unfiltered operation – 280,000 cfm
- Filtration Mode - 1 860 fan in filtered operation – 60,000 cfm
- Operating one or two 860 fans in unfiltered (by-pass) mode (reduced and minimum flow)
- Operating a main 700 fan in parallel with a unfiltered (by-pass) 860 fan (maintenance)

Note: Airflows shown are nominal and at surface fan location

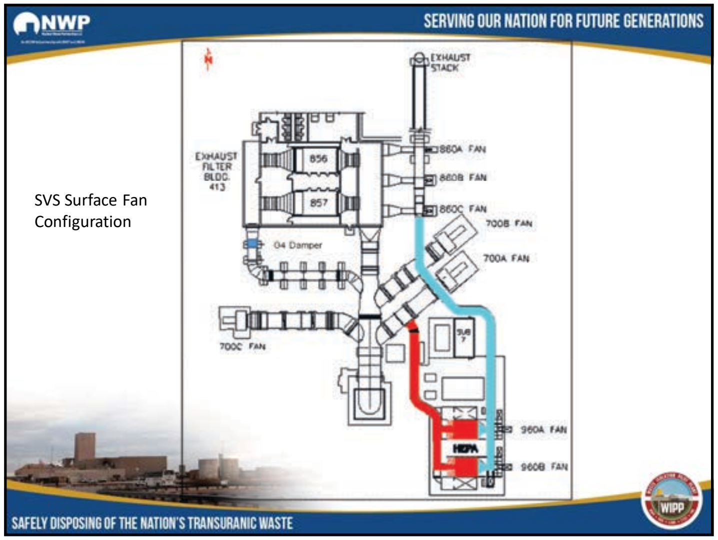


Ventilation Upgrades Post Radiologic Event



Current Filtered Ventilation System – Adding the Interim Ventilation System (IVS) fans

- IVS added two additional filter units
  - Two 960 fans with each fan having a 27,000 cfm capacity
  - Flow increased to 114,000 cfm
  - Limited ability to provide ventilation to the construction and north circuits
  - Does allow for limited emplacement operations

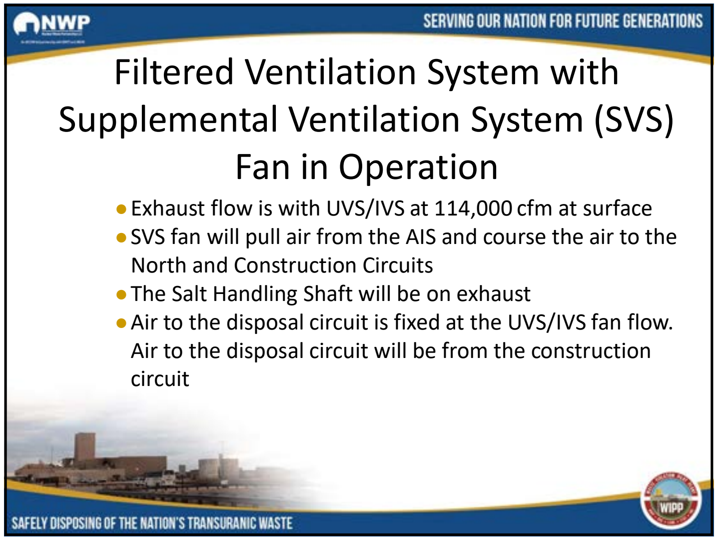


NWP

SERVING OUR NATION FOR FUTURE GENERATIONS

SVS Surface Fan Configuration

SAFELY DISPOSING OF THE NATION'S TRANSURANIC WASTE



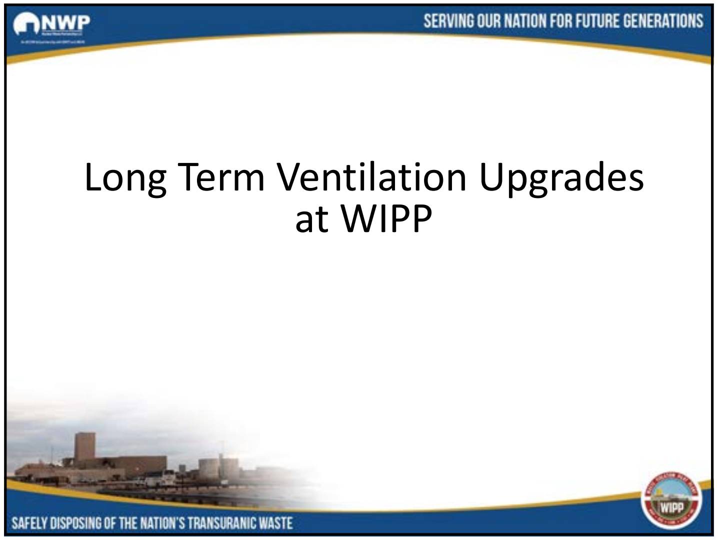
NWP

SERVING OUR NATION FOR FUTURE GENERATIONS

Filtered Ventilation System with Supplemental Ventilation System (SVS) Fan in Operation

- Exhaust flow is with UVS/IVS at 114,000 cfm at surface
- SVS fan will pull air from the AIS and course the air to the North and Construction Circuits
- The Salt Handling Shaft will be on exhaust
- Air to the disposal circuit is fixed at the UVS/IVS fan flow. Air to the disposal circuit will be from the construction circuit

SAFELY DISPOSING OF THE NATION'S TRANSURANIC WASTE



NWP

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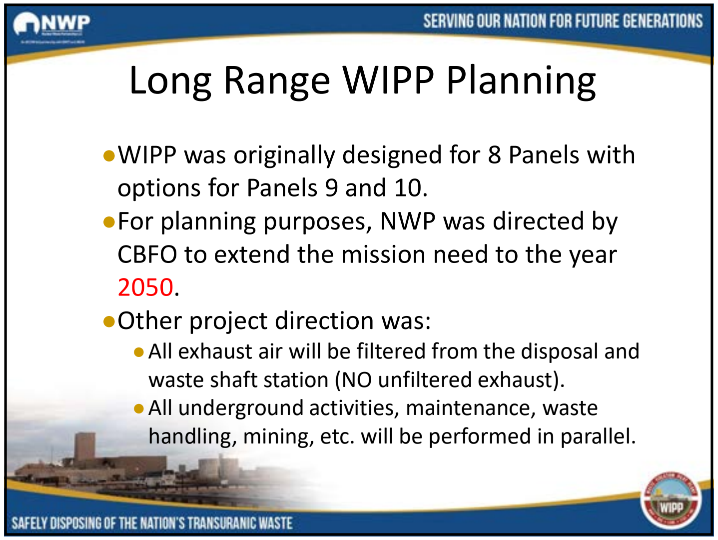
Long Term Ventilation Upgrades at WIPP

SAFELY DISPOSING OF THE NATION'S TRANSURANIC WASTE



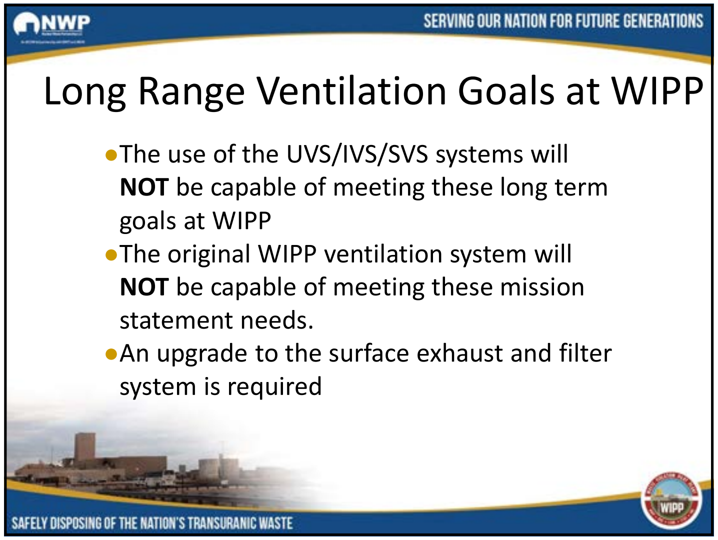
NWP

SERVING OUR NATION FOR FUTURE GENERATIONS

Long Range WIPP Planning

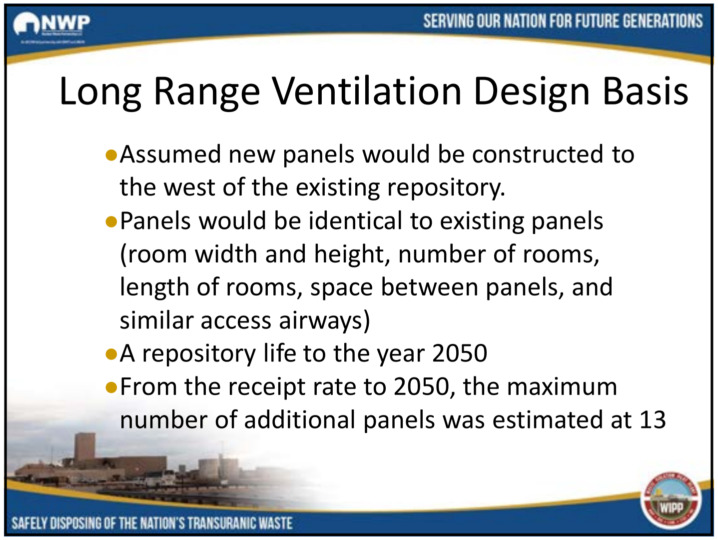
- WIPP was originally designed for 8 Panels with options for Panels 9 and 10.
- For planning purposes, NWP was directed by CBFO to extend the mission need to the year 2050.
- Other project direction was:
  - All exhaust air will be filtered from the disposal and waste shaft station (NO unfiltered exhaust).
  - All underground activities, maintenance, waste handling, mining, etc. will be performed in parallel.

SAFELY DISPOSING OF THE NATION'S TRANSURANIC WASTE



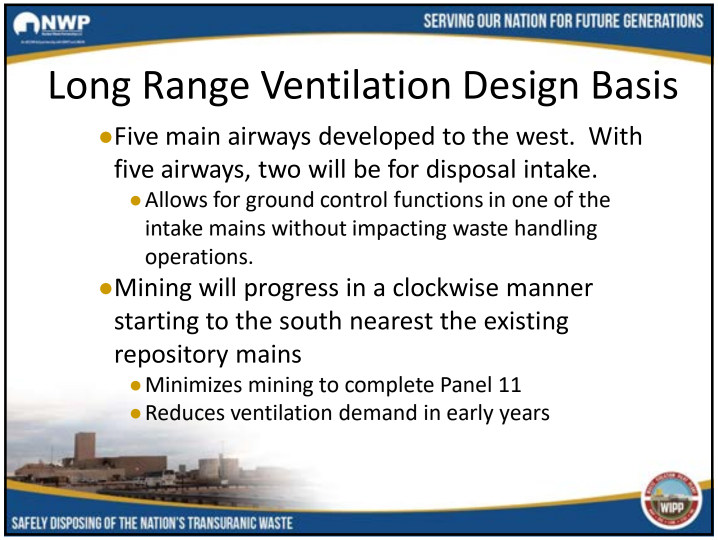
Long Range Ventilation Goals at WIPP

- The use of the UVS/IVS/SVS systems will **NOT** be capable of meeting these long term goals at WIPP
- The original WIPP ventilation system will **NOT** be capable of meeting these mission statement needs.
- An upgrade to the surface exhaust and filter system is required



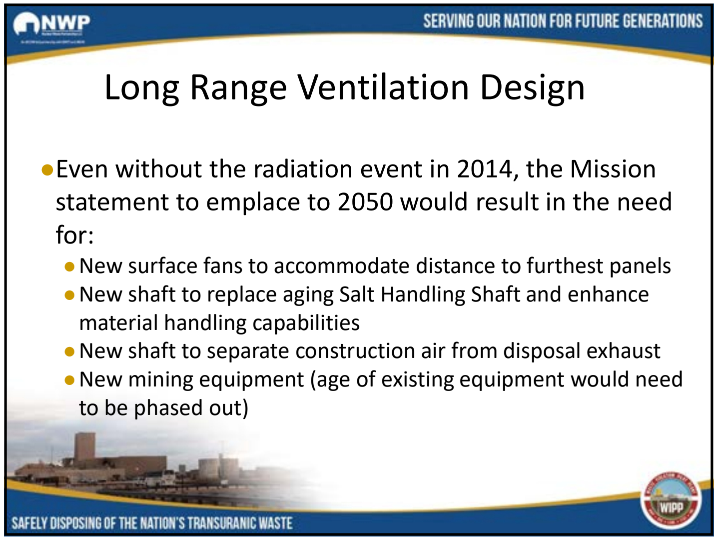
Long Range Ventilation Design Basis

- Assumed new panels would be constructed to the west of the existing repository.
- Panels would be identical to existing panels (room width and height, number of rooms, length of rooms, space between panels, and similar access airways)
- A repository life to the year 2050
- From the receipt rate to 2050, the maximum number of additional panels was estimated at 13



Long Range Ventilation Design Basis

- Five main airways developed to the west. With five airways, two will be for disposal intake.
  - Allows for ground control functions in one of the intake mains without impacting waste handling operations.
- Mining will progress in a clockwise manner starting to the south nearest the existing repository mains
  - Minimizes mining to complete Panel 11
  - Reduces ventilation demand in early years



Long Range Ventilation Design

- Even without the radiation event in 2014, the Mission statement to emplace to 2050 would result in the need for:
  - New surface fans to accommodate distance to furthest panels
  - New shaft to replace aging Salt Handling Shaft and enhance material handling capabilities
  - New shaft to separate construction air from disposal exhaust
  - New mining equipment (age of existing equipment would need to be phased out)

WIPP Upgrade Projects

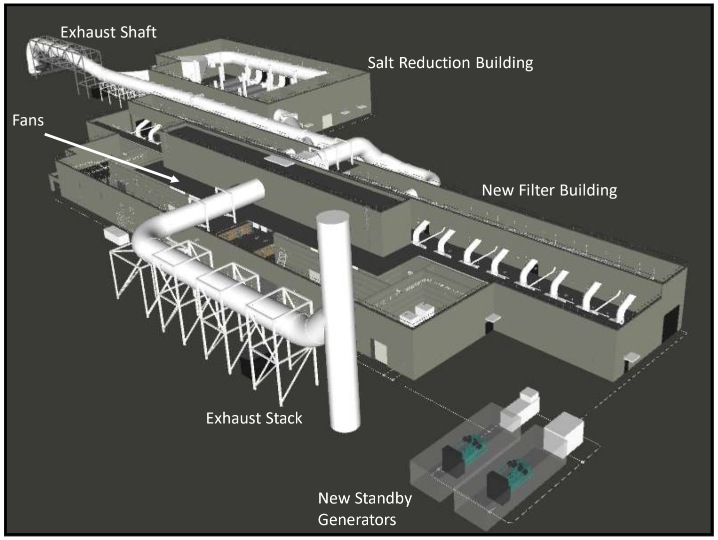
- Two new projects are considered to achieve the mission statement:
  - New surface fans with new filter system (sufficient for all exhaust air as per DOE direction).
  - New shaft (to achieve long term goals at WIPP regarding hoisting and separation of construction [mining] and waste handling operations)

Current New Filter Building (NFB) Design

- Principal underground ventilation design criteria for NFB
  - Maximum airflow of 540,000 cfm (at the fans)
  - Consider a salt reduction system to minimize salt dust from reaching containment filters

---

Permanent Ventilation System Project Status
New Filter Building General Layout



Exhaust Shaft (ES) Location

ES Project

- A new intake shaft results in all construction (mining) air to be routed to the AIS for exhausting to surface
  - Eliminates a significant dust source to Exhaust Shaft filtration system and possibly eliminates the need for a salt reduction system on surface
  - Greatly reduces any salt build up in duct work on Exhaust Shaft

Hoisting System in New Shaft

- The current project does not include a hoisting system
- A separate project is being considered to install a hoisting system in the new shaft.

New Shaft with Hoisting Capability

- The need for a hoisting system is based on the following criteria:
  - Increased salt handling operations
  - Increased personnel and materials handling operations
- The design would allow for salt skipping and personnel and material handling operations to occur simultaneously
  - At least doubling current salt skipping operations
  - Large equipment can be hoisted via a large conveyance
  - Emergency egress is significantly enhanced

New Shaft with Hoisting Capability

- Basis of new hoisting system design
  - Need to replace existing Salt Handling Shaft (SHS)
    - The SHS has been in operation since the early 1980s and was designed for a 25 year life (currently over 30 years old)
    - The current SHS is a small 10 ft. diameter shaft with significant corrosion on internal shaft components.
    - At some stage this shaft will need a major overhaul – which will result in a cessation of salt skipping from the underground during shaft renovation.
    - **A complete shaft overhaul with updated controllers on the hoist system could take up to 12 months.**
    - **This will impact mining to new panels to the west.**

Loading pocket corrosion.

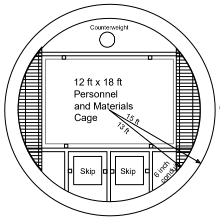
SHS liner and bunton corrosion

SHS bunton and wall connection corrosion

New Shaft with Hoisting Capability

- The need for a hoisting system is based on the following (continued):
  - The SHS has only an 8 ton skipping capacity for salt removal. Bottlenecks were common with this limited skip capacity (storing salt in underground airways waiting to be skipped)
  - The SHS has two functions, personnel and material conveyance and salt removal. The two functions **CANNOT** occur simultaneously.
  - If the SHS is skipping salt, then all personnel and material handling is moved to the Waste Shaft – potentially limiting any waste handling operations.

Shaft Conveyances and Shaft Diameter



- Twin skips – doubling salt hoisting capacity
- A 12 ft. x 18 ft. personnel and material conveyance:
  - Increased productivity since personnel can be sent underground more efficiently
  - Increased productivity in handling supplies, e.g. rock bolts, mesh, equipment, diesel fuel, etc.
  - Can handle about 100 personnel in an emergency (egress) and is closer to new panel development then the Waste Shaft or SHS – **A Significant Safety Improvement**
- A 12 ft. x 18 ft. personnel and material conveyance with two skips and up to 500,000 cfm results in a shaft diameter of 30 ft. (26 ft. finished)

Sandia's Salt Design Concept for High Level Waste and Defense Spent Nuclear Fuel

Ed Matteo, Ernie Hardin, and Teklu Hadgu
Sandia National Laboratories

Middelburg, The Netherlands
September 5-7, 2017

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2017-9337 C.

Disclaimer

- This research was performed as part of the Defense Waste Repository (DWR) project. Based on revised DOE priorities in mid-2017, the development of a DWR has been discontinued; current work unique to the development of a DWR is being closed out and documentation will be completed by the end of fiscal year (FY) 2017. Implementation of any recommendations made in this report for further research regarding a DWR would require resumption of the DWR project at some future time.

Key Acronyms

- HLW = High Level Waste
- DSNF = Defense Spent Nuclear Fuel (or DOE-Managed Spent Nuclear Fuel)
- CSNF = Commercial Spent Nuclear Fuel

Preliminary Disposal Concepts for Salt Repository: Identify Candidate Concepts for Evaluation

- Main Objectives: Operational and post-closure safety
- Disposal Concept ≡ waste form + geologic setting + concept of operations
  - Waste form:
    - Mostly High Level Waste (HLW) glass, low heat output, Stainless Steel pour canisters
    - Defense Spent Nuclear Fuel (DSNF) of various types, pre-canistered
  - Geologic setting: Salt
  - Concept of operations: ?

Preliminary Disposal Concepts for a Salt Repository: Defense Waste Characteristics

- Low-thermal (up to 1 kW per 3- or 5-m canister)
- Long-lived radionuclides (~10^6-year assessment)
- Large numbers of canisters (data from Carter et al. 2012)
  - 3,542 DSNF (99.4% < 1 kW in 2030)
  - 23,032 HLW (Savannah River Site(SRS, Hanford & Idaho; all < 1 kW)
- Small canisters (mostly 18- and 24-inch diameters)
  - Neglecting Naval SNF which is most similar to Commercial Spent Nuclear Fuel (CSNF)
  - (Assume Idaho calcine is package in standardized canisters.)
- Canister Handling Weights
  - DSNF 2267 kg to 4536 kg + overpack ~15 MT
    - Shielded transport wt. >34 MT
  - HLW 2500 kg to 4200 kg (no overpack)
    - Shielded transport weight > 32 MT
  - Material: stainless steel (welded, no heat treatment)

Preliminary Disposal Concepts for a Salt Repository: Salt Geologic Setting

- Plastic formation
  - Creep behavior impacts concept of operations
    - Excavations will close due to creep
    - Just-in time drift construction
    - Self-healing
- Geochemical environment
  - Brine pore water
- Virtually impermeable media (diffusion dominated)
- Repository Access
  - For bedded salt, shaft access <u>only</u>
  - For domal salt, shaft or ramp access

Preliminary Disposal Concepts for a Salt Repository: Design Considerations

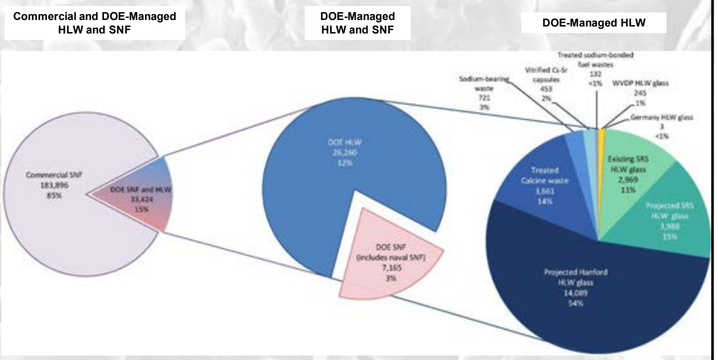
- Bedded or Domal Salt Constructability
  - Opening stability
  - Salt backfill
- Superior Heat Dissipation
- Nominal and Disturbed Performance
  - Releases dominated by human intrusion
- Natural Barrier
  - Insignificant groundwater abundance and mobility (nominal)
  - Brine saturation (esp. human intrusion)
- Engineered Barriers
  - Backfill and seals
  - Robust containment during operations
  - Emplacement borehole behavior (e.g., backfill reconsolidation)

Preliminary Disposal Concept for a Salt Repository

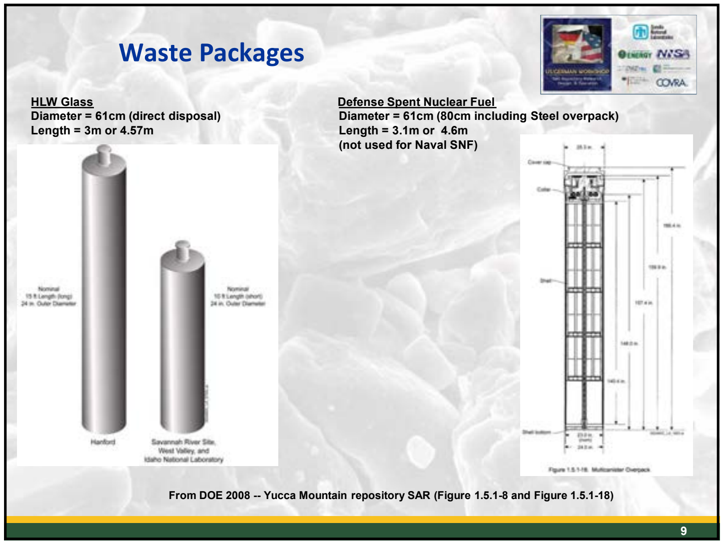
- Direct Disposal of Pour Canisters
  - HLW glass stability in operational environment
- Robust Overpack for Other Waste Forms
  - Carbon steel overpack (e.g., DSNF)
- Just-in-Time Drift Construction
  - Minimize handling of crushed salt
- In-Drift Emplacement (axial or transverse)
  - Relatively small, lightweight canisters (e.g., 6 MT HLW)
  - Immediate backfilling with crushed salt
- Constructability Challenges
  - Remote operation in unshielded environments

The Inventory is ~80% by volume is glass

Projected volumes in the year 2048 (m^3)



data from SNL 2014

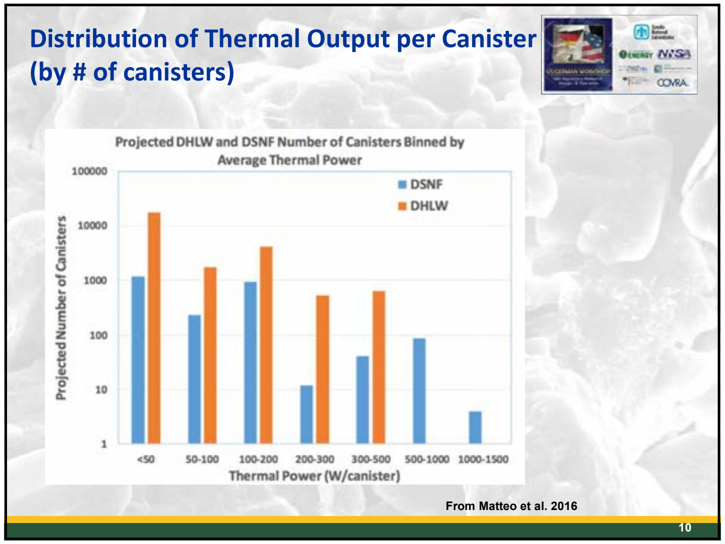


Waste Packages

HLW Glass
Diameter = 61cm (direct disposal)
Length = 3m or 4.57m

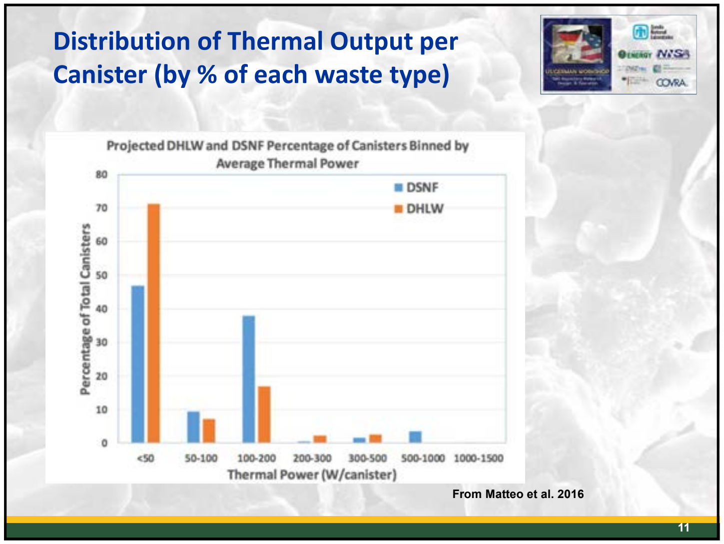
Defense Spent Nuclear Fuel
Diameter = 61cm (80cm including Steel overpack)
Length = 3.1m or 4.6m
(not used for Naval SNF)

From DOE 2008 -- Yucca Mountain repository SAR (Figure 1.5.1-8 and Figure 1.5.1-18)



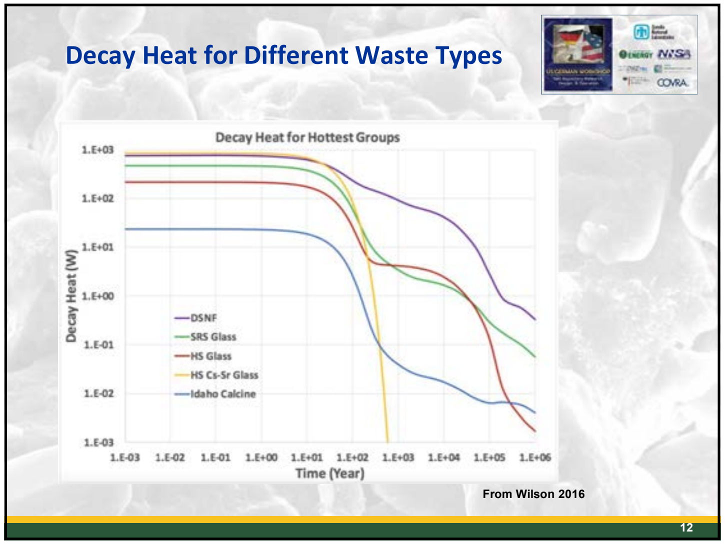
Distribution of Thermal Output per Canister (by # of canisters)

From Matteo et al. 2016



Distribution of Thermal Output per Canister (by % of each waste type)

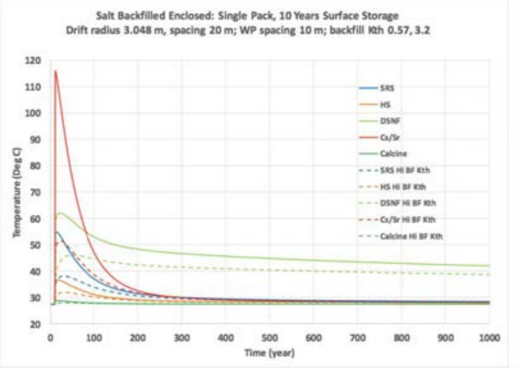
From Matteo et al. 2016



Decay Heat for Different Waste Types

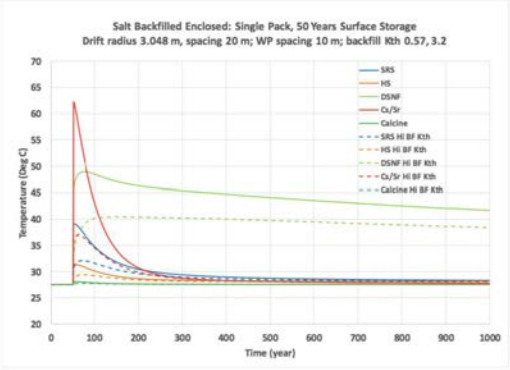
From Wilson 2016

Temperature Histories at Waste Package Surface (10 years surface storage)



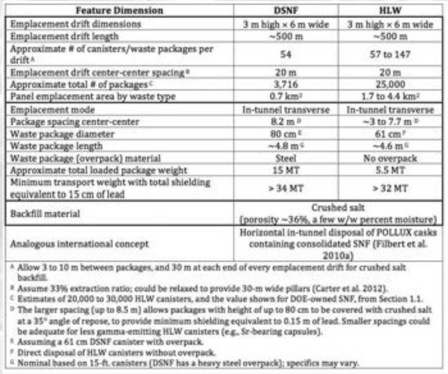
From Matteo et al. 2016

Temperature Histories at Waste Package Surface (50 years surface storage)



From Matteo et al. 2016

Salt Preliminary Design Concept by the Numbers

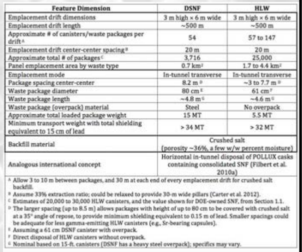


Feature Dimension	DSNF	HLW
Emplacement drift dimensions	3 m high × 6 m wide	3 m high × 6 m wide
Emplacement drift length	~500 m	~500 m
Approximate # of canisters/waste packages per drift[A]	54	57 to 147
Emplacement drift center-center spacing[B]	20 m	20 m
Approximate total # of packages[C]	3,716	25,000
Panel emplacement area by waste type	0.7 km²	1.7 to 4.4 km²
Emplacement mode	In-tunnel transverse	In-tunnel transverse
Package spacing center-center	8.2 m[D]	~3 to 7.7 m[D]
Waste package diameter	80 cm[E]	61 cm[F]
Waste package length	~4.8 m[G]	~4.6 m[G]
Waste package (overpack) material	Steel	No overpack
Approximate total loaded package weight	15 MT	5.5 MT
Minimum transport weight with total shielding equivalent to 15 cm of lead	> 34 MT	> 32 MT
Backfill material	Crushed salt (porosity ~36%, a few w/w percent moisture)	
Analogous international concept	Horizontal in-tunnel disposal of POLLUX casks containing consolidated SNF (Filbert et al. 2010a)	

[A] Allow 3 to 10 m between packages, and 30 m at each end of every emplacement drift for crushed salt backfill.
[B] Assume 33% extraction ratio; could be relaxed to provide 30-m wide pillars (Carter et al. 2012).
[C] Estimates of 20,000 to 30,000 HLW canisters, and the value shown for DOE-owned SNF, from Section 1.1.
[D] The larger spacing (up to 8.5 m) allows packages with height of up to 80 cm to be covered with crushed salt at a 35° angle of repose, to provide minimum shielding equivalent to 0.15 m of lead. Smaller spacings could be adequate for less gamma-emitting HLW canisters (e.g., Sr-bearing capsules).
[E] Assuming a 61 cm DSNF canister with overpack.
[F] Direct disposal of HLW canisters without overpack.
[G] Nominal based on 15-ft. canisters (DSNF has a heavy steel overpack); specifics may vary.

Preliminary Design Parameters Selected on the Basis of Design Criteria Thermal Analysis, 1/2

- Waste Package Emplacement Concept is simple and cost effective
  - Just-time- construction
    - Run-of-mine (ROM) salt from advancing drift used for backfill on adjacent drift post-emplacement
    - Minimizes ROM handling operation
    - Provides shielding for DSNF packages
  - The tranverse emplacement of packages keeps the repository footprint compact
  - DSNF overpack is robust, direct disposal of HLW reduces handling burden



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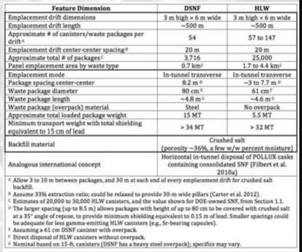
Preliminary Design Parameters Selected on the Basis of Design Criteria Thermal Analysis, 2/2

- Drift details
  - Drift length = 500m
    - ~50 DSNF packages per drift (~3000 total)
    - ~50-150 HLW packages per drift (~25,000 total)
    - 14m pillars could be increased to 30m, if necessary
  - Waste Package Spacing
    - DSNF - ~8m (center to center)
    - HLW - ~3 to7.7m (center to center)



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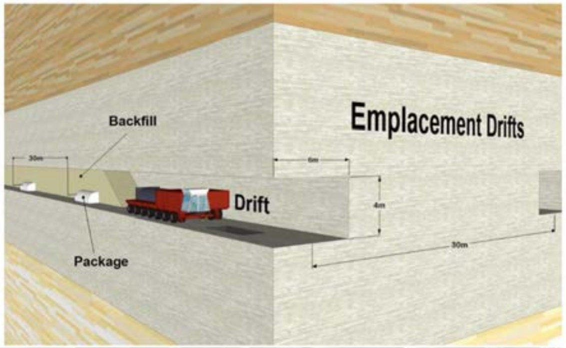
An Approximate Illustration of the Preliminary Design in Salt including notable differences



From Hardin et al. 2015

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Actinide and Brine Chemistry in a Salt Repository: Updates from ABC Salt (V)

Donald Reed (LANL)
Marcus Altmaier (KIT–INE

Middelburg, The Netherlands
September 5-7, 2017

LA-UR 17-27994

Overview

- ☐ Venue, Participation, and Overview of Workshop Sessions
- ☐ Key Results of Various Sessions
  - WIPP and International Updates
  - Salt Research Project Updates
  - Microbial Effects
  - Corrosion and Sorption
  - Modeling and Solubility Studies
  - Temperature Effects
  - Actinide Redox and Solubility
  - Special Topic Sessions: Solubility studies and Actinide Redox
- ☐ Overlap and Connectivity with Geotechnical Issues
- ☐ Summary and Announcement of ABC Salt (VI)

Venue

March 26-28, 2017
Convention Center, Ruidoso NM, USA

MCM Eleganté Lodge and Suites

Ruidoso Convention Center

Workshop Participation

Total Participants: 36
- ☐ ~ 28 Researchers/Staff
- ☐ 8 students or postdocs

Attendance from 5 Countries (but mainly USA and Germany)
- ☐ USA (26), Germany (7), France, Switzerland and UK

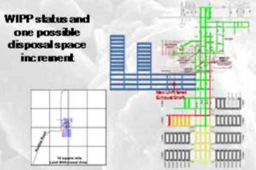
Institutional Involvement
- ☐ WIPP: DOE-CBFO, Los Alamos, Sandia
- ☐ German Labs: KIT/INE, HZDR and GRS
- ☐ Regulatory/Agency: EPA, NEA, NWRB, RWM
- ☐ Universities and others: FSU, ND, FIU, Freiberg, CEMRC/NMSU, AF-Consult

Overview of Sessions

Overview of ABC Salt (V) Workshop	
Sunday PM	Welcome from WIPP International Program Updates
Monday AM/PM	Project-Specific Updates (Salt Repository Research) Microbial Effects Studies Corrosion and Sorption Poster Session – all topics
Tuesday AM/PM	Modeling and Solubility Studies (Discussion: Solubility Experiments) Temperature Effects Redox and Actinide Chemistry (Discussion: Redox Chemistry)

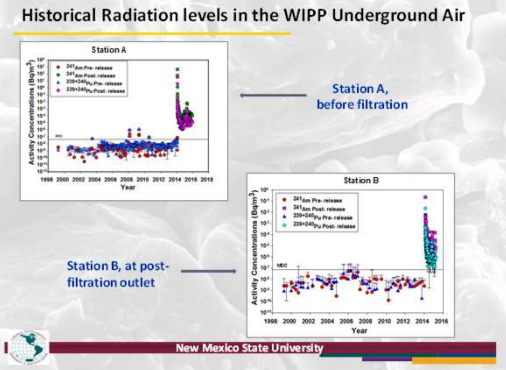
WIPP/International Updates

- ☐ WIPP-Specific Updates
  - Shipments were resumed on January 4
  - Full recovery process continues (currently estimated to be ~ 2021)
  - Progress on recertification was statused – this was predicted/expected – this has since been received (July 19, 2017)
  - Monitoring program continues to show compliance
- ☐ German Updates (Bernhard Kienzler)
- ☐ RWM (UK) high ionic strength research needs (Amy Shelton)



Main point: This has been a tough few years, but progress in key and essential areas continues

Historical data – WIPP Underground Air (from Punam Thakur, CEMRC)

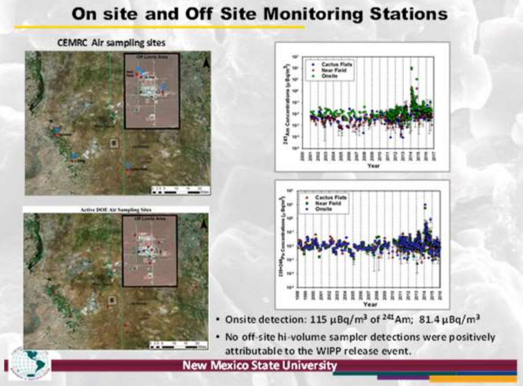


Historical Radiation levels in the WIPP Underground Air

Station A, before filtration

Station B, at post-filtration outlet

Offsite monitoring data
Punam Thakur (CEMRC)



On site and Off Site Monitoring Stations

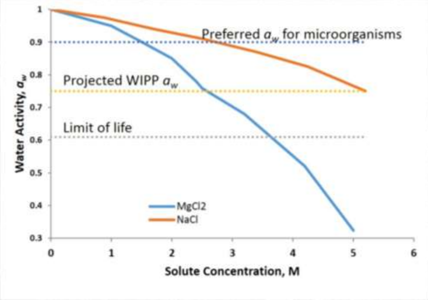
- Onsite detection: 115 µBq/m³ of ²⁴¹Am; 81.4 µBq/m³
- No off-site hi-volume sampler detections were positively attributable to the WIPP release event.

Microbial Effects

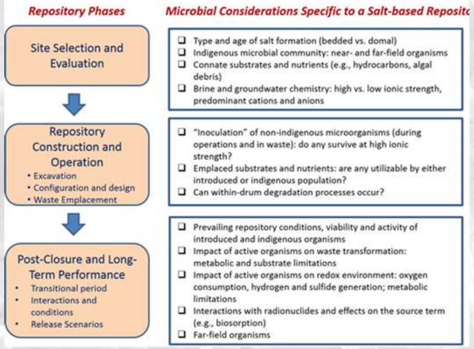
- ❑ Updates from both the WIPP project and HZDR (German) research were given.
- ❑ Key results:
  - ➢ We are seeing null results (no GG) under anoxic WIPP-specific conditions (this is consistent with prior results in the project)
  - ➢ No viable microorganisms have been identified under anaerobic conditions – this places the likely time of greatest microbial effects during the early repository times that are likely suboxic and lower I
  - ➢ High sorption and bioassociation is being observed over a range of pH and brine compositions with various microorganisms (bacteria >> archaea)

Status: Good progress is being made in this area. Remaining issues are in the areas of 1) defining microbial contributions to the source term and 2) a better understanding of the initial suboxic unsaturated time period

Relationship between water activity, Brine composition, and likely microbial activity (J. Swanson)



Repository phases and microbial issues to be considered for salt-based repositories. (Swanson et al, LAUR 16-28895)



Repository Phases

Microbial Considerations Specific to a Salt-based Reposit

Site Selection and Evaluation

- ❑ Type and age of salt formation (bedded vs. domal)
- ❑ Indigenous microbial community: near- and far-field organisms
- ❑ Connate substrates and nutrients (e.g., hydrocarbons, algal debris)
- ❑ Brine and groundwater chemistry: high vs. low ionic strength, predominant cations and anions

Repository Construction and Operation
- Excavation
- Configuration and design
- Waste Emplacement

- ❑ "Inoculation" of non-indigenous microorganisms (during operations and in waste): do any survive at high ionic strength?
- ❑ Emplaced substrates and nutrients: are any utilizable by either introduced or indigenous population?
- ❑ Can within-drum degradation processes occur?

Post-Closure and Long-Term Performance
- Transitional period
- Interactions and conditions
- Release Scenarios

- ❑ Prevailing repository conditions, viability and activity of introduced and indigenous organisms
- ❑ Impact of active organisms on waste transformation: metabolic and substrate limitations
- ❑ Impact of active organisms on redox environment: oxygen consumption, hydrogen and sulfide generation; metabolic limitations
- ❑ Interactions with radionuclides and effects on the source term (e.g., biosorption)
- ❑ Far-field organisms

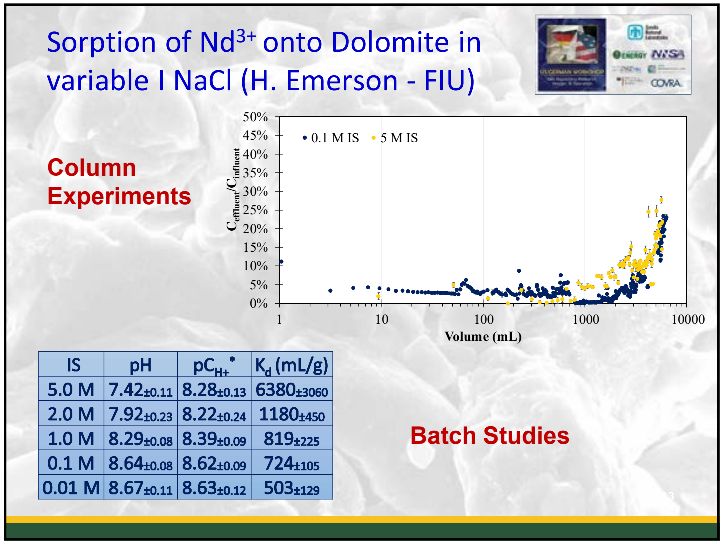
Corrosion and Sorption

Sorption

- Collaborative work between FIU and Los Alamos were presented on sorption (H. Emerson and T. Dietrich).
- Not a high priority for the WIPP project as to far-field interactions (small potential contribution to overall release)
- Potential contributions that affect the actinide source term are important and being investigated (but we do not fully account for sorption in the source term).

Corrosion

- INE (B. Kienzler) presented a summary of 10 year corrosion data in salt (these are largely consistent as to mass loss data)
- New KORSO Project (Corrosion and sorption processes onto steel surfaces at elevated temperatures under saline conditions) was announced.

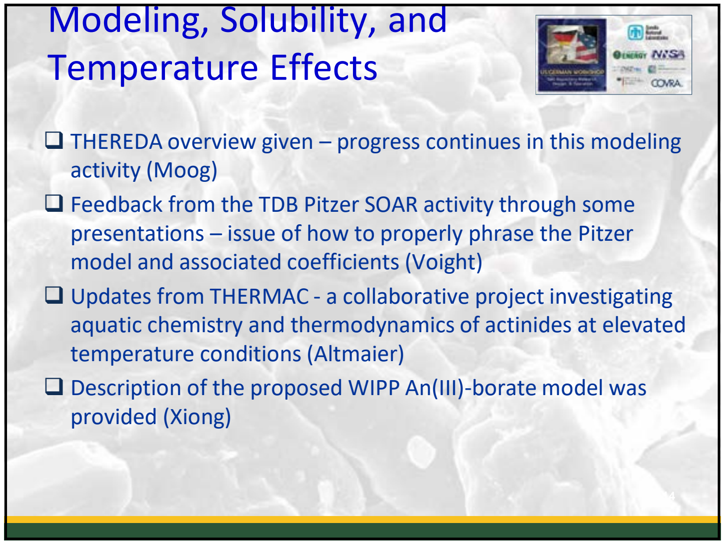


Sorption of Nd^{3+} onto Dolomite in variable I NaCl (H. Emerson - FIU)

Column Experiments

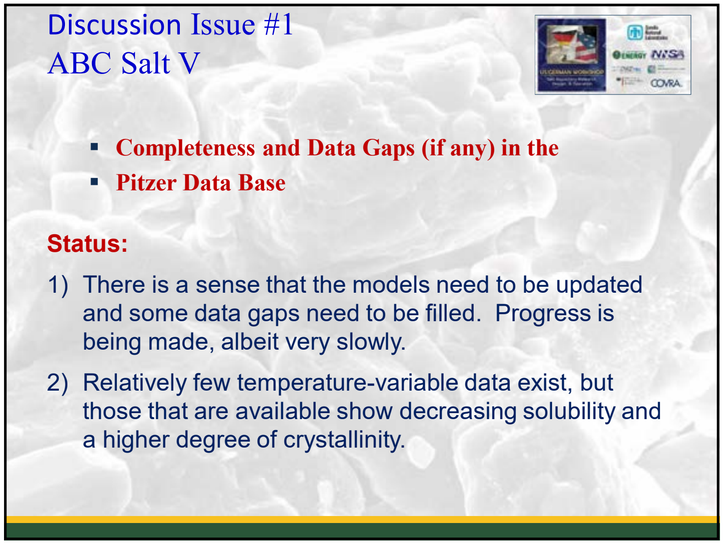
IS	pH	pC_{H+}*	K_d (mL/g)
5.0 M	7.42±0.11	8.28±0.13	6380±3060
2.0 M	7.92±0.23	8.22±0.24	1180±450
1.0 M	8.29±0.08	8.39±0.09	819±225
0.1 M	8.64±0.08	8.62±0.09	724±105
0.01 M	8.67±0.11	8.63±0.12	503±129

Batch Studies



Modeling, Solubility, and Temperature Effects

- ☐ THEREDA overview given – progress continues in this modeling activity (Moog)
- ☐ Feedback from the TDB Pitzer SOAR activity through some presentations – issue of how to properly phrase the Pitzer model and associated coefficients (Voight)
- ☐ Updates from THERMAC - a collaborative project investigating aquatic chemistry and thermodynamics of actinides at elevated temperature conditions (Altmaier)
- ☐ Description of the proposed WIPP An(III)-borate model was provided (Xiong)

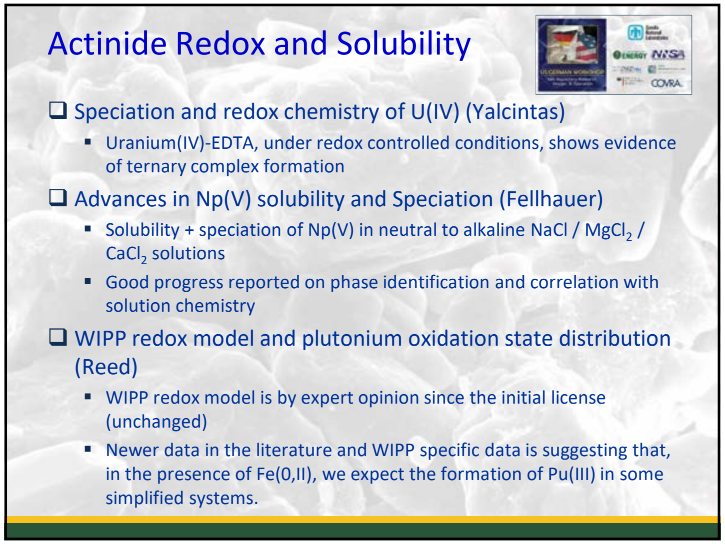


Discussion Issue #1
ABC Salt V

- **Completeness and Data Gaps (if any) in the**
- **Pitzer Data Base**

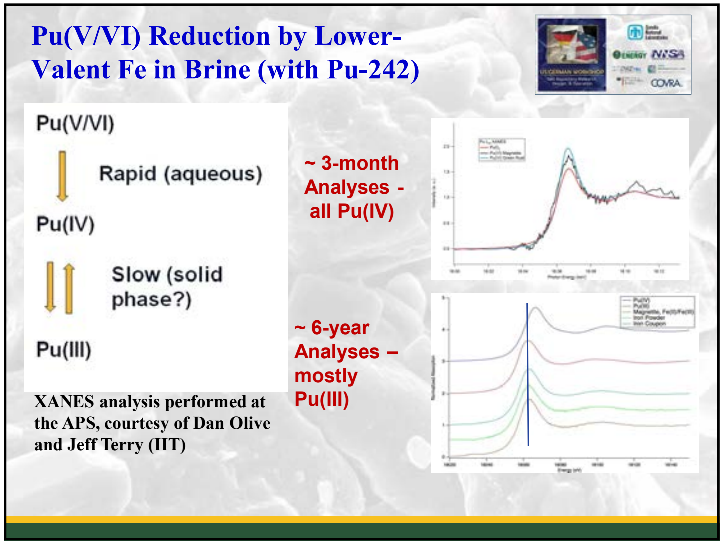
Status:

1) There is a sense that the models need to be updated and some data gaps need to be filled. Progress is being made, albeit very slowly.
2) Relatively few temperature-variable data exist, but those that are available show decreasing solubility and a higher degree of crystallinity.



Actinide Redox and Solubility

- ☐ Speciation and redox chemistry of U(IV) (Yalcintas)
  - Uranium(IV)-EDTA, under redox controlled conditions, shows evidence of ternary complex formation
- ☐ Advances in Np(V) solubility and Speciation (Fellhauer)
  - Solubility + speciation of Np(V) in neutral to alkaline NaCl / $MgCl_2$ / $CaCl_2$ solutions
  - Good progress reported on phase identification and correlation with solution chemistry
- ☐ WIPP redox model and plutonium oxidation state distribution (Reed)
  - WIPP redox model is by expert opinion since the initial license (unchanged)
  - Newer data in the literature and WIPP specific data is suggesting that, in the presence of Fe(0,II), we expect the formation of Pu(III) in some simplified systems.

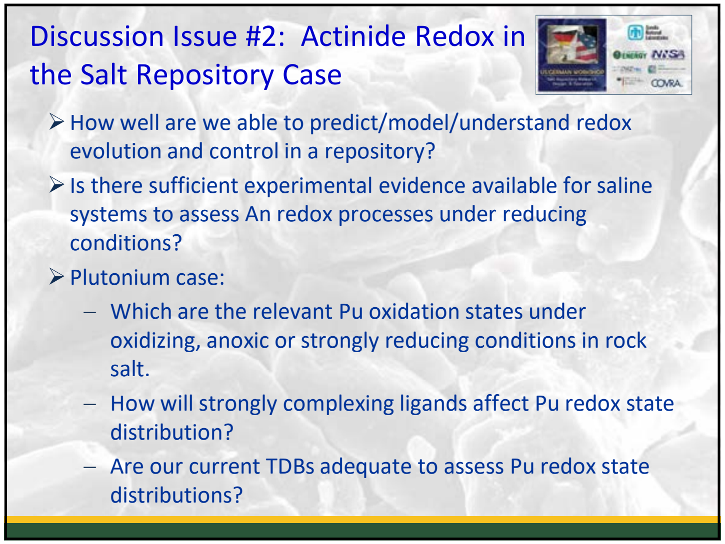


Pu(V/VI) Reduction by Lower-Valent Fe in Brine (with Pu-242)

~ 3-month Analyses - all Pu(IV)

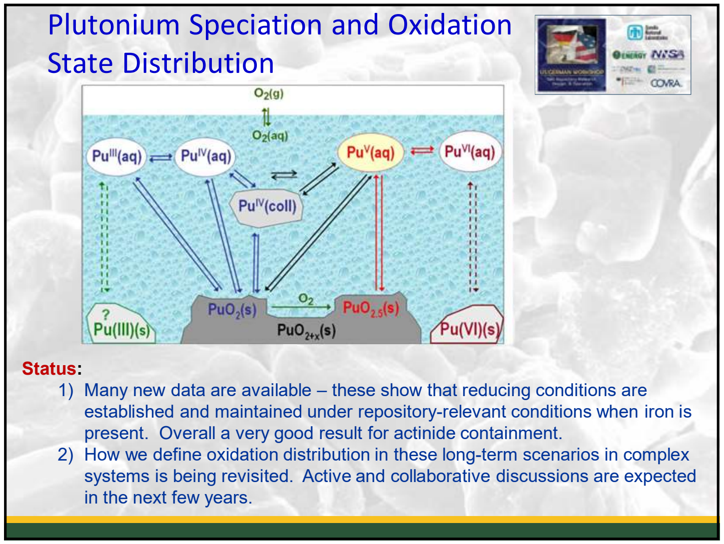
~ 6-year Analyses – mostly Pu(III)

XANES analysis performed at the APS, courtesy of Dan Olive and Jeff Terry (IIT)



Discussion Issue #2: Actinide Redox in the Salt Repository Case

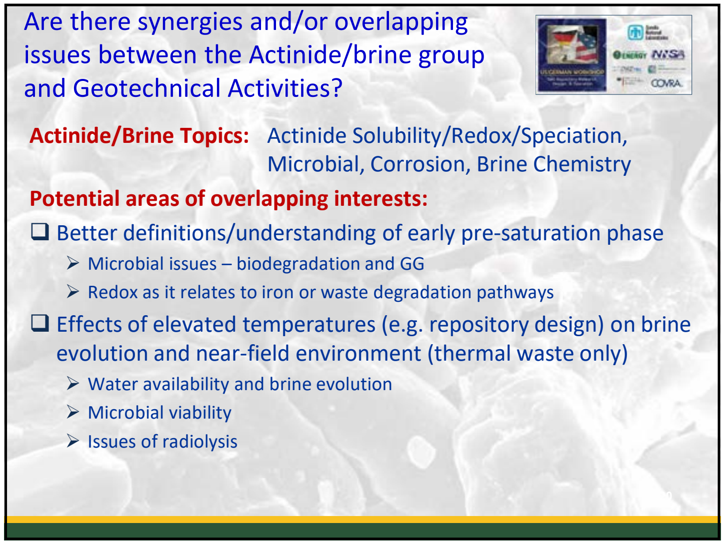
- How well are we able to predict/model/understand redox evolution and control in a repository?
- Is there sufficient experimental evidence available for saline systems to assess An redox processes under reducing conditions?
- Plutonium case:
  - Which are the relevant Pu oxidation states under oxidizing, anoxic or strongly reducing conditions in rock salt.
  - How will strongly complexing ligands affect Pu redox state distribution?
  - Are our current TDBs adequate to assess Pu redox state distributions?



Plutonium Speciation and Oxidation State Distribution

Status:

1) Many new data are available – these show that reducing conditions are established and maintained under repository-relevant conditions when iron is present. Overall a very good result for actinide containment.
2) How we define oxidation distribution in these long-term scenarios in complex systems is being revisited. Active and collaborative discussions are expected in the next few years.



Are there synergies and/or overlapping issues between the Actinide/brine group and Geotechnical Activities?

Actinide/Brine Topics: Actinide Solubility/Redox/Speciation, Microbial, Corrosion, Brine Chemistry

Potential areas of overlapping interests:

- ☐ Better definitions/understanding of early pre-saturation phase
  - Microbial issues – biodegradation and GG
  - Redox as it relates to iron or waste degradation pathways
- ☐ Effects of elevated temperatures (e.g. repository design) on brine evolution and near-field environment (thermal waste only)
  - Water availability and brine evolution
  - Microbial viability
  - Issues of radiolysis

Key Results and Observations

- ❑ Welcome presentation by Tod Shrader (Manager, DOE-CBFO) that announced that the WIPP had re-opened and is again receiving waste.
- ❑ Outstanding discussion throughout the workshop – a good mix of attendees.
- ❑ Excellent discussions on actinide solubility studies and redox – these led to recommendations for future direction/focus.
- ❑ Plenary talk by Marilena Ragoussi (NEA-TDB) on database activities (there was also a coupled Pitzer SOAR meeting after the workshop).
- ❑ Salt repository research continues (despite distractions) – this shows that Salt continues to be a good geology for nuclear waste disposal.

Sponsorship and Support

This workshop is co-organized by Los Alamos and KIT-INE. We wish to acknowledge and express thanks to the following support and sponsorship:

	Department of Energy, Carlsbad Field Office (DOE-CBFO) for programmatic support
	Carlsbad Environmental Monitoring and Research Center (CEMRC) for sponsoring the Sunday PM reception, AV support, and staff support for the logistics of the workshop
NEA	Nuclear Energy Agency (NEA), this workshop is a listed activity of the NEA Salt Club
Federal Ministry for Economic Affairs and Energy	Federal Ministry for Economic Affairs and Energy (Germany) for programmatic support
Los Alamos NATIONAL LABORATORY	Los Alamos National Laboratory Civilian Nuclear Programs Office and Conference Management team for logistical support

ABC Salt Workshop

ABC Salt V Workshop, Ruidoso NM USA
March 26-28, 2017

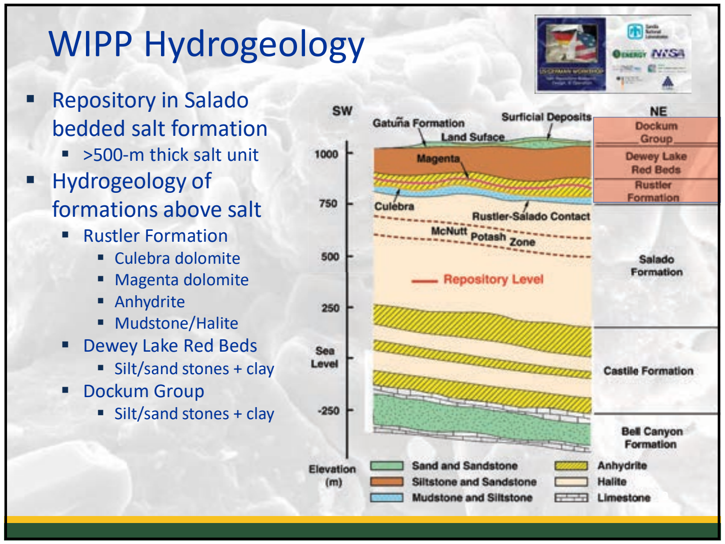
ABC-Salt (VI) is tentatively planned for Spring/Summer of 2019 and will be combined with HITAC and hosted by KIT/INE in Germany

Basin-Scale Density-Dependent Groundwater Flow Near a Salt Repository

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

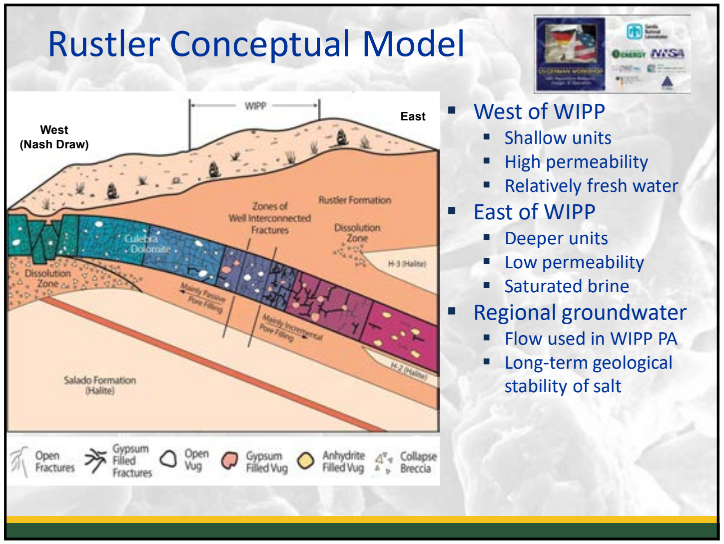
Middelburg, The Netherlands
September 5-7, 2017

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2017-9392 C.



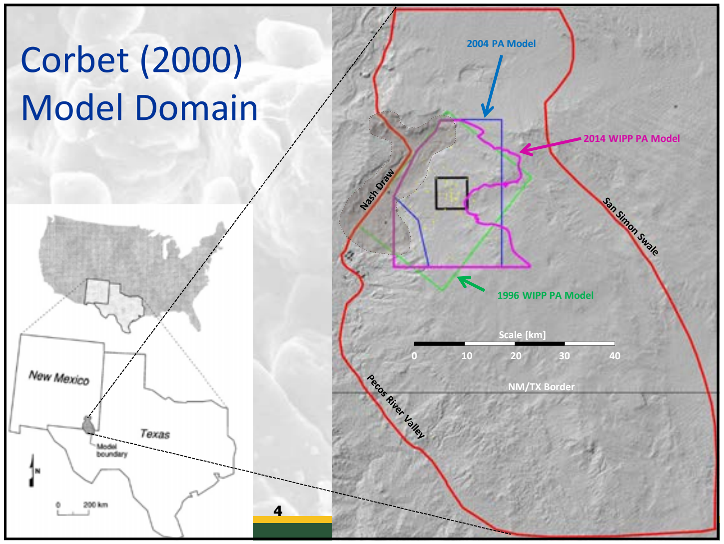
WIPP Hydrogeology

- 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

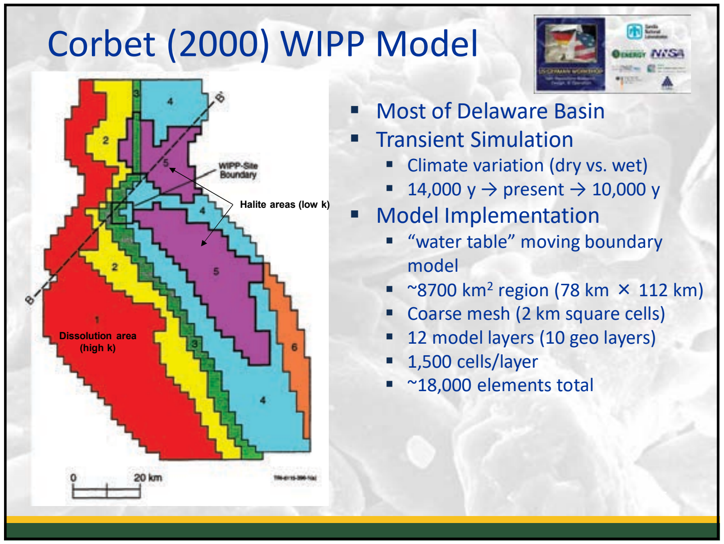


Rustler Conceptual Model

- 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

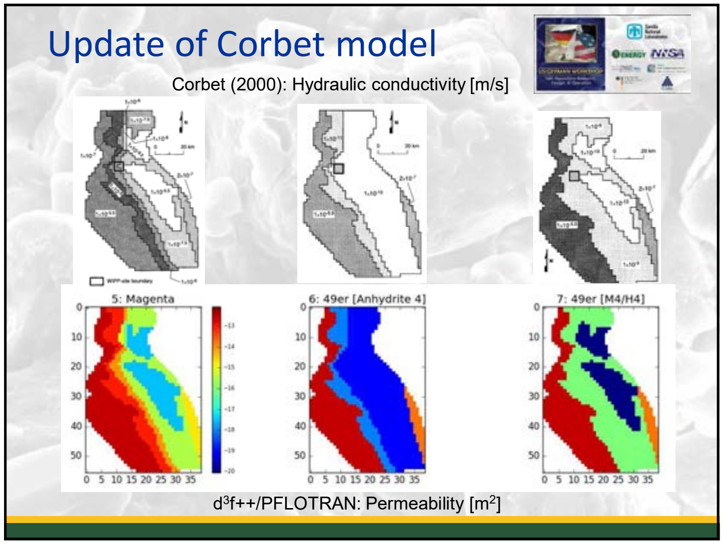


Corbet (2000) WIPP Model

- 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

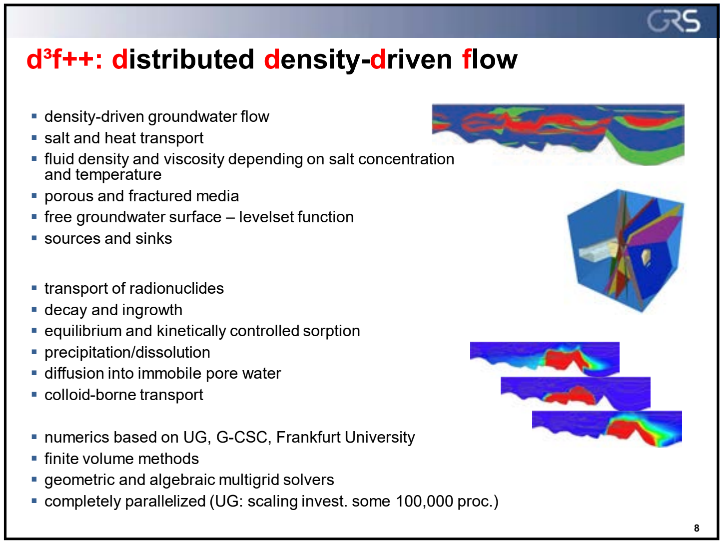
- Benchmark against existing solution (Corbet, 2000)
- Comparison with original model
  - Old mesh, model parameters & boundary conditions
- Include new processes, features & data
  - Include density-driven flow (e.g., Davies, 1989)
  - Include chemistry & mineral dissolution
  - Investigate flow & chemistry 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)



Update of Corbet model

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

d^{3}f++/PFLOTRAN: Permeability [m^2]

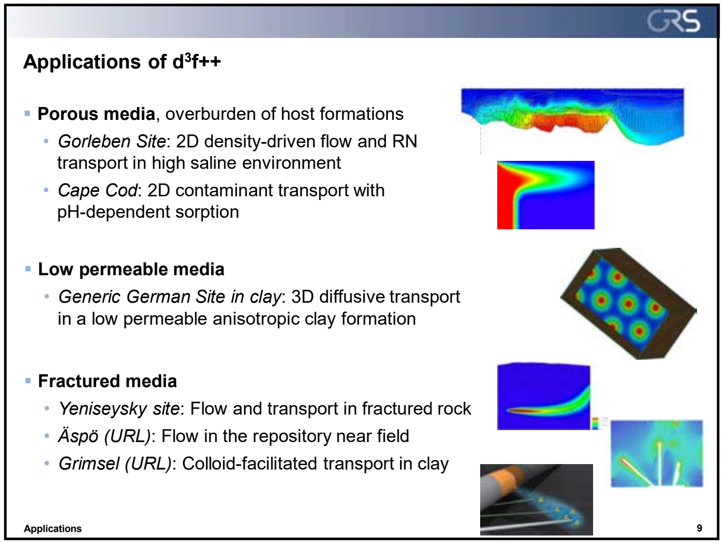


d³f++: distributed density-driven flow

- 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

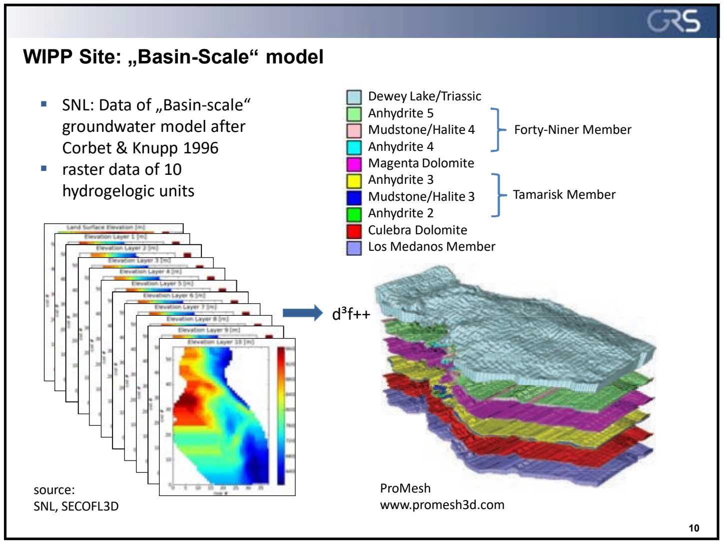
- transport of radionuclides
- decay and ingrowth
- equilibrium and kinetically controlled sorption
- precipitation/dissolution
- diffusion into immobile pore water
- colloid-borne transport

- 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

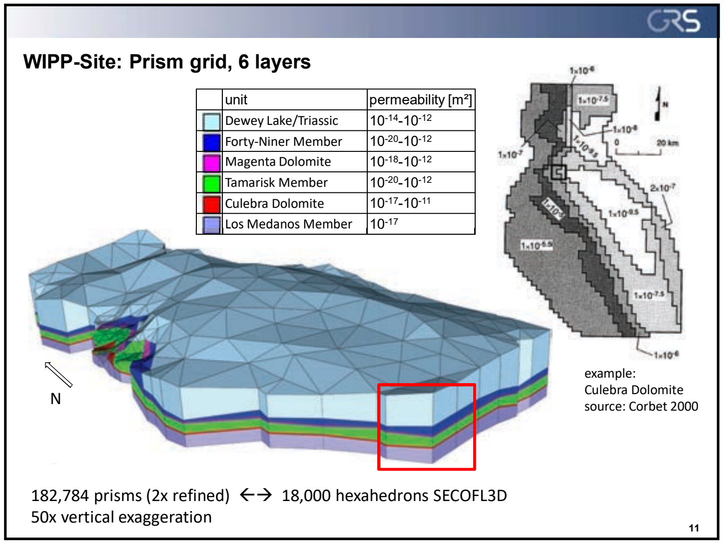


WIPP Site: „Basin-Scale“ model

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

source:
SNL, SECOFL3D

ProMesh
www.promesh3d.com

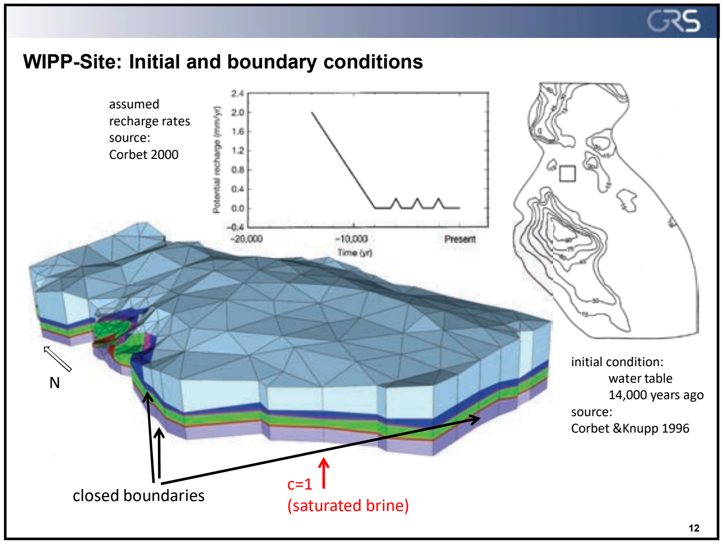


WIPP-Site: Prism grid, 6 layers

	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



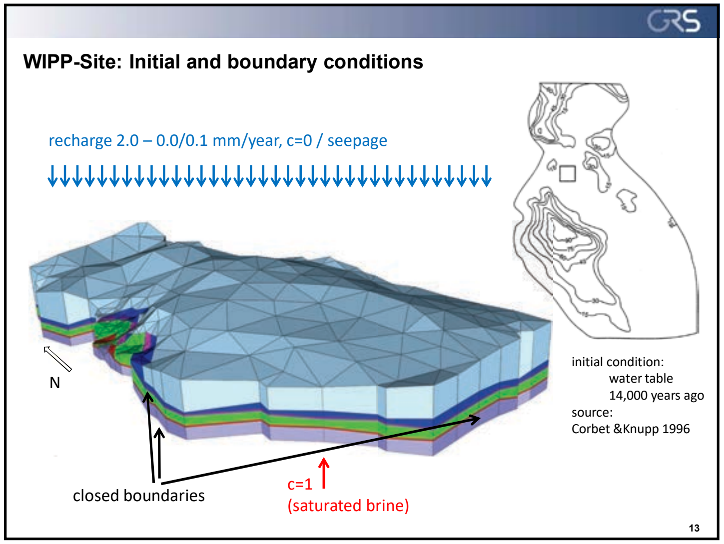
WIPP-Site: Initial and boundary conditions

assumed
recharge rates
source:
Corbet 2000

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

closed boundaries

c=1
(saturated brine)



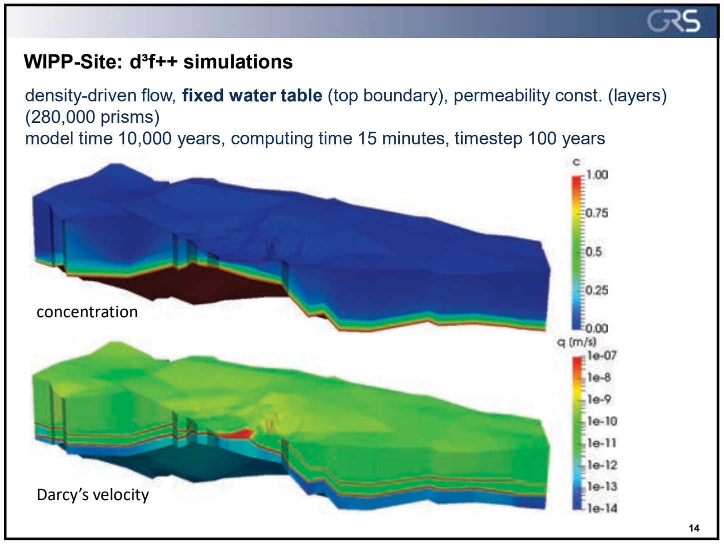
WIPP-Site: Initial and boundary conditions

recharge 2.0 – 0.0/0.1 mm/year, c=0 / seepage

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

closed boundaries

c=1
(saturated brine)

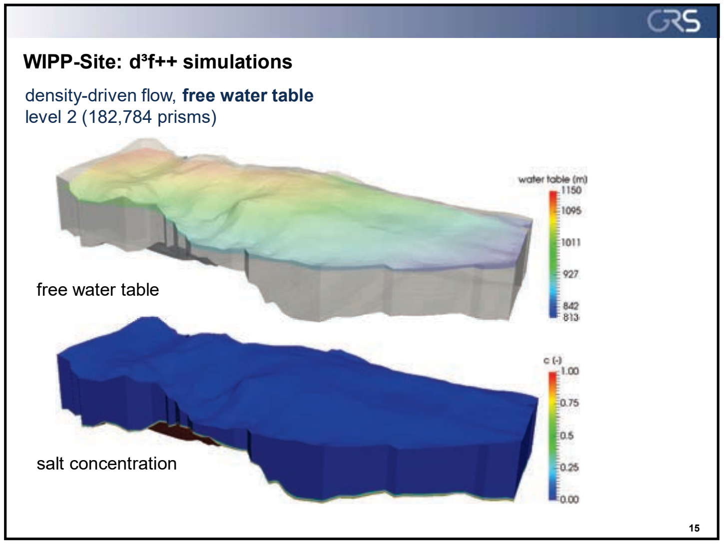


WIPP-Site: d³f++ simulations

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

concentration

Darcy's velocity

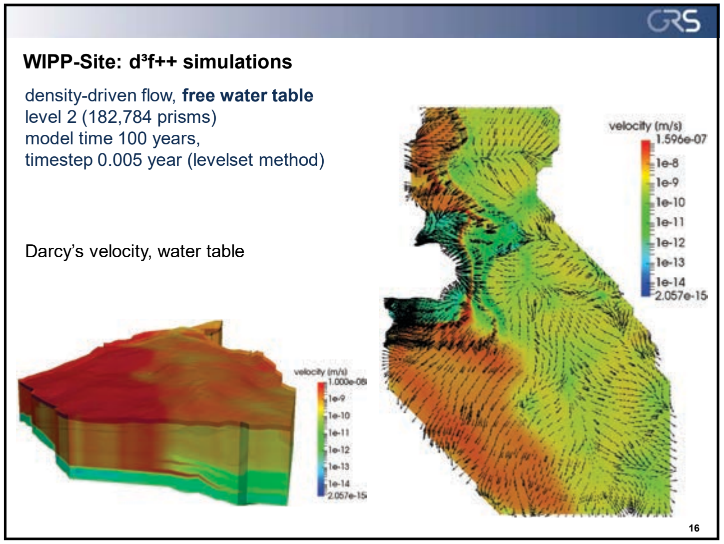


WIPP-Site: d³f++ simulations

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

free water table

salt concentration



WIPP-Site: d³f++ simulations

density-driven flow, **free water table**
level 2 (182,784 prisms)
model time 100 years,
timestep 0.005 year (levelset method)

Darcy's velocity, water table

Summary and outlook

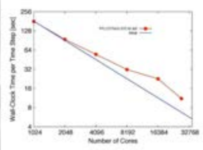
Difficulties:
- non steady-state density-driven flow model
- strongly anisotropic (thin layers, jumping coefficients)
- free groundwater surface 8,700 km²

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
- simulation 14.000 years past
- reproduction of SECOFL3D results (Corbet & Knupp, 1996)

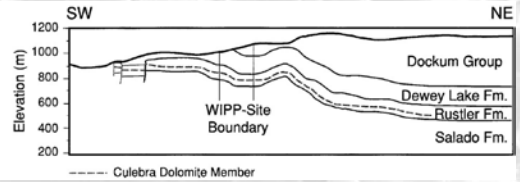
PFLOTRAN

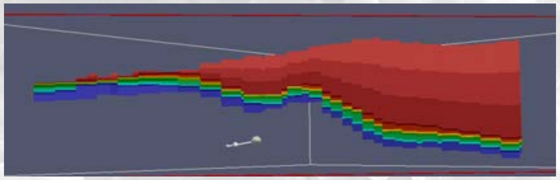
- Reactive multiphase flow and transport code for porous media
- Open source license (GNU LGPL 2.0)
- Object-oriented Fortran 2003/2008
  - Pointers to procedures
  - Classes (extendable derived types with member procedures)



- Founded upon well-known (supported) open source libraries
  - MPI, PETSc, HDF5, METIS/ParMETIS/CMAKE
- Demonstrated performance
  - Maximum # processes: 262,144 (Jaguar supercomputer)
  - Maximum problem size: 3.34 billion degrees of freedom
  - Scales well to over 10K cores

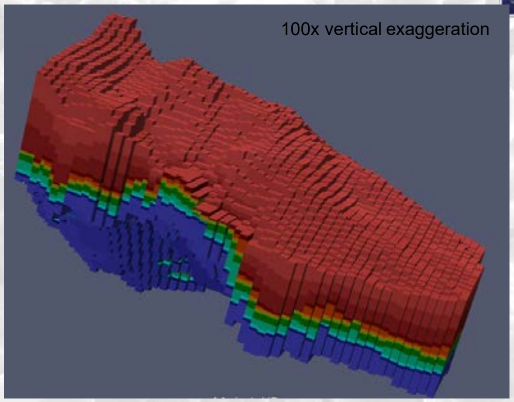
SNL PFLOTRAN version





~25x vertical exaggeration

SNL PFLOTRAN version



Original Mesh: 13-layer hexahedral (cuboid) elements (18,000 elements)

Issues Encountered

- Old Mesh is very coarse
  - **PFLOTRAN and d^{3}f++ have difficulty with mesh**
  - Mesh violates conventions regarding
    - Regularity (Δz varies too much in space)
    - **Connectivity (must build mesh “by hand”)**
    - Aspect ratio (2 km × 2 km × 1s-100s m)
  - Anke (GRS): re-mesh using modern tools (LARGE)
  - Kris (SNL): struggle with old mesh (COARSE)
- Moving water table ≠ Richards equation
  - Unsaturated flow parameters are guessed
  - Recharge applied at water table vs. applied at land surface
- CFL condition requires very small time steps
- Too few elements to capitalize on parallel
- Smaller elements → smaller time steps!

Schedule

Year 1

- **SECOFL3D data provided by SNL**
- **GRS begins building d^{3}f++ model**
- **SNL begins building PFLOTRAN model**
- **SNL consults**

Year 2

- **GRS builds d^{3}f++ model equivalent to Corbet (2000)**
- **SNL builds PFLOTRAN equivalent to Corbet (2000)**
- **GRS ‘includes’ density-driven flow**
- **SNL includes density-driven flow to PFLOTRAN**

+Year

- **WIPP basin-scale model is:**
  - **Numerically difficult**
  - **Uses non-ideal mesh (pancake elements)**
  - **Has complex boundary conditions**
- **Try benchmarking simpler (2D) problems:**
  - **Compare processes**
  - **Use PFLOTRAN QA suite problem?**

Thank you for your attention!

Supported by:
Federal Ministry of Economics and Energy
on the basis of a decision by the German Bundestag

Current research on deep borehole disposal of nuclear spent fuel and high-level radioactive waste - considerations within a German research project

Tino Rosenzweig
TU Bergakademie Freiberg

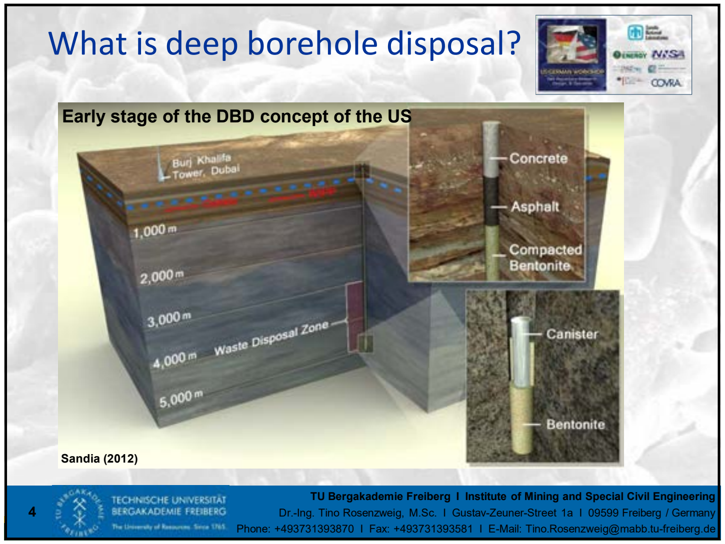
Middelburg, The Netherlands
September 5-7, 2017

Research Team and Co-Authors

- Prof. Matthias Reich - Christin Dieterichs	TU Bergakademie Freiberg Institute of Drilling Engineering and Fluid Mining
- Prof. Wolfram Kudla - Dr. Tino Rosenzweig	TU Bergakademie Freiberg Institute of Mining and Special Civil Engineering
- Wilhelm Bollingerfehr - Maxi Herold	DBE TECHNOLOGY GmbH Department research and development
- COORDINATION:	Karlsruhe Institute of Technology (KIT) Project Management Agency Karlsruhe (PTKA)

Content

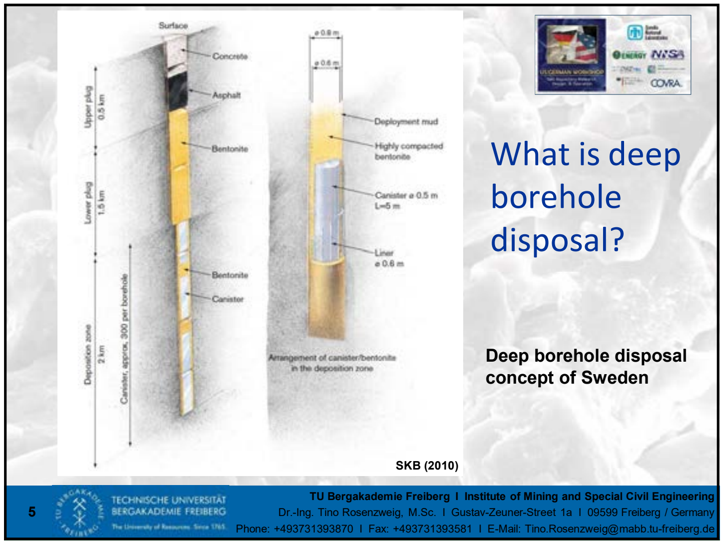
- What is deep borehole disposal?
- What are the challenges?
- What is the aim of the research project?
- What was our approach to solve the task?
- First results of the research project
- Summary



What is deep borehole disposal?

Early stage of the DBD concept of the US

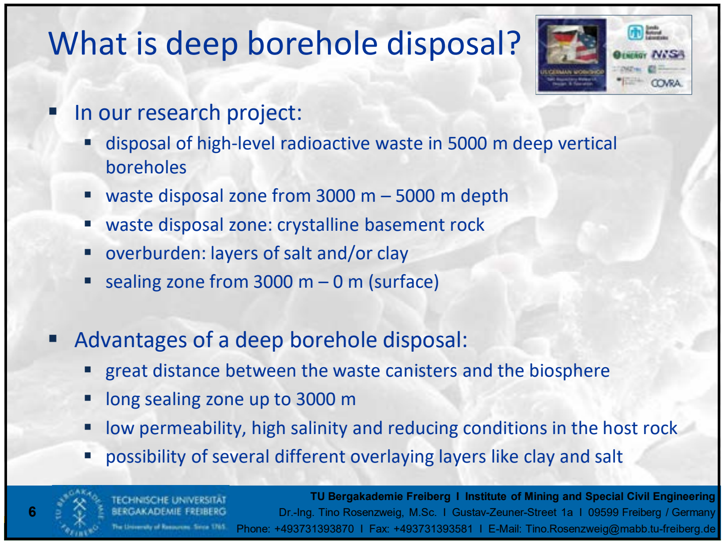
Sandia (2012)



SKB (2010)

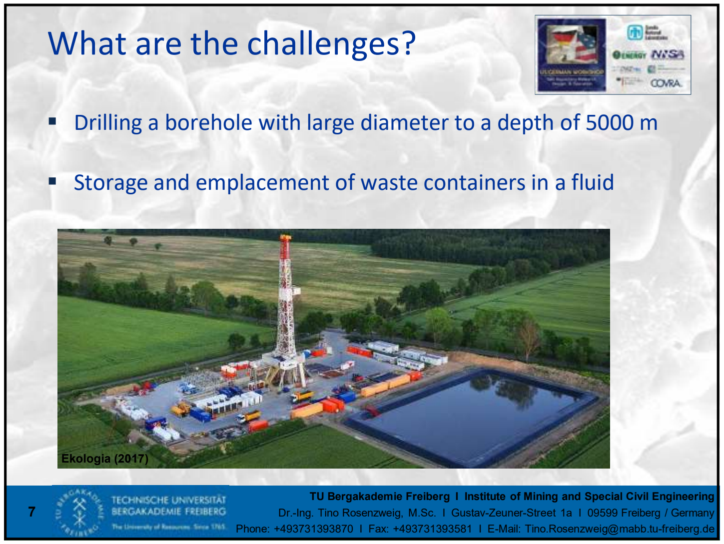
What is deep borehole disposal?

Deep borehole disposal concept of Sweden



What is deep borehole disposal?

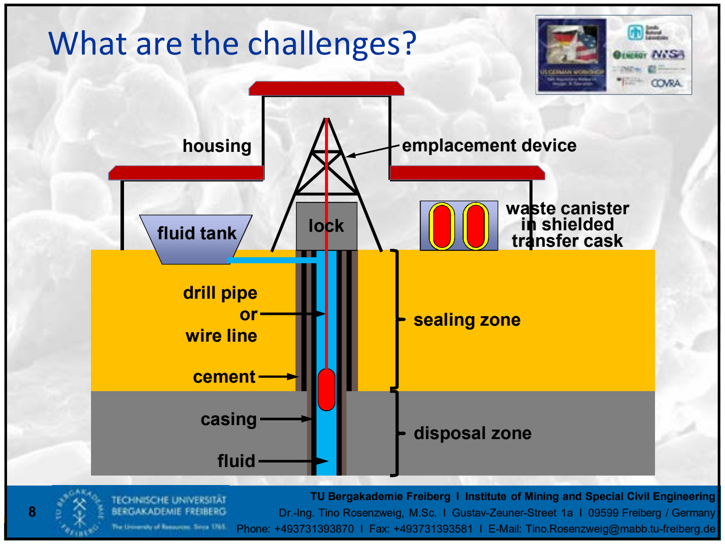
- In our research project:
  - disposal of high-level radioactive waste in 5000 m deep vertical boreholes
  - waste disposal zone from 3000 m – 5000 m depth
  - waste disposal zone: crystalline basement rock
  - overburden: layers of salt and/or clay
  - sealing zone from 3000 m – 0 m (surface)
- Advantages of a deep borehole disposal:
  - great distance between the waste canisters and the biosphere
  - long sealing zone up to 3000 m
  - low permeability, high salinity and reducing conditions in the host rock
  - possibility of several different overlaying layers like clay and salt



What are the challenges?

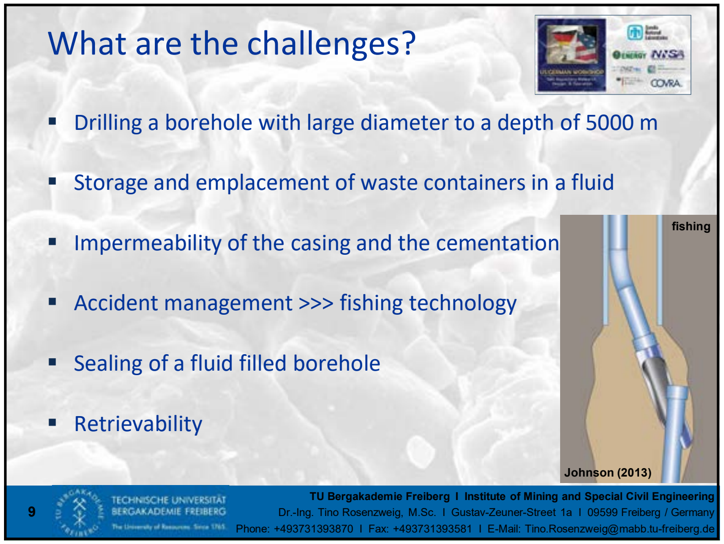
- Drilling a borehole with large diameter to a depth of 5000 m
- Storage and emplacement of waste containers in a fluid

Ekologia (2017)



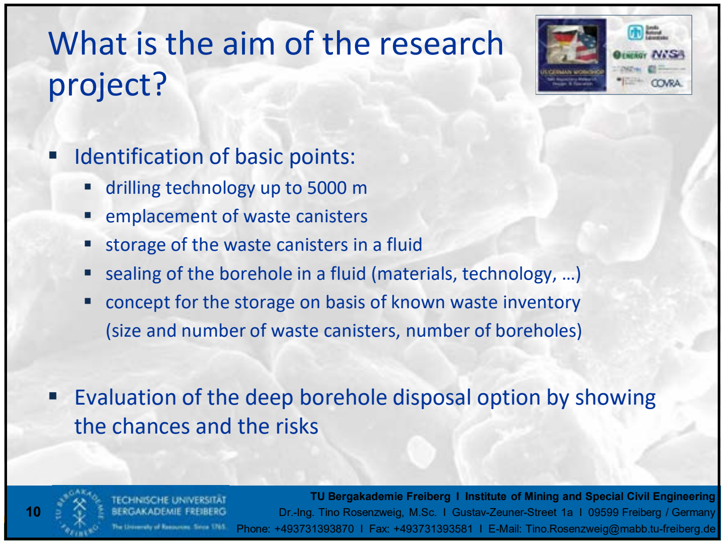
What are the challenges?

housing
emplacement device
fluid tank
lock
waste canister in shielded transfer cask
drill pipe or wire line
sealing zone
cement
casing
disposal zone
fluid



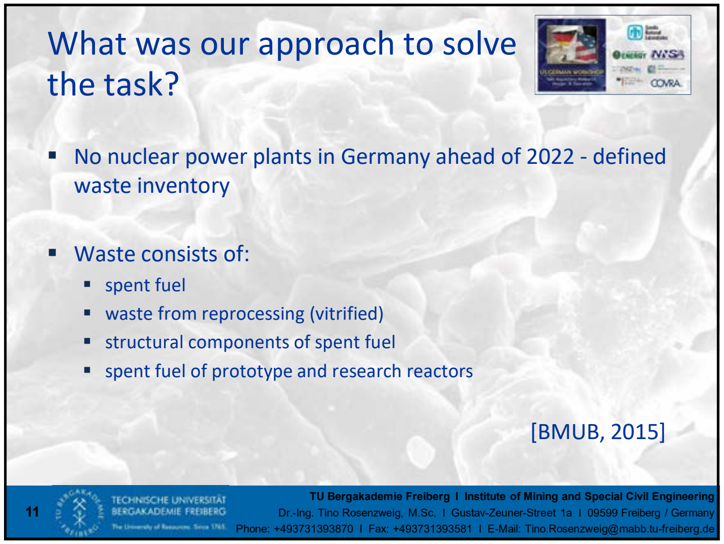
What are the challenges?

- Drilling a borehole with large diameter to a depth of 5000 m
- Storage and emplacement of waste containers in a fluid
- Impermeability of the casing and the cementation
- Accident management >>> fishing technology
- Sealing of a fluid filled borehole
- Retrievability



What is the aim of the research project?

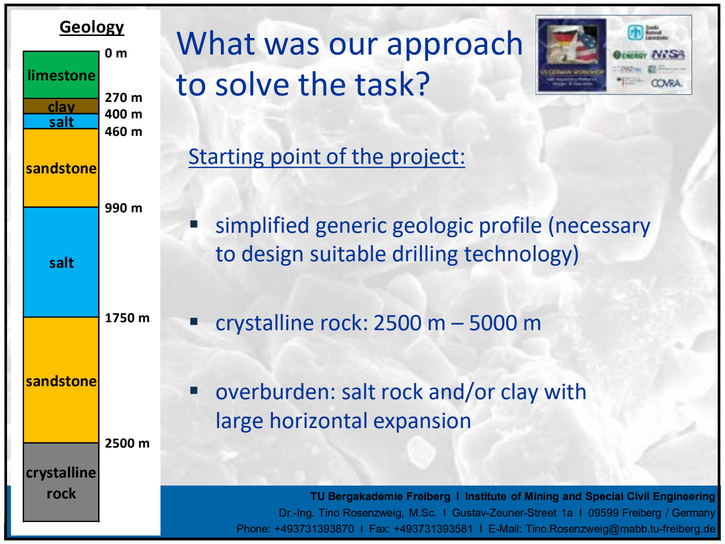
- Identification of basic points:
  - drilling technology up to 5000 m
  - emplacement of waste canisters
  - storage of the waste canisters in a fluid
  - sealing of the borehole in a fluid (materials, technology, …)
  - concept for the storage on basis of known waste inventory (size and number of waste canisters, number of boreholes)
- Evaluation of the deep borehole disposal option by showing the chances and the risks



What was our approach to solve the task?

- No nuclear power plants in Germany ahead of 2022 - defined waste inventory
- Waste consists of:
  - spent fuel
  - waste from reprocessing (vitrified)
  - structural components of spent fuel
  - spent fuel of prototype and research reactors

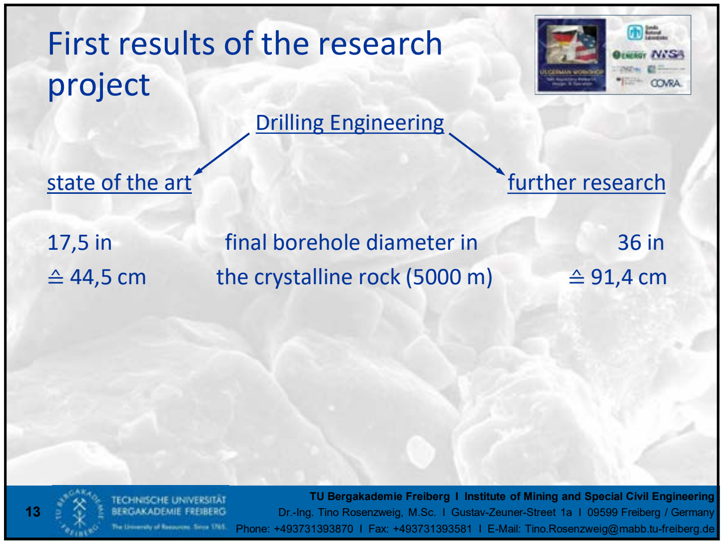
[BMUB, 2015]



What was our approach to solve the task?

Starting point of the project:

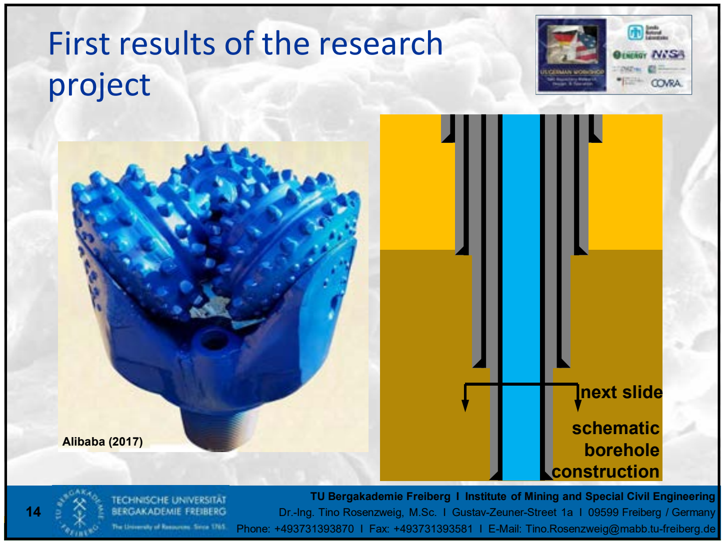
- simplified generic geologic profile (necessary to design suitable drilling technology)
- crystalline rock: 2500 m – 5000 m
- overburden: salt rock and/or clay with large horizontal expansion



First results of the research project

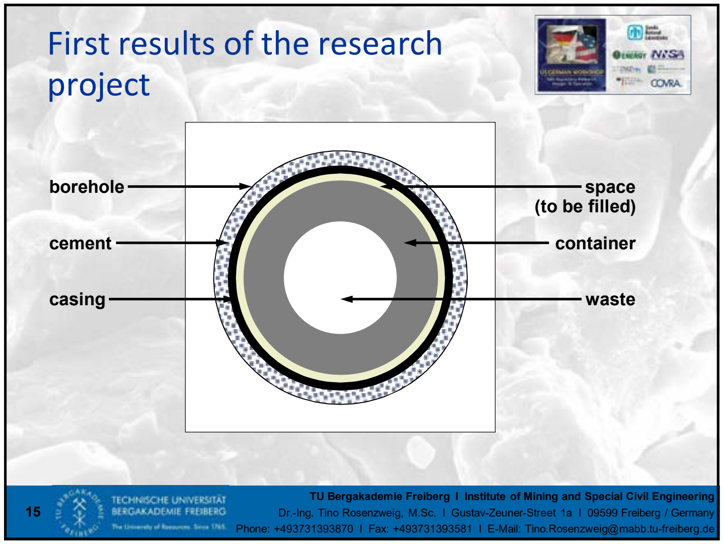
Drilling Engineering

state of the art		further research
17,5 in	final borehole diameter in	36 in
≙ 44,5 cm	the crystalline rock (5000 m)	≙ 91,4 cm

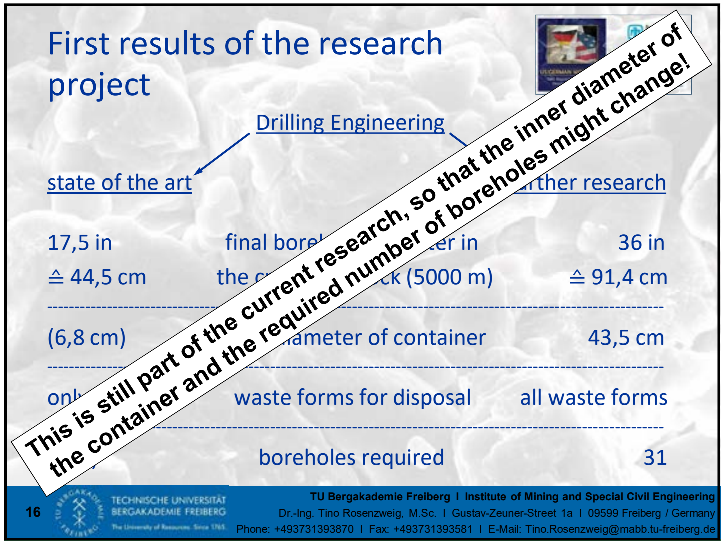


First results of the research project

Alibaba (2017)



First results of the research project

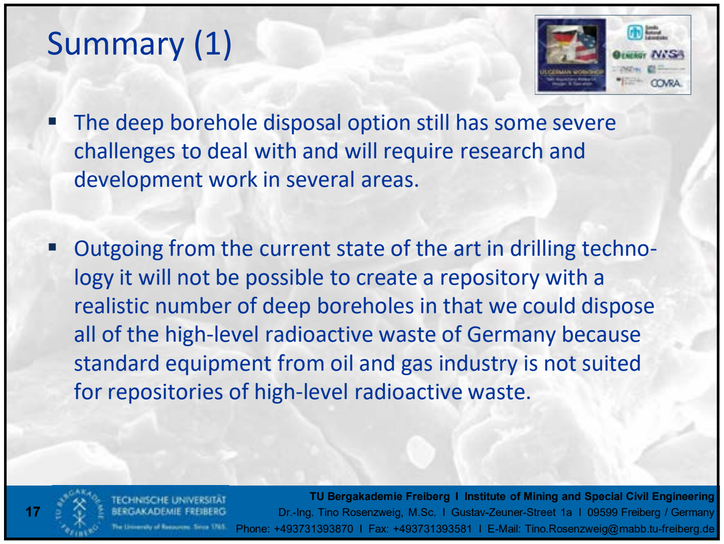


First results of the research project

Drilling Engineering

state of the art		rther research
17,5 in	final bore er in	36 in
≙ 44,5 cm	the c ck (5000 m)	≙ 91,4 cm
(6,8 cm)	ameter of container	43,5 cm
onl	waste forms for disposal	all waste forms
	boreholes required	31

This is still part of the current research, so that the inner diameter of the container and the required number of boreholes might change!



Summary (1)

- The deep borehole disposal option still has some severe challenges to deal with and will require research and development work in several areas.
- Outgoing from the current state of the art in drilling technology it will not be possible to create a repository with a realistic number of deep boreholes in that we could dispose all of the high-level radioactive waste of Germany because standard equipment from oil and gas industry is not suited for repositories of high-level radioactive waste.

Summary (2)

- There are still some unsolved problems that might never be solved specifically the issue of retrievability, which is demanded in Germany.
- By solving the uncertainty of retrievability and with further research especially in drilling technology (development of required technology appears feasible - provided there will be a "market" for the service companies), the deep borehole disposal option could be an alternative for the future.

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Thank you for your attention!

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