Proceedings of the 7th US/German Workshop on Salt Repository Research, Design, and Operation

Spent Fuel and Waste Disposition

Prepared for
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SUMMARY

The 7th US/German Workshop on Salt Repository Research, Design, and Operation was held in Washington, DC on September 7-9, 2016. Over fifty participants representing governmental agencies, internationally recognized salt research groups, universities, and private companies helped advance the technical basis for salt disposal of radioactive waste. Representatives from several United States federal agencies were able to attend, including the Department of Energy´s Office of Environmental Management and Office of Nuclear Energy, the Environmental Protection Agency, the Nuclear Regulatory Commission, and the Nuclear Waste Technical Review Board. A similar representation from the German ministries showcased the covenant established in a Memorandum of Understanding executed between the United States and Germany in 2011. The US/German workshops´ results and activities also contribute significantly to the Nuclear Energy Agency Salt Club repository research agenda.

United States and German salt repository scientists and engineers have a lengthy history of collaboration in experimental rock physics, underground testing, geomechanical modeling, seal system design and evaluation, repository design and demonstration, and numerous subsidiary investigations. When annual workshops reinitiated in 2010, organizers committed to focus on selected technical issues. Fundamental investigations, such as geomechanical modeling and the safety case, are central and long-term. However, the US/German workshop agenda also reflects emerging issues, such as percolation and operational safety, explored in the 2016 workshop. An evolving agenda for 2017 concludes these Proceedings.

Key subjects at the 7th US/German workshop included the safety case, operational safety, geomechanics, plugging and sealing, and percolation. The current Proceedings continues a practice of highlighting key technical issues in individual Chapters and these topics provide Chapter titles within this document. Expert participants contribute Chapters that are internally reviewed by peers. A list of Chapter authors is provided in the Acknowledgements section. Also in this document are the final technical agenda, list of participants, biographical information, abstracts, and presentations. Proceedings of all workshops and other pertinent information are posted on websites hosted by Sandia National Laboratories and the Nuclear Energy Agency Salt Club. Proceedings can also be found easily by searching the internet.

The US/German workshops provide knowledge preservation, where information is mature and well-known, continuity for ongoing long-term research, as well as a means to address arising issues. Knowledge documentation, incorporated by the Proceedings itself, provides an exposé of each topic and significant reference citations for further investigation. Workshop participants have historically developed ongoing research pursuits after review and discussion. Address of open or arising issues is commonly worked into the agenda, as well as special topics. In the following Proceedings, five selected topics are developed in detail.

Safety Case. Comparisons are made between German and US approaches to establishing robustness within a safety case. Guideline documents published by knowledgeable agencies provide functional references; however, participants in these workshops have developed actual safety cases for repository licensing (US) or advanced safety case/safety assessment approaches and applications (Netherlands, Germany). Processes and an associated program time-line are illustrated in this Chapter. Added confidence in a safety case derives from natural analogues, safety indicators, and inclusion of stakeholder concerns. Germany and US salt repository programs are now performing generic studies while addressing features, events, and processes; treating uncertainty; and relating operational and long-term safety.

Operational Safety. In view of developments at the Waste Isolation Pilot Plant the concept of safety by design or engineered safety is at the forefront of salt repository concerns. In 2016, the International Atomic Energy Agency and Nuclear Energy Agency organized a workshop in Paris to review guiding principles of operational safety. Beginning with an overview from that workshop, participants of the 7th US/German workshop compared real-life examples of operational safety experiences at the Waste Isolation Pilot Plant against five overarching safety challenges identified by Paris workshop participants. The notion of a safety culture was a recurring theme. Operators and management at WIPP were cited

for allowing a culture to exist where there are differences in the way waste-handling equipment and non-waste-handling equipment are maintained and operated. Salt repositories can implement safety-by-design principles that add robustness to the facility and minimize exposure to accidents.

Geomechanical Issues. Collaboration in the realm of geomechanics includes laboratory and field testing, constitutive model development and comparisons, benchmarking calculations, case study experiences, and analogues. All of these topics were discussed in terms of salt repositories. Over the last few years, modelers have compared computational results to field tests and recommended a series of laboratory experiments as part of a research agenda, which is now underway. Creep of salt at low deviatoric stress states is thought provoking because projections from our rich database seem to under-predict creep rates, believed to contribute to under-predicting measured room closure. Collaboration in constitutive model development and laboratory testing is ongoing.

Plugging and Sealing. International collaboration continues to evaluate our ability to seal drifts in salt workings. A historic perspective of several sealing experiences in Germany emphasizes salt-concrete and MgO-concrete, bentonite, asphalt, and bitumen. Construction practices are summarized along with performance perspectives, such as chemical compatibility, strength, permeability, and excavation damage zone amelioration. Information here furthers discussion from the previous workshop as reported in the 6th Proceedings by providing an up-to-date synopsis of case-study experience with dam construction in salt using high-density material. Reconsolidation of granular rock salt is not reviewed in this summary of drift seals because that topic has reached a mature level and joint publications have been issued to the Nuclear Energy Agency Salt Club web site and elsewhere.

Percolation. Deformation-assisted fluid percolation in salt is an example of an arising issue. Percolation is new to the US/German workshops because a recent publication on the topic was sensationalized in the press and undermined the viability of salt repository performance to the general public. Several experts contributed to open discussion regarding limitations of the recently published experimental results and their applicability to salt repositories. Stark differences were noted in mineralogical composition, grain size, texture, and brine chemistry between laboratory experiments and realistic bedded or domal salt deposits. An avenue for future research includes laboratory and field experiments using salt-relevant permeability testing methods and data analysis techniques. Participants were not able to definitively state that deformation-assisted enhancements in percolation should not be anticipated in salt repository host rocks.

Research activities related to geologic disposal, such as retrievability, disposal in deep boreholes, and aging of spent fuel, are addressed in special presentations based on recommendations of the organizing committee. The appropriate state of the art for such technical issues was shown and consequences described relative to a geologic disposal of high-level waste or spent fuel. Thus, it was revealed that retrieval of emplaced waste packages is possible, but requires adjusted design steps in the early phase of a repository program. A single presentation on the deep borehole disposal program launched in 2016 in the US clarified that the emphasis was alternative disposal solutions for a specific type of geometrically small radiation sources. As implementation of repository programs is protracted, storage of spent fuel creates an increasingly complex inventory queued for disposal.

Topics described in this summary comprise the core of the Proceedings of the 7th US/German Workshop on Salt Repository Research, Design, and Operation. Presentations collated in Appendix F provide in-depth treatment of specific technical issues. Collaborations continue in several areas for the foreseeable future and new possibilities were identified in the closing session. The overarching goal of our workshop is to advance the technical basis for salt repository systems in a congenial, professional, and cost-effective manner.

ACKNOWLEDGEMENTS

The authors are profoundly grateful for the extensive effort contributed by Laura A. Connolly of Sandia National Laboratories in preparation of these Proceedings. All participants and many followers of the US/German Workshops know that Laura also organized events associated with the 7th Workshop and handled infinite details of rooms, food, and money with the hotel. By her efforts, everything ran smoothly which helped to made the workshop a success. We hope Laura can continue her vital role as these workshops move to the Netherlands next year and to Hannover, Germany in 2018.

Special thanks to Dr. S. David Sevougian for shooting photos throughout the Workshop. His handiwork as well as other cameo photographs can be seen on our website: http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/2016-usgerman-workshop-on-salt-repository-research-design-and-operation/.

Workshop feedback suggests that content, format, breakout discussions, and organizational structure were near optimal. A sharper focus on a limited number of issues supported open discussion and promoted active participation among attendees. The workshop character of the event was regained. Centering the Workshop in Washington, DC permitted several federal agencies of the United States to be represented and their presentations and participation enhanced overall productivity.

Once again, these Proceedings are compiled from contributions of several topical leaders, who wrote concise summaries comprising Chapters herein. As with any endeavor of this magnitude, scope, and complexity, progress is testimony to dedication and contribution of participants.

Individual chapters and primary authorship are as follows:

Chapter 1: INTRODUCTION

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Chapter 2: SAFETY CASE

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Chapter 3: OPERATIONAL SAFETY

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Chapter 5: PLUGGING AND SEALING

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Chapter 6: PERCOLATION

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Chapter 7: CONCLUDING REMARKS

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

Voltaire

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REVISION HISTORY

Document Number/Revision	Date	Description
SFWD- SFWST-2017-000008 Sandia Tracking # 567206	January 23, 2017	***Not yet approved for Unlimited Release*** Satisfies SFWD Milestone Number M2SF-17SN010303011 (WBS SF-17SN01030301)
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ACRONYMS

ALARA	as low as reasonably achievable
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany))
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy (Germany))
CBFO	Carlsbad Field Office
CON	conclusion
COVRA	Central Organisation for Radioactive Waste (Centrale Organisatie Voor Radioactief Afval, (Dutch nuclear waste processing and storage company)
DAEF	Deutsche Gesellschaft für Endlagerforschung (German Association for Repository Research)
DBE TEC	DBE Technology GmbH
DBM2	a specific salt-concrete mixture
DOE	US Department of Energy
EDZ	excavation damaged zone
ENTRIA	Entsorgungsoptionen für radioaktive Reststoffe: Interdisziplinäre Analysen und Entwicklung von Bewertungsgrundlagen (*Disposal Options for Radioactive Residues: Interdisciplinary Analyses and Development of Evaluation Principles*)
ERAM	Endlager für Radioaktive Abfälle Morsleben (Repository for Radioactive Waste Morsleben)
FEPs	features, events, and processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) GmbH
HAW	high-activity waste
HLW	high-level (radioactive) waste
IAEA	International Atomic Energy Agency
IfG	Institut für Gebirgsmechanik (Institute for Rock Mechanics (German))
ISMS	Integrated Safety Management System
JON	judgment of need
KIT	Karlsruhe Institute of Technology
MgO	magnesium oxide
MoU	Memorandum of Understanding
NEA	Nuclear Energy Agency (of OECD)
NWP	nuclear waste partner

OECD	Organisation for Economic Co-operation and Development
PTKA-WTE	Project Management Agency Karlsruhe, Water Technology and Waste Management
R&D	research and development
SNL	Sandia National Laboratories
THM	thermal-hydrological-mechanical
TM	thermal-mechanical
TRL	technical readiness level
TSDE	thermal simulation of drift emplacement
USA	United States of America
UT	University of Texas
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	Waste Isolation Pilot Plant

Proceedings of the 7th US/German Workshop on Salt Repository Research, Design, and Operation

1 INTRODUCTION

Collaborations between the United States (US) and West Germany began in the 1970′s when both countries were investigating salt for the option of radioactive waste disposal. However, technical evaluations for disposal of heat-generating waste in salt experienced a rather long hiatus in the US after certification of the Waste Isolation Pilot Plant (WIPP) and issuance of the Nuclear Waste Policy Act Amendment, which ended salt disposal research for the civilian disposal program. In Germany, salt repository research was influenced by political decisions in connection with the phase-out decision, and especially with the debates regarding the use of Gorleben as a potential repository site. To clarify questions, a ten-year moratorium was imposed, which ended in 2010. At that time, developments in Germany and the US led to renewed efforts in salt repository investigations. Representatives of institutions in both countries wished to renew collaborations and cooperation on overall salt repository science, to coordinate a potential research agenda of mutual interest, and to leverage collective efforts for the benefit of their respective programs. Proceedings chronicle workshops held since 2010; this is the seventh iteration. Acknowledging both the importance of the rejuvenated activity for the programs and the quality of salt science researcher in both countries, a Memorandum of Understanding (MoU) between the US and Germany, was signed in 2011. Participants have engaged enthusiastically to great technical achievements under this flagship MoU.

The 7th US/German Workshop on Salt Repository Research, Design, and Operation was held in Washington, DC and accommodated over 50 participants. This gathering closely approached ideals for a *workshop* environment, as these Proceedings record. Holding the venue in Washington, DC permitted several federal agencies of the US to participate, enriching outreach and perspective. Welcome addresses from the federal ministry of Germany and the US Department of Energy initiated the workshop.

Excerpt from Mr. Wirth's address.

Our cooperation is based on close personal contacts and excellent relations on the scientific and technological side, which in turn lead to a high level of mutual trust.

It was almost exactly five years ago that the U.S. Department of Energy and the German Federal Ministry for Economic Affairs and Energy signed their Memorandum of Understanding.

In doing so, they stated that they were serious about jointly pursuing research and development on final disposal in rock salt.

Federal Ministry for Economic Affairs and Energy (Germany)

Excerpt from Ms. Forinash's address.

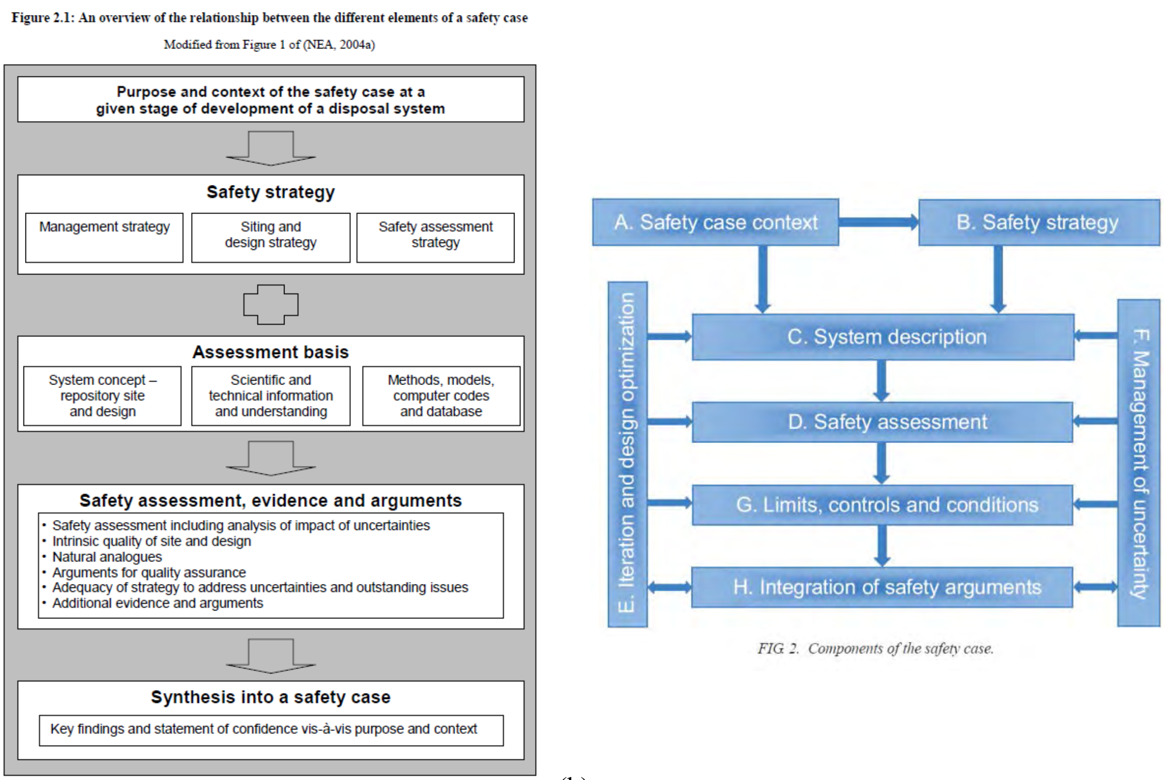
Both the United States and Germany have successful repositories in salt. From site characterization through the last 15 years of WIPP operation, what we have learned reinforces that the properties of a stable salt formation are exceptionally well suited to provide the isolation and containment we seek for nuclear waste over centuries. International collaboration is incredibly valuable in further advancing our understanding of the properties and the behavior of salt.

US Department of Energy

Following opening welcome comments, an aggressive, interesting, and challenging agenda complemented with breakout sessions ensued. The following Chapters recap the meeting events.

2 SAFETY CASE

The role and evolution of the safety case were examined during the Workshop, with several examples given from US and German programs, as well as lively discussion of key technical issues related to robustness of the safety case. The major components or elements of a safety case have been depicted with slight differences among various national programs and agencies. The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA of OECD) and International Atomic Energy Agency (IAEA) representations for a *post-closure* safety case are shown in Figure 2-1, while a more comprehensive version that also factors in *pre-closure* (construction and operations) safety is shown in Figure 2-2. The latter depiction of the safety case illustrated in Figure 2-2 is important because interplay between post-closure and pre-closure safety cases was a focus of discussion during the workshop (also see Chapter 3 regarding operational safety). Operational safety takes on added importance in light of recent developments at the US WIPP repository for transuranic wastes. See abstract and presentation by T. Reynolds in Appendices E and F, respectively. Requirements for safety cases during repository operations constitutes periodic recertification.



(a) (b)

Figure 2-1. Major components of the post-closure safety case: (a) from NEA (2013), and (b) from IAEA (2012).

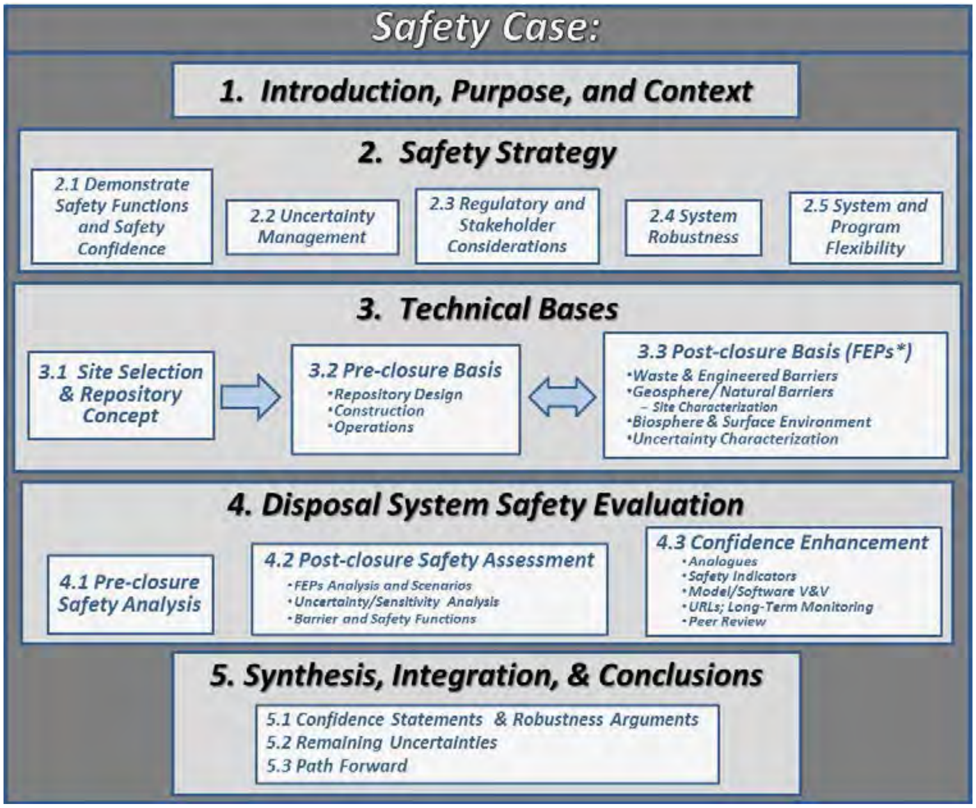


Figure 2-2. Major components of the complete safety case.

Within the context of an ongoing research and development (R&D) program, the repository safety case is matured through issue resolution and uncertainty reduction, with the associated key elements of the safety case (such as safety strategy, safety assessment, and technical bases) evolving concomitantly to reflect the current state of knowledge and confidence in the repository concept. Figure 2-3 schematically illustrates the maturation of the safety case and safety confidence with ongoing R&D and major project decision points. It reflects the advanced phased approach in repository development, which is applied in all programs and illustrates the association between flexibility and adaptability of the safety case and the respective R&D program. This means, that the maturation of the safety case is mainly driven by iteration between *knowledge gathering* (through R&D related to the technical bases) and *repository safety assessment* (both pre-closure and post-closure) based on that knowledge. This also means that there is close interdependency with respect to prioritization of R&D. The latest version of the safety assessment (at any major decision point) then guides future project R&D on the technical bases (i.e., design of engineered components, and testing and characterization of the natural system, optimization, etc.). This iteration between R&D on technical bases and evaluation of system performance is depicted in more detail in Figure 2-4.

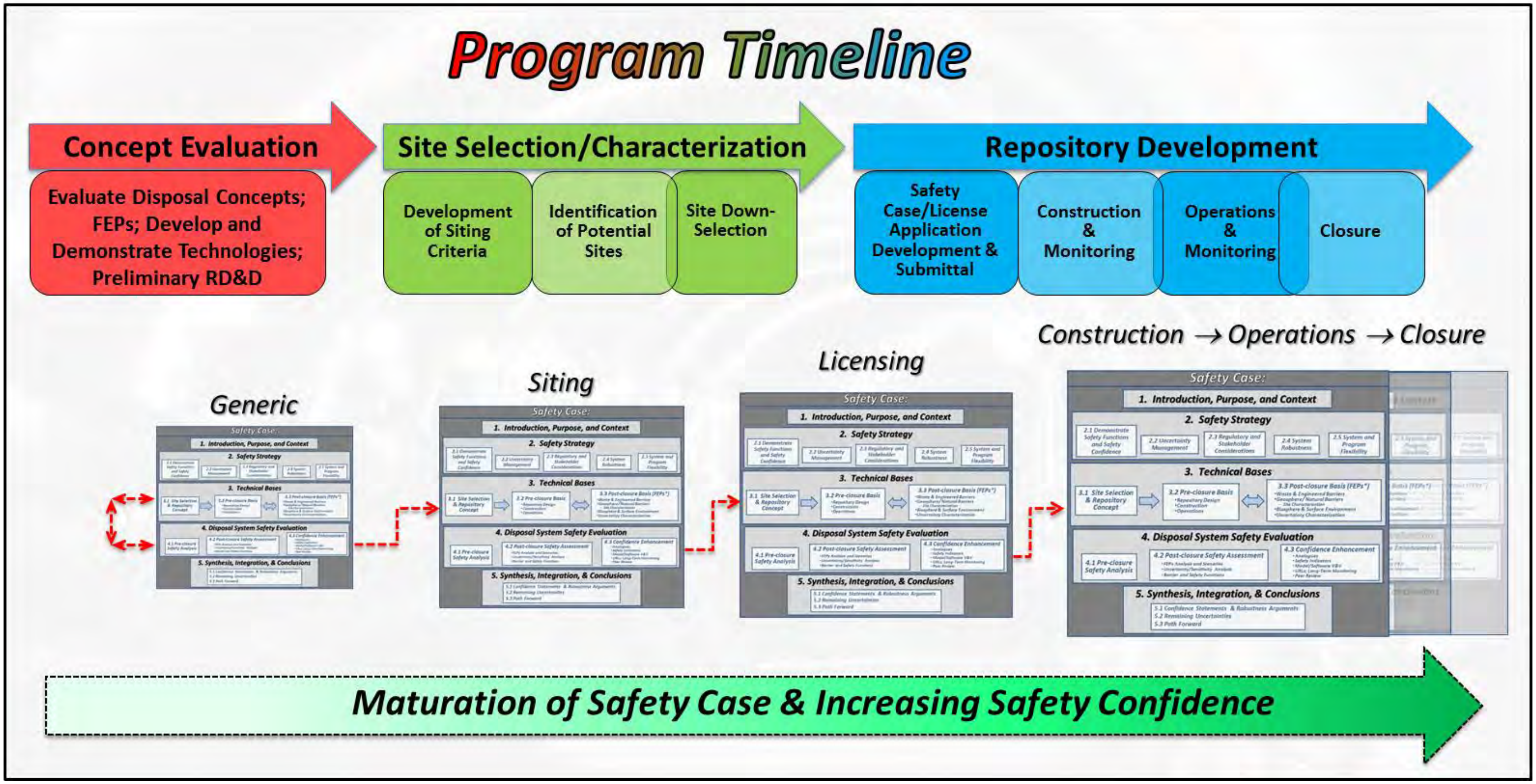


Figure 2-3. Evolution of the safety case and safety confidence with major project decision points.

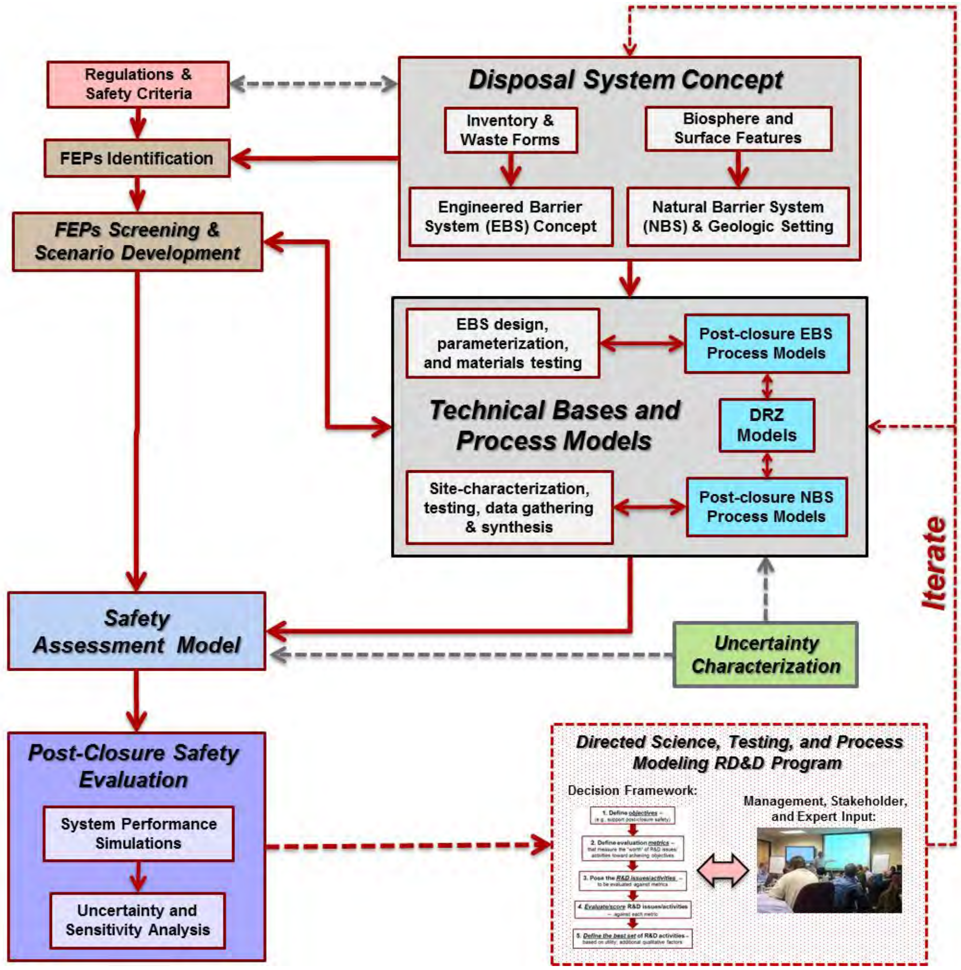


Figure 2-4. Evolution and iteration of technical bases and safety assessment.

During generic R&D stages (Figure 2-3, left-hand side), prior to site selection, almost all R&D activities (in the beginning more or less influenced by fundamental science) directly feed the (non-site specific or generic) safety assessment exercise, which is viewed as the most important component of the safety case regardless of program stage (IAEA 2012, Sec. 4.4). However, after site selection and as the project approaches licensing, other pillars of safety confidence, such as natural analogues, safety indicators (NEA 2012), and additional stakeholder-specific concerns, must be addressed in more detail. This also has consequences for R&D, which moves toward applied and prioritized activities and away from basic scientific aspects. Both the US and German programs are currently in the generic stage, but both are planning ahead for the maturation of the safety case.

National programs worldwide are in different stages of advancement. Some like the Swedish, Finnish, French and Swiss programs are applying the safety case approach in siting and licensing activities. Less advanced programs are currently engaging a generic approach, but planning for the maturation of the safety case. Other programs, specifically WIPP, are already past licensing, into the operational phase, and have experienced how even during the construction/operations phase, the safety case must still evolve via additional R&D, engineering, and safety requirements. Also, during this phase, operational safety takes on as much, or more, importance to the safety case as post-closure safety, particularly from the viewpoint of many stakeholders and the implementers. Integration and interplay between these two types of safety (Components 4.1 and 4.2 of Figure 2-2) was an important topic of discussion in a workshop breakout session, with a possible future collaborative effort being the application of the post-closure features, events, and processes (FEPs) process to pre-closure (operational) safety issues—see FEPs discussion below.

With regard to four of the major components of a safety case (safety strategy, technical bases, safety analysis, synthesis/integration of safety arguments—see Figure 2-2), the German approach in RDD tries to resolve four safety related questions (see Wolf presentation in Appendix F):

Q. How to achieve safety?	A. Through a sound safety strategy.
Q. How to demonstrate safety?	A. Mainly through safety assessment.
Q. How to manage uncertainties?	A. Through systematic uncertainty characterization, uncertainty propagation in models, and uncertainty analysis.
Q. How to communicate safety?	A. Through an integration of all safety arguments.

Based upon Federal regulatory requirements for the disposal of high-level (radioactive) waste (HLW) a methodological approach for a safety concept based on the containment of radioactive waste in a so-called *containment-providing rock zone* is used. Based on a few guiding principles, specific design requirements were formulated, which led to a set of objectives and associated strategic measures underlying repository design and layout.

Demonstrating safety is accomplished by a "demonstration concept" on the basis of the safety concept. The primary metrics to demonstrate safety include integrity proofs for the geological and geotechnical barriers, analysis of the salt backfill compaction, and use of radiological indicators to demonstrate the state and/or degree of radionuclide release from the containment-providing rock zone. An integral part of this quantitative safety demonstration is scenario development and FEPs analysis—both in the German and the US programs.

As outlined in Sevougian et al. (2012) and Sevougian et al. (2013a), FEPs analysis and scenario development are a key part of the iterative process shown in Figure 2-4, and help inform the construction of a post-closure safety assessment model based on the most important FEPs (i.e., the included FEPs), as well as ensuring completeness of the safety assessment model. Uncertainty and sensitivity analyses of the results produced by the safety assessment model indicate which FEPs are most important to post-closure repository performance. This information can then be used during the next project update to help refine the set of included FEPs and their representation in the safety assessment model. FEPs and scenarios also provide a logical method for organizing and cataloging both existing knowledge and needed R&D within the context of the entire safety case, especially the remaining "issues" and uncertainties that must be addressed by future R&D (DOE 2012; Sevougian et al. 2013b; Sevougian and MacKinnon 2014).

Figure 2-5 indicates the relationship between the value of an R&D activity and its cost, which can be used to determine its priority during each stage of the project. In particular, R&D activities to resolve remaining issues during any of the project stages shown in Figure 2-3 will be prioritized according to the following general categories:

- Importance to components of the safety case, e.g., to safety assessment, technical bases, and/or confidence-building
- Potential to reduce key uncertainties
- Other factors (e.g., cost, maturity or technical readiness level (TRL) of activity, redundancies with other activities, synergies with other activities)

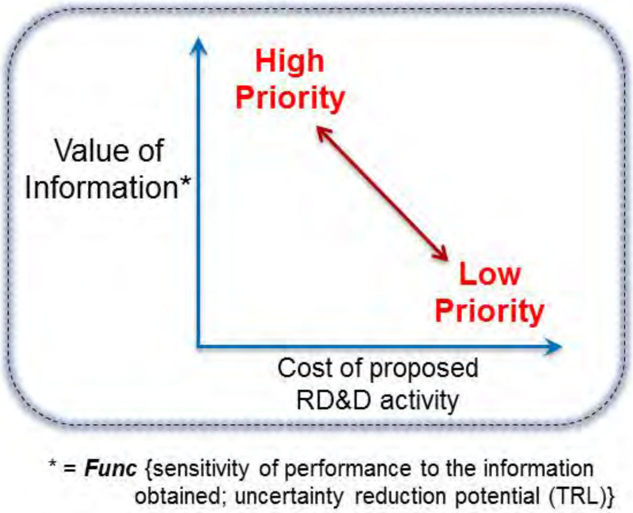


Figure 2-5. R&D prioritization as a function of value of information gained and activity cost.

FEPs analysis and scenario development are also two key components of the safety case for the WIPP repository (see Shoemaker presentation in Appendix F).

Because of the central role of FEPs analysis in the safety case and safety assessment (as a basis for the safety assessment model, as a means to demonstrate completeness—of both the safety assessment and safety case, as a means to organize remaining issues and uncertainties, and as a way to help prioritize R&D), a major US-German collaboration on FEPs organization and FEPs database creation has been ongoing for several years (see Sevougian presentation in Appendix F).

This collaborative effort involves the organization of FEPs around a 2-dimensional matrix structure that facilitates the ability to analyze groups of FEPs related to specific topical areas, i.e., all FEPs relevant to the behavior of a specific repository feature, or all FEPs directly affecting or potentially coupled to a specific long-term process (Freeze et al. 2014; Sevougian et al. 2015). Accompanying the new matrix-based FEPs organization, is the creation of a comprehensive FEPs database (www.saltfep.org), which is organized not only by FEP but also by "Associated Processes," which is a finer division of FEPs that facilitates building of scenarios and safety assessment models. FEPs screening now occurs at the level of associated processes, which have also been reformulated to be more directly related to the mathematical and numerical representation of physical-chemical processes and their couplings as implemented in safety assessment models.

The FEPs Database has now been populated with a comprehensive list of FEPs potentially relevant to a salt repository. It can be accessed by anyone who registers online at saltfep.org. The website includes the FEP list (linked to an interactive FEP matrix), references, and background information and documents. The FEP list can be exported in xls or pdf format. The fully populated electronic database helps organize future FEP analyses.

A final important component of the safety case is management of uncertainties (see Figure 2-1(a)). There are many aspects uncertainty management, including

- Appropriate characterization of uncertainties (based on the current state of knowledge and/or state of the art, including expert elicitation and independent peer review)
- Use of conservatism in models and parameters, when uncertainty characterization is too difficult or costly
- Appropriate propagation of uncertainties in process models and the system safety assessment model

- Iteration of the safety case during the operational phase, as new data is gathered and uncertainties are reduced

Much discussion occurred in this regard, especially with respect to the proper time interval for updating the input parameters of the safety assessment model and associated safety case as more date becomes available during the operational phase (see Economy and Shoemaker presentations in Appendix F). Different programs may have different regulatory requirements in this regard, but it is clearly an important safety-confidence issue for all programs.

It was suggested mutually by German and US participants that a collaborative R&D activity be initiated with respect to management and analysis of uncertainties, both as a general subject, and also with respect to certain key process important to salt repositories, e.g., coupled thermal-hydrologic-mechanical (THM) processes, such as creep closure. In this regard, Figure 2-6 shows the general sources and types of uncertainties for the process of creep closure (of rooms or emplacement drifts).

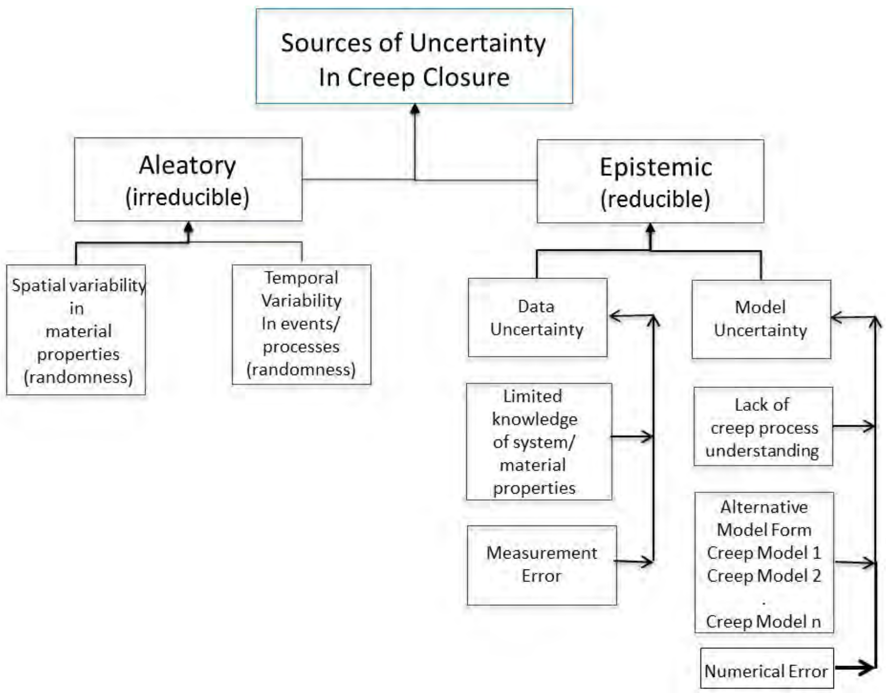


Figure 2-6. Sources and types of uncertainties in creep closure of emplacement drifts/rooms in a salt host rock repository.

It was suggested during the workshop (see Sevougian and Bollingerfehr presentations in Appendix F) that a more formal effort to address these uncertainties would include

- Sensitivity analyses to determine how uncertainty in THM models affects uncertainty in post-closure system performance (e.g., dose), i.e., how much does uncertainty in THM processes “really matter” to overall system safety; and
- Prioritization of the sources of THM uncertainty in order to focus future R&D, e.g., which constitutive model best represents THM uncertainty or how many different constitutive models are needed to encompass the full range of potential behavior.

Summarizing important technical issues and future areas of collaboration related to the safety case results in the following topics:

1. Uncertainty management and sensitivity analysis, both from a general perspective and with respect to key coupled processes related to salt host rock repositories (both with heat and without).

2. Importance and interplay between pre-closure (operational) and post-closure (long-term) safety.
3. Use of FEPs and scenario development in the safety case, including their possible application to pre-closure safety analysis—e.g., see SNL (2008) for a possible methodology in this regard.
4. Interval and necessity for updating the safety case during the construction and operations phases as knowledge-gathering continues—role of conservatism and effect of uncertainty reduction.
5. Effect of program phase (program maturity) on the role and form of R&D.
6. System model benchmarking and quality assurance.
7. How to improve other pillars of the safety case besides quantitative safety analysis, i.e., both confidence-building arguments (e.g., natural analogues, safety indicators) and synthesis/integration arguments that represent the entire safety case.

3 OPERATIONAL SAFETY

US/German workshops on salt repository research, design, and operation recognize the overriding importance of operational safety. Workshop leadership dedicated sessions to operational safety beginning in 2013, prophetically before events at WIPP occurred. In fact, international repository programs represented in the Implementing Geologic Disposal-Technology Platform, the NEA's Integrated Group for the Safety Case, and the IAEA formally addressed various operational safety issues over time. Consequently, NEA and IAEA organized a common workshop to share information and experiences at NEA-OECD-headquarters in Paris, July 2016. At the 7th US/German Workshop, Wilhelm Bollingerfehr provided overview of guiding principles of operational safety for nuclear waste repositories.

The 45 participants in the Paris workshop explored how implementers address operational safety in developing geological repositories for radioactive waste disposal. They evaluated adequacy and comprehensiveness of existing regulatory frameworks. Perhaps most importantly, they examined effective and practical design alternatives used to achieve operational safety, an approach often referred to as *engineered safety* or *safety by design*.

The 7th US/German workshop environment allowed comparison of real-life examples of operational safety challenges at WIPP against accounts developed by Paris workshop participants. First, suggestions and findings of the Paris colloquium are itemized. Draft guidelines and principles are then contrasted to causes and solutions of WIPP operational challenges and recovery pathway. Tammy Reynolds reported on actual examples from WIPP and her presentation as well as that of Bollingerfehr can be found in Appendix F of these Proceedings.

Traditional practices of safety espouse accident prevention and a safety-conscious work environment. Training and procedure-driven processes are used to lower fire and radiological risk, for example, as part of a *Safety Culture* underscoring operations. Repository disposal of nuclear waste juxtaposes potentially dissimilar cultures of mining practice and those governing a nuclear facility. Diligence is required to ensure schedules and cost concerns do not compromise safety. In addition to surface and subsurface hazards recognition, a primary goal for geologic disposal is ALARA—to keep radiological exposure As Low As Reasonably Achievable. Deep geological repositories will be sited, designed, constructed, operated, and closed to isolate nuclear waste from the accessible biosphere, thus achieving ALARA objectives through long-term isolation. To accomplish final isolation objectives, surface and underground operations must function securely, ensuring and guaranteeing infrastructure stability and surety for periods of 100 years, or longer. Operational strategies—such as defense-in-depth and engineered barriers—contribute to ALARA goals. Repository operations implement ALARA principles in surface facilities where typical processes include waste acceptance, encapsulation of conditioned waste, inspection, and canister preparation. Acceptable packages are transferred in shielded transfer cask for underground disposal. Exposure to workers and general public during the operational phase is expected to be similar to other nuclear facilities.

The Paris workshop identified operational safety challenges in five classes:

1. Regulatory Environment. Demonstrate compliance with a wide range of relevant regulations. A noted lack of international guidance focused on operational safety presents an opportunity for international collaboration to harmonize regulations.
2. System Design and Controls. Waste characteristics are variable today and are expected to give rise to specific safety concerns as additional waste forms are developed over future generations. Projecting forward, operational safety will have to be responsive to ongoing safety assessments, as envisioned by Swedish Nuclear Fuel and Waste Management Company and Posiva, by implementing a system of change management.
3. Operational Safety Assessment and Risk Management. Investigate the possibility to develop standardized high-level approaches, such as to fire risk management. If needed, ensure waste retrieval operations can be accomplished. Promote completeness in risks or hazards evaluation and potential consequences.
4. Monitoring and Compliance Control. Clarify regulatory expectations and demonstrate and maintain monitoring equipment. Identify responsive action when parameter values exceed their respective safety envelopes.
5. Safety Culture. This concept promotes safety as the main focus over extended periods of operations. A safety culture must pervade the organization, and therefore, management must ensure continued support for training, which preserves staff competence. Experience creates wisdom and corporate memory.

Participants in US/German workshops on salt repository research, design and operation initiated open discussion, goals, and strategies for operational safety in advance of the catastrophic events at WIPP. However, these serious operational events provide sharp focus and tangible reality to the topic of operational safety. Participants gained deeper appreciation for the seriousness of operational safety and the complexity involved with recovery from off-normal events. The specific WIPP safety breaches have now been extensively analyzed and photographs, such as those shown in Figure 3-1, and reports are easily obtained from the internet (www.wipp.energy.gov).

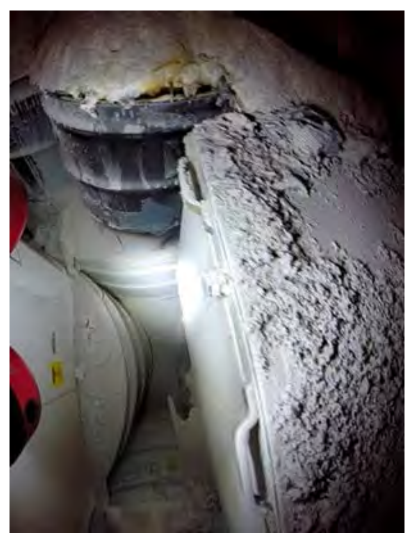


Figure 3-1. WIPP operational accidents: Salt haul truck fire (left) and radiological release (right).

The preventable and ill-fated events at WIPP closed the facility for disposal operations since February 2014. On February 5, a gear box on a salt haulage truck overheated, leading to ignition of diesel fuel and rear tires (Figure 3-1 left). After the truck fire, almost no access to underground areas was possible before a radiologic release on February 14, which occurred near midnight when, fortunately, no persons were in the underground. An improperly packaged drum violently aerosolized plutonium 239/240 (Pu) and americium 241(Am) (Figure 3-1 right).

Root cause findings identified a difference between a nuclear facility and mining culture, such as differences in expectations between waste handling and non-waste handling vehicles. Maintenance lapsed and critical safety equipment was impaired. Insufficiency was cited for training, drills, emergency response, communication systems, and fire hazard awareness. The two incidents, a truck fire and an apparently unrelated radioactive release, occurred after fifteen years of successful operation. Despite independence of the two events, a root cause was found to be insufficient safety culture, which resulted in ineffective nuclear safety, maintenance, radiation protection, and emergency management programs. Relevance of these general proclamations can be appreciated from the Accident Investigation Reports (DOE 2014a; 2014b). Underlying findings are grouped in these reports as CON (conclusion) and JON (judgment of need). There were 22 CONs and 35 JONs in the Salt Truck Fire Accident Investigation Report (DOE 2014a). Similar numbers of conclusions (CON = 31) and judgment of need (JON = 47) were reported for the radiological release. One example from each report is given in Table 3-1.

Table 3-1. Examples of operational safety findings from WIPP accidents

CON 22 (fire)	NWPs and CBFO management allowed a culture to exist where there are differences in the way waste-handling equipment and non-waste-handling equipment are maintained and operated.
JON 35 (fire)	NWPs and CBFO management need to examine and correct the culture that exists regarding the maintenance and operation of non-waste handling equipment.
CON 21 (release)	NWPs and CBFO did not analyze and disposition differences between waste-handling and non-waste-handling vehicles for similar hazards and impacts, e.g., allowing a truck in this condition to be at the waste face.
JON 34 (release)	NWPs and CBFO need to identify and control the risk imposed by non-waste-handling equipment, e.g., combustible buildup, manual vs. automatic fire suppression system, fire-resistant hydraulic oil, etc., or treat waste-handling equipment and non-waste-handling equipment the same.

Note: NWPs = Nuclear Waste Partners. CBFO = Carlsbad Field Office.

One of the five building blocks of the Paris meeting on Operational Safety is called Regulatory Environment, a heading meant to demonstrate compliance with a range of regulations. Judgment assigned in the Accident Investigation Report on the Radiological Release Event (DOE 2014b) cited failure of the Los Alamos Field Office and National TRU Program/Carlsbad Field Office to ensure that Los Alamos National Security, LLC and the Central Characterization Program complied with Resource Conservation and Recovery Act requirements in the WIPP and Los Alamos National Laboratory Hazardous Waste Permits, as well as the WIPP Waste Acceptance Criteria, providing specific examples of the range of regulations encountered in disposal operations.

Discussion at the 7th workshop considered relationships between operational and long-term safety. Multiple lines of reasoning are used to establish safety-case arguments with the regulatory agency in a framework of governing licensing criteria. For decades, demonstration of long-term safety used elaborate models to project repository performance over mind-boggling periods of ten thousand or even a million years. Recently and for good reason, operational aspects are receiving increased attention. Operational considerations and long-term safety have synergistic relationships and disposal concepts can positively impact long-term safety.

Risk can be mitigated by design. Focused research can quantify certain operational and closure strategies and based on an existing body of information can advocate for future salt repositories that include safety-by-design in a modular build-and-close concept. Inherent safety would include minimized exposed real estate, a disposal procedure that would begin in a far corner and work progressively back toward the shafts. When a module of design dimension is filled, an advanced salt-based closure system would be emplaced. Closing and permanently sealing each module as disposal operations move forward creates a safety-by-design situation since radiological exposure is systematically minimized (ALARA). Because disposal begins at outer reaches of repository dimensions, underground manpower, equipment, and ventilation never breach the disposal module once it is filled, closed and licensed.

In addition to identified operational safety challenges at the Paris workshop, a final and critical challenge is how to communicate residual or unresolved uncertainties to the public. Despite best efforts of implementers and regulators, risks such as human error cannot be eliminated. Reducing human error will remain a topic of future workshops. Residual uncertainties concerning operational safety will attend the most pragmatic and disciplined program. While remaining uncertainties should not be down-played, it must be emphasized to the public that risks associated with the alternative of leaving the waste indefinitely on the surface can, in the long term, become a much higher and irresponsible risk to future generations.

In addition to clean-up of soot and radionuclides, recovery activities at WIPP included reexamination of the safety culture and reflection on the concept of operational safety. Principles promoted by the Paris workshop at NEA-OECD-headquarters in Paris become particularly noteworthy in design and operation of salt repositories.

4 GEOMECHANICAL ISSUES

As in past US/German workshops, the 7th workshop placed an emphasis on the thermo-mechanical behavior of salt. Structural simulations, laboratory experiments, and *in situ* monitoring all play crucial roles in salt repository engineering. Operations personnel can use salt mechanics to determine how long they can operate in an area before structural stability becomes a concern. Furthermore, closure designs involve backfilling the repository with crushed salt and installing geotechnical seals at various critical locations. Modeling and monitoring can help predict the waste isolation process as seals mature, backfill reconsolidates, and excavation damaged zone (EDZ) heals. These evaluations and predictions of safety and long-term integrity require a strong scientific foundation and robust engineering tools, both of which continue to evolve.

One of the important topics discussed at the workshop was creep behavior at low effective (deviatoric) stresses. Andreas Hampel, Sandra Fahland, and Leo Van Sambeek all touched on this area in their presentations. Historically, salt creep tests in the laboratory have focused on medium to high effective stresses. At low effective stresses, creep rates are extremely small. The time required to reach steady-state creep thus increases dramatically, and control of temperature and humidity to tight tolerances is a challenge. Nevertheless, Bérest et al. (2015) applied low uniaxial compressive stresses of 0.1 to 0.5 MPa at 14.4 °C to Avery island salt samples. They found significantly higher creep rates occur than would be predicted by extrapolating behavior from triaxial compression tests at higher stresses down to lower stresses, using a constant stress exponent. At the 7th workshop, Sandra Fahland compared the Bérest et al. measurements with results from Joint Project III and three new Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources(Germany)) (BGR) tests (see Figure 4-1). Bérest used Avery Island Salt, Joint Project III used WIPP salt, and BGR used Morsleben salt. Thick curves correspond to Günther/Salzer model fits and thin curves to Norton model fits of the Joint Project III data.

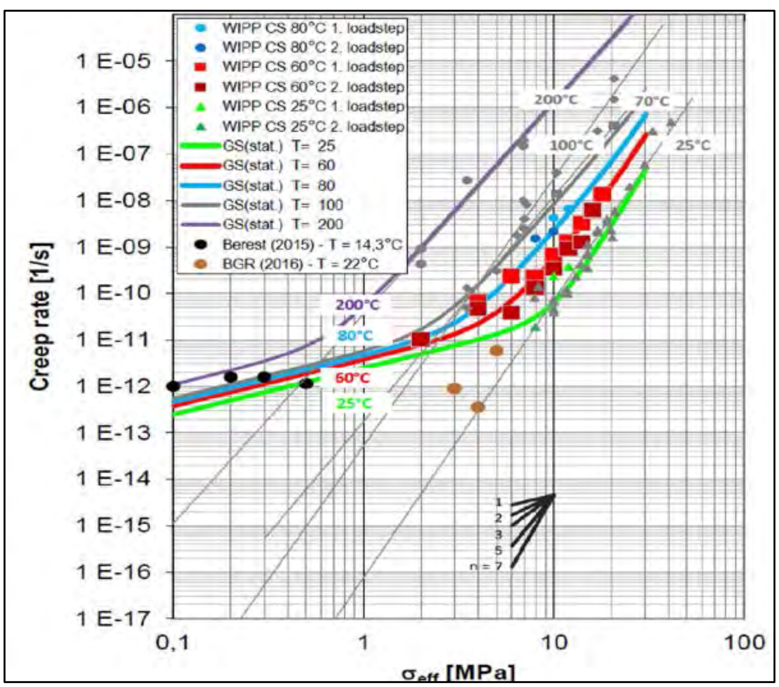


Figure 4-1. Steady-state creep rate versus effective stress at several temperatures (Fahland 2016).

In Joint Project III, the Institut für Gebirgsmechanik (IfG) ran triaxial compression tests with effective stress ranging from 2 MPa to 18 MPa. A confining pressure of 20 MPa was applied to ensure a stress state below the dilatancy boundary and exclude an influence of damage and dilatancy. The tests were conducted with preconsolidated WIPP salt specimens for about 120 days at 25 °C, 60 °C, and 80 °C, but the low effective stress tests beneath 8 MPa were only performed at 60 °C. A specific test design with two-stage creep tests was used to achieve better estimations of steady-state creep rates, consisting of transient approaches from above in the first stage and from below in the second stage. In these tests, steady-state rates were also found higher than would be expected from extrapolating the creep behavior at higher stresses to the low stress regime with a constant stress exponent.

The BGR uniaxial compression tests on different types of Morsleben salt were run at 3 to 5 MPa effective stress and 22 °C for roughly 500 days. Interestingly, the BGR creep rates are much lower than the Bérest et al. and the Joint Project III results. The results, however, are difficult to compare because the three parties used salt from three different locations, applied different stress states (uniaxial vs. triaxial), and utilized different temperatures. Hopefully future triaxial low effective stress experiments within joint project 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)) will help resolve these discrepancies.

Leo Van Sambeek's talk (presented by Stuart Buchholz) focused entirely on the effect of a multi-segmented creep law on the closure of an axisymmetric shaft. By including higher creep rates at low effective stresses, the closure increased by factors of 2 or more. The large volume of salt at low effective stress far away from the borehole increases radial displacement of the small volume of salt at high effective stresses near the borehole.

In conclusion, it is important that the salt community discovers the true creep behavior at low effective stresses, despite the experimental difficulties. In the new joint project WEIMOS, triaxial creep tests at room temperature with differential stresses below 8 MPa and a confining stress of 20 MPa will be conducted in the IfG laboratory on WIPP salt with stable boundary conditions and precise displacement measurements.

Another area covered by multiple presenters was the determination of model parameters to capture *in situ* measurements. Steven Sobolik discussed modeling of several salt caverns at the US Strategic Petroleum Reserve. Laboratory tests often present a limited picture of salt properties surrounding the cavern, so certain model parameters are often adjusted to match historical *in situ* data. After parameter adjustment, simulations produce useful predictions about future surface subsidence and cavern closure.

Along similar lines, Benjamin Reedlunn showed that several modeling choices were adjusted in the late 1980's to match *in situ* closure measurements of Room D at the WIPP. This tuned model successfully predicted other underground experiments at the WIPP without further adjustment, but it would likely fail to predict room closures at a new repository, in a new location. In the past year, Benjamin Reedlunn resolved several numerical issues and re-calibrated the Munson-Dawson salt constitutive model against the new laboratory tests of IfG on WIPP salt from Joint Project III. New simulations under-predict Room D closure by roughly 3 times. A list of potential areas for improvement, including creep at low effective stresses, was discussed to enable laboratory-based predictions of *in situ* room closure.

Two presentations considered the integrity of the salt barrier. Till Popp discussed the situation at the Teutschenthal mine after a rock burst in 1996 caused collapse of a 2.5 km^2 area (see Figure 4-2 on the left). Geomechanical modeling was able to predict the correlation between the rock burst and subsequent subsidence measurements (see Figure 4-2 on the right). Direct inspection of the rock salt above the collapsed area was made possible by excavation of a new drift in 2005. Boreholes into the ribs of the new drift in 2010 found the compressive stresses had recovered from zero to roughly 11 MPa, which is 5 MPa beneath the lithostatic pressure of 16 MPa. In addition, the permeability was 10^{-22} m^2, which concurred with the observation that no water inflow was observed after the collapse. Thus, Till Popp concluded that the collapse did not affect the integrity of the salt above the Teutschenthal mine.

Sandra Fahland brought up the criteria used to assess local integrity of rock salt. Today, modelers typically compare (1) the stress state to the dilatancy boundary (“dilatancy criterion”) and (2) the minimum principal stress to the fluid pressure (“minimum stress criterion” or “fluid pressure criterion”). Sandra Fahland discussed several other potential criteria, including a load-dependent dilatancy criterion, an anisotropic fluid pressure criterion, and a percolation threshold.

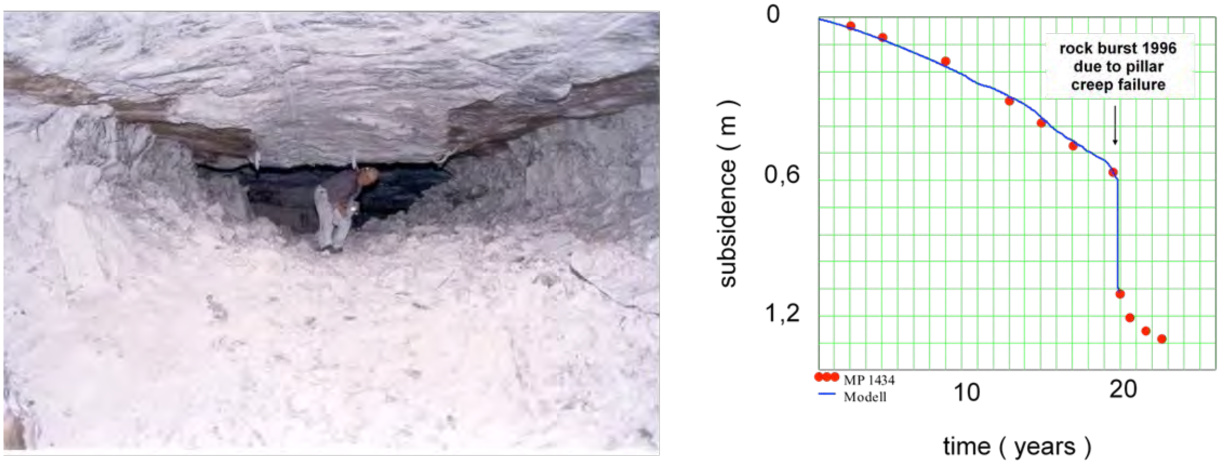


Figure 4-2. Mine collapse following a rock burst (Popp 2016), left: a photo in the collapsed region, right: measured surface subsidence compared against simulation predictions at the time of the rock burst.

Finally, Ralf Wolters discussed THM modeling of a repository concept approach “with and without a secondary monitoring level above the waste emplacement level” (see Figure 4-3). It is believed, that monitoring of physical and chemical processes on the emplacement level would increase stakeholder confidence in the waste isolation process. Preliminary THM simulations performed within the ENTRIA-Project (Entsorgungsoptionen für radioaktive Reststoffe: Interdisziplinäre Analysen und Entwicklung von Bewertungsgrundlagen (*Disposal Options for Radioactive Residues: Interdisciplinary Analyses and Development of Evaluation Principles*) a joint research project financed by the Federal Ministry of Education and Research (BMBF)) showed a maximum temperature of 50 °C on the monitoring level, which is low enough to permit most monitoring equipment. In addition, gas escapes from the emplacement level to the monitoring level through boreholes, resulting in reduced gas pressures on the emplacement level.

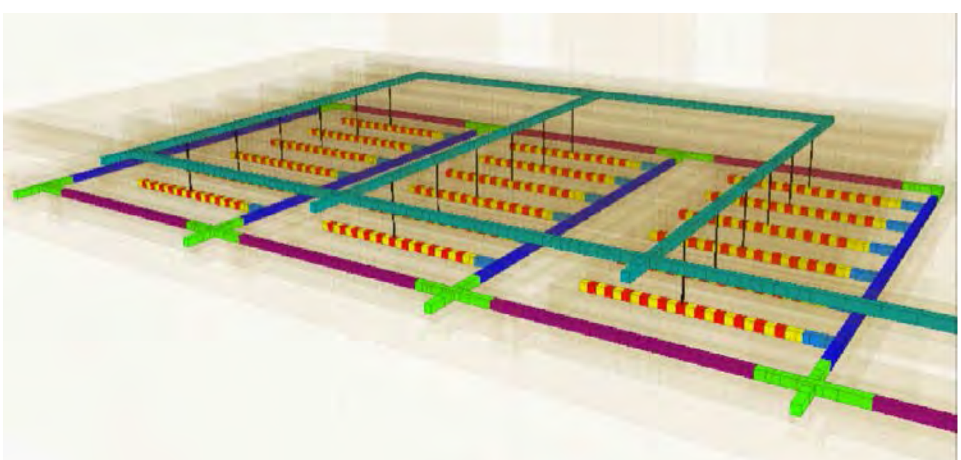


Figure 4-3. A generic repository concept with an emplacement level below and a monitoring level above, used in the ENTRIA project.

5 PLUGGING AND SEALING

US/German workshops on salt repository research, design, and operation collect the experience made in plugging and sealing of salt repositories. Typical sealing materials under discussion are various types of concrete (salt concrete and magnesium oxide (MgO) concrete), bentonite, and asphalt and bitumen. Crushed salt possibly with brine or clay added also shows sealing capabilities for the long-term. As the sealing capabilities of the crushed salt are classified according to the rock salt barrier, they are not discussed in this chapter. The seal and dam structures for which extensive knowledge has been gained in Germany are identified below.

Historically, based on empirically gained experience, through trial and error practices, four drift seals constructed in German mine works from the early 1900's have demonstrated a high degree of tightness:

- Dammbauwerk Leopoldshall I/II – III, built in 1903
- Dammbauwerk Leopoldshall III – IV, built in 1922
- Dammbauwerk Bismarckshall (Thomas Münzer) built in 1916 and improved 1923
- Dammbauwerk Sachsen - Weimar built in 1929, injection of silica grout was necessary to achieve tightness

These seals were constructed to separate mine panels permanently as a precautionary measure or as emergency actions to control intruding brine and water, both for human protection and to minimize potential for financial losses. From a compositional perspective, these seals have several common characteristics. They were each constructed from various elements consisting of different construction materials – e.g., brickwork, clay, rammed concrete, asphalt, and wood. The materials used were a direct consequence of availability and construction techniques employed at that time. Further information on these historic drift seals is summarized in Müller-Hoeppe and Pöhler (1999).

In the second half of last century seals were constructed to separate mine panels before controlled flooding as either a precautionary measure or as an emergency action in the following facilities:

- Abschlussbauwerk Hope made from salt concrete and asphalt, built in 1983 before the adjacent mine panel was flooded. The seal was outfitted with measuring devices to gain knowledge for future use in seal emplacements for chambers filled with radioactive waste. However, due to the failure of measuring devices, the tightness of the Abschlussbauwerk Hope can only be assessed indirectly. Thus, the quality of information is debatable (Fischle and Schweiger 1987; Thyssen 2002).
- Dammbauwerk Rocanville made from MgO-concrete and bentonite and including a so-called Dowell Chemical Seal, built in 1984 as an emergency action against brine intrusion, appears to have adequate tightness (Thyssen 2002).
- Dammbauwerk Immenrode made of salt concrete and bentonite, built in 1998/99 as a precautionary measure separating mine panels, has not yet been loaded. Thus, its tightness cannot yet be assessed (Thyssen 2002; Aland et al. 1999).

Systematic *in situ* investigations to construct seals and plugs for radioactive waste repositories in rock salt started around 1998 following two lines of evidence. One line focused on the sealing body where bentonite was the first choice of sealing materials because bentonite´s long-term stability was assumed to be confirmed by the natural analogue of salt clay. After re-ripping of the drift, respectively shaft contour, the following seals were outfitted with measuring devices and constructed:

- Schachtverschluss Salzdethfurt made of bentonite, built and instrumented in 1998 - 2000 (Breidung 2002; Gruner et al. 2003; and Sitz et al. 2003).
- Dammbauwerk EU-1 Sondershausen made of bentonite and asphalt, built in 1999 (Sitz et al. 2003).

Shaft seal Salzdetfurth as well as Dammbauwerk EU-1 Sondershausen demonstrated the functionality of the seals in principle; however, problems associated with piping effects and bypasses became evident.

The second line of evidence focused on the EDZ because it has been historically documented that the EDZ often formed migration paths. Thus, investigations were performed at the adjoining rock salt of load bearing structures that were installed in the past in order to investigate the healing process of the former EDZ and to assess the duration of the healing process. Investigations were performed at

- Dammtor Asse (Wieczorek and Schwarzianeck 2004)
- Asse-Vordamm (Gläß et al. 2005)
- Altes Dammtor, 3. Sohle ERAM (Endlager für Radioaktive Abfälle Morsleben (Repository for RadioactiveWaste Morsleben)) (DBE 2009 unpublished)

The lessons learned from these investigations were that damaged rock salt may be tight if the porosity is significantly low and the fluid pressure criterion is fulfilled. Furthermore, because experience has demonstrated that interfaces may form preferential migration paths, investigations at the Asse-Vordamm and the Altes Dammtor were performed to gain information on hydraulic properties of the contact zone, comprising the interface between the sealing body and the EDZ. Over the course of the investigations it became evident that the sealing body of the Asse-Vordamm, made from salt concrete, showed very low permeability values.

Based on this knowledge the *in situ* pilot seal, Abdichtbauwerk im Steinsalz, built in the ERAM was also made of salt concrete and is presently undergoing performance testing. Preliminary results are available (Mauke 2013).

In parallel, in situ pilot seals were tested in the Teutschenthal Mine and the Asse facility. Due to the carnallitic environment of both mines MgO-concrete was used for construction of the sealing bodies.

In the Teutschtenthal Mine two pilot seals made of MgO-concrete were constructed (Knoll et al. 2010):

- Großversuch 1 (GV1)
- Großversuch 2 (GV2)

In the case of GV1 cast-in-place MgO-concrete was used while for GV2 MgO-shotcrete was applied. Due to tachydrite layers at the drift contour, temperature increases during the hardening process was significantly restricted. Thus, the boundary conditions of the Teutschenthal Mine are not representative for a repository of radioactive waste in rock salt. Nevertheless, practical experience was gained from the experiments performed in the Teutschenthal Mine.

In the Asse facility five pilot seals made from MgO-concrete were constructed:

- Pilotströmungsbarriere A2 (PSB A2) made from MgO-concrete mixture A2, built in 2003 (Heydorn et al. 2008)
- Pilotströmungsbarriere A1 (PSB A1), made from MgO-concrete mixture A1, built in 2006 (Kamlot et al. 2012; Heydorn et al. 2016)
- Bauwerk K2C-750-1

- Bauwerk Blindschacht 4
- Bauwerk Kavernenhals

Test results from the PSB A2 demonstrated that the stiffness of the sealing body is decisive for good functionality of the seal because a sealing body of insufficient stiffness can lead to exceedance of the fluid pressure criterion in the EDZ thus forming a migration path. Although the required hydraulic resistance was achieved by the PSB A2, a further pilot seal using an MgO-concrete with improved stiffness for the mixture A1 was initiated. The pilot seal PSB A1 successfully fulfilled the requirements and was used for further sealing measures in the Asse facility.

The pilot seals Bauwerk K2C-750-1, Bauwerk Blindschacht 4, and Bauwerk Kavernenhals were made from MgO-concrete A1 and served to further clarify specific aspects of the seals. However, to date the results have not yet been published.

Additionally, the sealing capacity of MgO-concrete mixture (DBM2) was tested at an anhydrite location in the Bleicherode Mine. Specifically, Großversuch Bleicherrode was a conducted as the first test for sealing an anhydrite location. More information on this pilot seal is given in Mauke (2015).

For some applications asphalt and bitumen may be adequate sealing materials as they do not react with the salt environment. Consequently, a pilot test using asphalt as the sealing material was performed in the Teutschenthal Mine, referred to as Großversuch 3 (GV3) (Knoll et al. 2010). This test showed technical difficulties in joining the gaps between asphalt blocks. Therefore, the test could not be finalized as planned.

Another pilot test is the Großversuch Vertikales Dichtelement (Stielow et al. 2016) in the ERAM. It successfully tested installation of a bitumen seal stabilized by gravel.

Finally, the conclusion may be drawn that *in situ* pilot seals were installed considering all typical sealing materials. Some of them are tested under *in situ* conditions and the tests are still running. Thus, test results are still being evaluated and not yet documented in final reports.

6 PERCOLATION

A session titled “Percolation Issues” was held to discuss the possibility that percolation of salt rock occurs under the temperature and pressure conditions of a repository of high-level radioactive waste. This possibility was raised in a 2015 scientific paper published by Ghanbarzadeh et al. in Science. When the paper came out, it attracted some media attention in the US and in Germany, since in the abstract and final paragraphs of the paper suggest salt rock may not be as impermeable as previously thought.

In the session, Marc Hesse from the University of Texas (UT), Till Popp from the IfG, and Jörg Hammer from BGR presented their views. This chapter summarizes the presentations and subsequent open discussion among speakers, moderators (Jörg Mönig of Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) gGmbH (GRS) and Kristopher Kuhlman of Sandia National Laboratories), and meeting attendees.

6.1 Marc Hesse (UT)

Marc Hesse introduced the work presented in the 2015 Science paper “Deformation-assisted fluid percolation in rock salt” by Ghanbarzadeh, et al. along with some additional unpublished work.

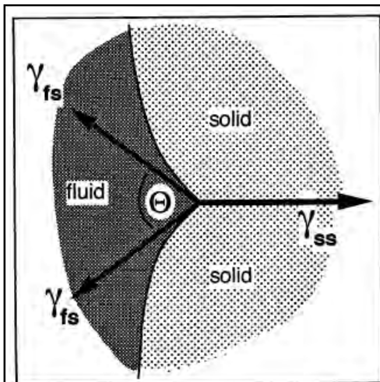


Figure 1. Geometry of two-phase junction in texturally equilibrated polycrystal. Dihedral angle, Θ, is established by balancing of grain boundary energy, γ_{ss}, and fluid-solid interfacial energy

Figure 6-1. From Lewis & Holness (1996).

The paper adds laboratory and field evidence to the observational work of Lewis & Holness (1996), which related the dihedral angle (see their Figure 1) between salt grains in a salt-brine system to the pressure-temperature conditions of the system. The presentation also included unpublished simulations of texturally equilibrated pore networks. When the dihedral angle is larger than 60° the intergranular fluid is trapped in isolated porosity pockets. When the dihedral angle is less than 60°, the isolated pockets evolve into a network thus enabling percolation of the intergranular fluids and leading to non-zero permeability. The UT Science paper summarizes lab experiments with table salt and distilled water, and analysis of data from oil wells in the Gulf of Mexico.

The laboratory experiments used X-ray microtomography to image two synthetic salt samples (fine-grained granular table salt with 15 weight-% distilled water) that had experienced undrained hydrostatic loading and heating. The samples were exposed to 20 MPa/100 °C and 100 MPa/275 °C. From the microtomography imaging, pore network connectivity was estimated, and 2D slices through the 3D image data were used to estimate dihedral angles (i.e., the contact angle between two salt grains in equilibrium with brine). The higher pressure and temperature sample corresponded to a median dihedral angle of 52° (computed porosity of ~5.5 %), while the other sample had a median dihedral angle of 67° (porosity ~2.5 %). The X-ray microtomography imaging showed the change in dihedral angle induces a change from isolated brine pockets at lower pressure and temperature to a percolating pore network at higher pressure and temperature. These data support the existence of a percolation thresholds for dihedral angles greater than 60°, given by Lewis & Holness (1996).

The analysis of well logs from the Gulf of Mexico generally showed hydrocarbon staining and lower resistivity in the lower half of the salt domes studied, under conditions ranging from 20 °C and 29 MPa to 111 °C and 186 MPa. Resistivity of salt which does not have a connected brine-filled porosity (does not percolate) should be higher than salt with a connected brine-filled porosity. The depth of the source rocks are commonly several hundred feet below the base of the salt, so that the hydrocarbons are believed to have migrated up from deeper oil-bearing source rocks into the lower portions of the salt. While some salt domes show good correspondence between the percolation criterion based on dihedral angle (for example Figure 3 in Science paper) other show hydrocarbons at much shallower depth. The presenter discussed deformation as mechanism to overcome the capillary percolation threshold.

6.2 Till Popp (IfG)

Till Popp presented several issues and questions the DAEF (German Association for Repository Research) had with the Science paper (DAEF, 2016).

Salt rocks are generally considered to be impermeable to fluids, i.e. liquids and gases. This notion is supported by laboratory investigations as well as by natural analogues. Loss of salt barrier integrity (i.e. development of permeability due to overcoming a percolation threshold) has been related to: 1) a dilatancy criterion (relation of confining and shear stresses, often exceeded near open excavations) and 2) a minimum stress criterion (which relates the pressure of a theoretical fluid column at the given depth to the least principal stress). These criteria and their effects on salt permeability are observable in the laboratory and the field. Does the dihedral angle (percolation when dihedral angle ≤60°) in a salt-brine system constitute a third threshold to monitor? Does this criterion explain observations in field and laboratory data?

The laboratory experiment of UT was conducted with table salt and distilled water under undrained hydrostatic conditions, with a high (brine-filled) porosity (7 to 16 %), and was quenched to room temperature. The experiment has striking differences from a natural salt system, and the sample likely was damaged due to thermal shrinking and mechanical decompaction during unloading. Till Popp pointed to the pore-scale microtomography images in Ghanbarzadeh et al. (2015) showing evidence for cracks in the salt crystals. Using the pore-scale microtomography imaging technique to infer the network connectivity and dihedral angle, is it possible damage from quenching had a significant impact on observations?

Static pore-scale modeling indicates connectivity depends on porosity (amount of brine) and dihedral angle. Laboratory testing at UT was done at high porosities (>5 %). Natural domal rock salt of the Staßfurt series (z2HS) is typically very low in porosity and brine content (e.g. <0.1 weight-%). What impacts does the porosity have on the percolation process?

Low resistivity and presence of hydrocarbons was used by UT as an indication that salt in domes has reached its percolation threshold. The observation of hydrocarbons in salt does not require the hydrocarbons to have traveled long distances. Hydrocarbons may be derived from inclusions of non-salt reservoir or source rocks within the salt dome.

Can we test the pressure-temperature dependence of dihedral angle and the pore network percolation and resulting increased permeability in the laboratory? Recent lab tests being conducted at IfG estimate salt permeability as sample pressure is increased, to the point where theory predicts the dihedral angle should be ≤60°. These experiments should lead to percolation, but no measurable gas permeability was observed.

6.3 Jörg Hammer (BGR)

Jörg Hammer presented geological data from the Gorleben site, where extensive studies were conducted to characterize the distribution of hydrocarbons in the salt dome. Only minor hydrocarbons (isolated streaks and clouds) were encountered in the drifts and in some boreholes. Ultraviolet light was used to characterize the distribution of hydrocarbons in drifts and drill cores. The distribution of hydrocarbons at the millimeter- and micrometer scale was characterized via microscopy.

The studies of hydrocarbons in German salt domes concluded that hydrocarbons are naturally occurring components of the salt rock formations, rather than being transported from distant source rocks.

Hydrocarbons are only observed along grain boundaries, healed fissures, within capillaries in anhydrite crystals or surrounding the boundaries between halite and anhydrite crystals. The hydrocarbons are always observed together with intragranular brines.

The majority of hydrocarbons have been fingerprinted to be related to the adjacent Staßfurt carbonate.

Some remarks were made regarding the UT experiments. The material tested in the UT laboratory experiments was 99.9 % pure halite (table salt) with 200 to 400 µm grains and distilled water, resulting in

7 to 16 % porosity. Gorleben natural rock salt is not a pure halite rock (which contains 1-2 % to 15 % anhydrite), with sizes ranging from <1 mm to 10 mm and a water content <0.02 wt.-% (Bornemann et al. 2008). Fabric and grain-size distributions in natural halite deposits are quite complex. Microtomography imaging shows complex non-ideal pore network topology in Gorleben salt.

Laboratory experiments were conducted to deform samples with both anhydrite and halite components at 345 °C. Fluid was expelled from anhydrite during deformation but only short distances (<1 mm). This is consistent with what is seen in Gorleben regarding deformation of anhydrite and hydrocarbon distribution.

6.4 Discussion

Discussion that followed the presentations focused primarily on topics of

1. How applicable is the UT study to mined geological repositories in salt?
2. What are the limitations of applying this study?
3. How is salt permeability related to percolation and dihedral angle?

Both Lewis & Holness (1996) and Ghanbarzadeh et al. (2015) indicated the pressure and temperature conditions associated with an equilibrium textural equilibrium are beyond the typical condition of mined geologic repositories. Given typical geothermal gradients and lithostatic stress gradients, these effects would be associated with depths of 3 km or greater. Both the Lewis & Holness (1996) paper and the Hesse presentation added that (at repository stress conditions) only very hot conditions around the waste packages could approach or cross the 60° dihedral angle boundary (e.g., around 250 °C at repository-relevant stress conditions). This would only be possible in the immediate vicinity (i.e., within cm) of the waste packages, within the engineered barrier system consisting of crushed salt and other emplaced seal materials. Very near the waste, the conditions would be modified significantly from far-field conditions due to construction and completion of the repository (e.g., crushed salt backfill or the presence of a disturbed rock zone due to excavation). During the thermal simulation of drift emplacement (TSDE) 9-year heater test at Asse, temperatures on the six heated casks did not significantly exceed 210 °C (Bechthold et al. 1999).

The textural equilibrium theory is based on the thermodynamic steady-state in a salt-brine system. To achieve this state requires adequate brine (along with the required pressure and temperature conditions) to facilitate recrystallization. Hotter conditions inside a repository near waste package would likely be very dry (e.g., see the TSDE experiment at Asse – Bechthold et al. 1999), preventing the salt system from reaching its thermodynamically preferred state. The lab samples analyzed by Ghanbarzadeh et al. (2015) were quenched to room temperature and pressure, but did not immediately re-equilibrate with ambient P-T conditions. There may be other kinetic controls or limitations of the theory that slow down or effectively stop the system from achieving its thermodynamic equilibrium, including: presence of additional solid minerals or ionic species (besides NaCl) in either the brine or crystalline phases of the system (textural equilibrium theory assumes the liquid and solid phases have the same chemical composition) and texture/grain size of natural salt. Further, the theory and experimental work to date do not rule out pressure/temperature path-dependence or rate-dependence.

Ghanbarzadeh et al. (2015) discusses the effect dihedral angle has on percolation of a brine-filled porosity, and the ramifications of the pressure-temperature sensitivity of the dihedral angle. Below the percolation threshold, it is agreed salt has no measurable permeability. Above the dihedral angle threshold, the permeability is considered finite. Estimates of the permeability magnitude, after crossing the 60° dihedral angle threshold, have been based on grain size and porosity data alone to date (Lewis & Holness 1996). These permeability estimates were derived solely from geometrical considerations for partially molten rocks with ideal texture (von Bargen & Waff 1986); they are not salt specific, based on realistic observed salt textures, or based on laboratory data. Laboratory and field experiments should be conducted using salt-relevant permeability testing methods and data analysis techniques to quantify what effect this process has on salt permeability.

The presentations and discussion seemed to confirm that a comprehensive understanding of processes affecting the barrier integrity of salt rocks under repository conditions exists. Proof of the geomechanical integrity analysis is done by using the generally accepted dilatancy and minimum stress criteria. However, the theory of textural equilibrium in salt-brine systems, and the subsequent pressure-temperature dependence of the percolation threshold, require additional information to conclusively say it applies to conditions relevant to mined repository systems. The pressure and temperature conditions under which percolation could occur (assuming no kinetic barriers and assuming compositional and textural effects have no impact) might prevail at repository lithostatic stresses, but only on the surface of waste canisters. These conditions might only exist in the engineered barrier system of a mined repository, not in the surrounding host rock. Questions remain regarding the impacts of the stark differences in mineralogical composition, grain size, texture, and brine chemistry between the UT laboratory experiments and numerical models and realistic bedded or domal salt deposits. These differences may further modify the idealized theory, or prevent repository systems from reaching the textural equilibrium during performance-assessment relevant time periods. Controlled testing of salt permeability remains to be done using relevant laboratory and field methods, as a function of pressure and temperature.

Regarding Percolation – Input from Abe van Luik

Upon publication of Ghanbarzadeh et al. (2015) *Deformation-assisted fluid percolation in salt*, Dr. Abraham van Luik took a proactive interest largely because sensational press releases declared “nuclear waste storage in rock salt may be more vulnerable than previously thought” (University of Texas, 2015). Similar alarm was sounded in Germany, where salt formations continue to be considered for disposal of heat-generating nuclear waste (Popp and Minkley 2016—7th Proceedings). Abe worked diligently and creatively to reconcile dramatic news releases with scientific evidence. Unfortunately, Abe died before resolution was obtained.

To Abe’s credit, he helped organize a percolation break-out session at the 7th US/German Workshop on Salt Repository Research, Design and Operation. Abe’s goal had been to collaborate with UT and write a joint response that (1) gives the basis for the UT repository-related recommendations and observations and (2) provides documented information showing the recommended work has already been done (both in the US and in Germany) concluding selected salt bodies to be stable for geological timeframes of interest. Abe wanted agreement that US and German repository salt host rocks in use or under consideration are indeed likely to be stable and need not anticipate deformation-assisted enhancements in percolation.

Chapter 6 of these Proceedings is dedicated to Dr. Abraham van Luik, a steadfast supporter of international collaboration in repository science and engineering.

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8 CONCLUDING REMARKS

Most the agenda for the 7th US/German Workshop on Salt Repository Research, Design and Operation derived from discussions at the 6th workshop. Typically, a consensus of topical areas is developed and modified slightly to accommodate arising issues, such as adding percolation to the 7th workshop.

The safety case remains an overarching subject of interest, including development of a universal salt features, events, and processes (FEPs) database. Discussion of the safety case in the 7th workshop probed the relationship between long-term safety and operational safety, a topic of great interest for waste management organizations, NEA and IAEA. Impact of operational choices for a salt repository may be superior to other geologic media because of the potential to engineer barriers with properties relevant to long-term performance.

Geomechanics modeling and testing continue to address our collective ability to predict performance of a salt environment. Having identified and prioritized laboratory testing of WIPP salt, an improved dataset will help modelers mechanistically describe underground evolution. Geomechanics continue to be a cornerstone in future collaboration.

As noted, emphasis of annual workshops progresses from year to year. Several topics reached noteworthy maturity, for example features, events, and processes analysis, granular salt reconsolidation, and the safety case. Ongoing collaboration continues on these topics and in several cases joint reports have been prepared or are in process. New issues arise and occasionally old, residual contentions warrant revisiting. For example, deformation-assisted percolation was added to the 2016 workshop because of controversy introduced to international media about its importance to salt repositories.

Review and preview of the technical agenda are important to timeliness and pertinence of these workshops. For example, after the 5th workshop in Santa Fe, participants prioritized a salt testing matrix, for which core was sent to German partners. This testing provides data to joint project WEIMOS.

Operational safety has been highlighted in the 4th workshop 2013 in Berlin, before the truck fire and radiological release at Waste Isolation Pilot Plant, which underscores how vital this topic remains. Therefore, as the 7th workshop ended, participants dedicated a short brainstorm period to identify ***Grand Challenges***, which may be developed in future collaborations.

Suggestions for 12 areas of exploration and cooperation were captured:

1. Salt primer,
2. Trapped gas,
3. Two-phase flow,
4. Waste packages and future implications,
5. Accommodating human error,
6. Transient responses to large pressure change,
7. Low deviatoric stress deformation mechanism,
8. Uncertainty quantification in thermomechanical models,
9. Lab/field tests for model validation, confidence building,
10. Benchmark/test/qualification for performance assessment models,
11. Temperature effects (e.g., TM to THM), and
12. Monitoring short- and long-term.

The listing from 1 to 12 does not imply priority; it was simply the order in which ideas were brought forth. A brief description of each idea is provided subsequently.

Salt primer: The idea is to collaborate on a salt primer containing a state-of-the-art synopsis of salt repository applications. The primer could include basic salt information leading to mechanical, hydrological and thermal behavior. A chapter on laboratory test techniques would explain how salt material properties are obtained. Isochoric deformation as well as damage and healing would comprise another chapter on mechanical behavior. Reconsolidation of granular salt for seal systems and long-term performance might be an appropriate chapter. Numerical modeling and applications would show how this foundation of data is applied to salt repositories. The primer could serve as a text book for college professors, short courses, or general reference. Moreover, it could serve as an "instrument" for knowledge management purposes.

Trapped gas: In the context of long-term safety assessment different gas sources were discussed in the past, e.g., radiolysis, corrosion, microbiological processes, and so on. The issue of trapped gas has multiple lines of potential importance. First, the simple issue of trapped gas has not been discussed—when the repository is backfilled with crushed salt air remains in the void space under normal pressure and temperature conditions. With increasing compaction and heating, gas pressure rises. If the gas was contaminated by gaseous radionuclides and the fluid pressure criterion exceeded, migration might occur. A second related observation involves trapped air when concreting horizontal geotechnical barriers. If the vent position is inaccurate the effective length of the barrier can be reduced. A third example involves a small amount of air trapped while filling a pressure chamber with brine. Gas compressibility can create a significant damping effect. This phenomenon can be directly related to safety case calculations. A collaborative research project is proposed to document what we already know and using additional information from cavern technology where gas cushions keep the internal pressure constant. Analogues such as the carbon dioxide glacier of Unterbreizbach would add to this proposed research.

Two-phase flow: Two-phase flow of brine and air through low permeability porous media is the dominant fluid flow state in and around geologic repositories. Even for initially saturated systems, excavation effects and thermal dry-out due to heat-generating waste lead to establishment of multiple fluid components and phases. Thus, successful numerical modeling of geologic disposal of nuclear waste in salt formations requires validated and verified constitutive models for brine and gas flow through intact, damaged, and reconsolidating crushed salt. Two-phase flow models for waste release scenarios in a geologic repository require constitutive relations for capillary pressure and relative permeability of the geologic medium. These media-specific empirical models require experimental measurement to parameterize and validate. Constitutive models developed for other subsurface media have been adopted but not experimentally parameterized for geologic salt, because experimental challenges are imposing. To date, no satisfactorily outcomes exist. Without direct measurements of important physical properties for geologic media of interest, the approach of relying on proxy data can lead to unquantified and uncharacterized uncertainties in distributions used in repository model calculations. (Note: Approximations and influence of uncertainties remain important in several areas.)

Waste packages and future implications: Waste inventory planned for geologic disposal has been accumulating for 60 years. Poor records and variable evolving strategies further complicate the relationship between inventory and disposal. As a case in point, US policy decisions coupled with interminable delay in geologic repository operations has contributed to major changes in waste packaging. Current storage decisions, future necessities of reactors, multiple designs for dry storage, and waste aging/evolution portend enormous issues for handling, transportation, and disposal. This is also applicable to Germany because there is no final disposal container concept, the licensing phase of storage containers will expire, and a final repository might not be available until 2050 or later. Given the historic time estimated to begin geologic disposal the wide variety of size, shape, weight and content creates a burgeoning issue for geologic disposal. New or modified concepts might be appropriate.

Accommodating human error: To err is human. What measures can be taken in design and operation of salt repositories to lessen risk of human error? To begin, a philosophy called Integrated Safety Management System (ISMS) commonly appears in Administrative Control documents, exemplified at the Waste Isolation Pilot Plant by Sandia National Laboratories, Department of Energy/Carlsbad Field Office, and subcontractors. Providing a safe workplace is the objective of ISMS and derives from DOE guidance. Core functions of ISMS are 1) Define work, 2) Identify hazards, 3) Develop controls, 4) Perform work, and 5) Provide feedback. Education and training are important, but how can a system be made foolproof? Concepts of safety culture and regulatory influence will remain a key topic of future workshops. Accident risk reduction can be provided by designing jobs to be inherently safe, which can be achieved by simplifying processes, standardizing equipment, and avoiding reliance on memory. For workers, human error is minimized through barriers, engineered safeguards, personal protective equipment, warnings, and alarms. Specific to salt repositories, a design for disposal operations can be optimized in a fashion that minimizes risk and exposed real estate. A modular-build-and-close disposal operation can increase robustness of a salt repository and make the system less vulnerable when accidents happen. Modular disposal allows monitoring during operations and proof of performance.

Transient responses to large pressure change: Measurement of transient strain is a recognized challenge. If planned appropriately, *in situ* tests implemented in a salt research facility provide an opportunity to characterize the host rock before, during, and after excavation of test rooms. Characterization of a test bed is essential to interpret structural deformation, creation and evolution of the excavation damage zone, and measurement of first-order hydromechanical properties as salt evolves from an impermeable undisturbed state to a more-transmissive damaged state. Transient response includes room closure effects from the far-field salt deforming at low deviatoric stress as well as near-field structural response.

Low deviatoric stress deformation mechanism: Accurate prediction of salt response is reinforced by understanding mechanistic processes. Modelers have been able to capture observed physical phenomena in computational mechanics applications. Micromechanics helps explain history effects, normal transient response, inverse transients, and dependence of creep rate on stress difference and temperature, which are a direct consequence of existing and evolving substructures. An underlying tenant states that long-term prediction can be made reliably if physical processes are understood. Extending this principle to micromechanics of deformation at low stress difference is especially challenging in the laboratory. Test control must be exact and deformation measurement precise over long test periods. Microstructural changes would likely be below detection and evaluation using normal microscopic techniques. Nonetheless, creep behavior of salt at low stress differences appears to be substantially faster than predicted from extension of power law models based on dislocation creep mechanisms.

Uncertainty quantification in thermomechanical models: Practical geomechanical simulations are almost always rife with uncertainties that have significant effects on predictions. Fortunately, a wealth of literature exists on how to perform uncertainty quantification (UQ) studies that capture both main and interaction effects. Analysts, however, often hesitate to undertake such studies because of model form error. If the model used to describe the behavior of salt fails to capture crucial aspects of the underlying physics, then the entire uncertainty quantification study will be biased, possibly in unpredictable ways. Despite this risk, the analyst must determine when the model is "good enough" to use in a UQ study. These studies not only provide confidence bounds on a prediction, they also identify model inputs to which predictions are sensitive. Such information is critical when it comes time to quantify and accept limitations of the model and decide if it is appropriate for its application.

Lab/field tests for model validation: US and German salt scientists have often collaborated on laboratory and field tests, which build confidence and provide data for predictive modeling. Test results are commonly modeled; in fact, the joint project WEIMOS includes significant laboratory testing and modeling. Previous workshops have reviewed several decades of applicable field experiments—to such an extent that there has not been a defined test that must be conducted before a safety case can be prepared for salt disposal of heat-generating nuclear waste. If an underground facility became available, collaborators have already identified priorities for field testing: large-scale consolidation and drift-seal demonstration.

Benchmark/test/qualification for performance assessment models: Benchmarking structural geomechanical models constitutes a common collaboration activity between Germans and Americans. Usually, actual test results are available against which to validate models and compare results.

Testing and qualification of performance assessment codes (such as PFLOTRAN – RepoTREND) has been brought forward as a workshop activity. Evaluation in this manner does not involve comparison to field measurement. However, it may be possible to run code comparisons as a means to validate or qualify respective capabilities. A set of requirements will be needed to compare safety assessment codes.

Temperature effects (e.g., TM to THM): It was suggested mutually by German and US participants that a collaborative R&D activity be initiated with respect to management and analysis of uncertainties, both as a general subject and also with respect to certain key process important to salt repositories, such as coupled processes contributing to underground evolution.

Monitoring short- and long-term: In a salt repository, monitoring can be grouped in three primary areas. *Environmental* monitoring includes sampling and evaluation of air, surface water, groundwater, sediments, soils, and biota for radioactive contaminants. This type of monitoring determines public and environmental impact of the site. Comparisons are then possible between baseline data gathered before site operations and data generated during disposal operations.

Compliance monitoring activities comply with regulatory requirements for general siting, facility operations, and decommissioning. These requirements are identified in regulations, state agreements or organizational agreements.

Performance confirmation constitutes a program of tests, experiments, and analyses conducted to evaluate adequacy of information used to demonstrate compliance with site-specific pre-closure and post-closure performance objectives. Performance confirmation monitoring starts with initial site characterization and is completed at some point after site closure. What can be monitored during short-term operation that directly influences long-term performance? What should be monitored when?

The forgoing ideas for salt repository research, design and operation provide examples of the growing benefits possible through international collaboration. Several collaborative activities already touch upon *Grand-Challenge* ideas. As organizers compile themes for the 8th workshop, some of these ideas may be developed into agenda topics and break-out sessions.

At our Washington, DC meeting we agreed that COVRA (Central Organisation for Radioactive Waste (Centrale Organisatie Voor Radioactief Afval, (Dutch nuclear waste processing and storage company)) would host the 8th US/German Workshop on September 5-7, 2017 (Tuesday, Wednesday and Thursday). The Nuclear Energy Agency Salt Club agreed to a full day SC-7 meeting on Monday September 4, 2017—one day before the 8th US/German Workshop. Although the Salt Club and the US/German workshop are independent meetings, time and cost savings are realized by coordinating location and schedule. The Nuclear Energy Agency Salt Club meeting agenda and organization are the responsibility of the Salt Club Steering Committee. A preliminary agenda for the US/German workshop appears in the box below.

PRELIMINARY AGENDA

Tuesday Morning:

Introductions, greetings from host, German Ministries, US Department of Energy

Technical Keynote Address (longer than 20 minutes)

Tuesday Noon—1.5 to 2.0 hour for walking tour and lunch

Tuesday Afternoon:

Percolation Breakout—Popp/Kuhlman Leads

Reconsolidation Breakout—Wieczorek/Hansen Leads

BREAKOUT SESSIONS/SUMMARY

Wednesday Morning:

WEIMOS: (1) Hampel, (2) Reedlunn

Salt creep at low deviatoric stress (3) Bérest (invited)

KOSINA: (1) Status, (2) Bedded/Domal salt comparison (3) WIPP stratigraphy

BREAKOUT SESSIONS/SUMMARY

Wednesday Noon—1.5 to 2.0 hour for walking tour and lunch

Wednesday Afternoon:

Operational Safety: (1) Bollingerfehr, (2) WIPP status/geomechanics of recovery/future

Open for other ideas

Thursday

Grand Challenges: Comparison of performance assessment codes PFLOTRAN – RepoTREND

Open for other ideas

I shall pass this way but once; any good that I can do or any kindness I can show to any human being; let me do it now. Let me not defer nor neglect it, for I shall not pass this way again.

Etienne de Grellet

Quaker Missionary

APPENDIX A: AGENDA

ACTUAL Technical Agenda

7th US/German Workshop on Salt Repository Research, Design, and Operation

September 6 – Tuesday, NEA Salt Club Meeting same venue

September 7 - Wednesday

Day 1	8:00-8:45	Registration	
	8:45-9:00	Welcome organizers	F. Hansen, SNL W. Steininger, PTKA W. Bollingerfehr, DBE TEC
	9:00-9:20	Welcome DOE-EM	B. Forinash, Director National TRU Program
	9:20-9:40	Welcome BMWi	H.-C. Pape/H. Wirth, BMWi
	9:40-10:00	Welcome DOE-NE	J. Kotek, Assistant Secretary
	10:00-10:20	Germany's new approach for siting a HLW repository	V. Bräuer, BGR
	10:20-10:40	Break and ***Group Photo***	
	Safety Case Issues		
	10:40-11:00	IAEA International perspectives on repository safety	A. Orrell, IAEA
	11:00-11:20	Safety Case: German approach (e.g. KOSINA + VSG)	J. Wolf, GRS
	11:20-11:40	Regulatory perspectives on the Safety Case	K. Economy, EPA
	11:40-12:00	Safety Case: US approach for WIPP	P. Shoemaker, SNL
	12:00-12:30	Discussion of key technical issues	Leaders: A. Orrell, IAEA J. Wolf, GRS
	12:30-13:30	Lunch	
	Components of the Safety Case		
	13:30-13:50	Introduction Generic FEPs for salt formations	D. Sevougian, SNL J. Wolf, GRS
	13:50-14:10	NEA/IAEA Workshop on operational safety: Report and discussion	W. Bollingerfehr, DBE TEC
	14:10-14:30	First results of the KOSINA-project: technical concepts and geological and numerical modeling.	T. Kühnlenz, BGR + KOSINA-Team (DBE TEC, GRS, IfG)
	14:30-14:50	WIPP recovery and lessons learned	T. Reynolds, NWP
	14:50-15:10	The past Dutch disposal concepts in salt	E. Neeft, COVRA
	15:10-15:30	Break	
	Repository Design (focus: Operational Safety)		
	15:30-17:00	Discussion of key technical issues	Leaders: W. Bollingerfehr, DBE TEC D. Sevougian, SNL
	DINNER @ Ted's Montana Grill Crystal City 7pm		

Actual, September 23, 2016 SAND2016-5324 O

ACTUAL Technical Agenda

7th US/German Workshop on Salt Repository Research, Design, and Operation

September 8 - Thursday

Day 2

Geomechanical Issues		
9:00-9:20	Joint Project on constitutive models: Conclusions from phases I-III and introduction of project WEIMOS	A. Hampel, Hampel Consulting
9:20-9:40	Salt modeling	B. Reedlunn, SNL
9:40-10:00	Further important topics in Rock/Salt/Geomechanics	S. Fahland, BGR N. Müller-Hoeppe, DBE TEC
10:00-10:20	Arising issues in field, laboratory and modeling	L. Van Sambeek, RESPEC S. Buchholz, RESPEC
10:20-10:40	Break	
10:40-11:00	Comparison of salt cavern and repository modeling	S. Sobolik, SNL
11:00-11:20	Fluid dynamic processes within a closed repository with or without long-term monitoring	R. Wolters, TUC K.-H. Lux, TUC
11:20-11:40	Closure of the Teutschenthal backfill mine – challenge for a geomechanical safety concept	T. Popp, W. Minkley, IfG
11:40-12:00	Wrap-Up	Leaders: A. Hampel and B. Reedlunn
12:00-13:30	Lunch	
Plugging and Sealing		
13:30-13:50	Full scale demonstration of plugs and seals (EC-DOPAS-Project)	K. Wieczorek, GRS
13:50-14:10	Shaft seals for HLW-repositories (ELSA project)	W. Kudla, TU BAF P. Herold, DBE TEC
14:10-14:30	Asse II mine - Retrieval of the waste taking into account the best possible emergency preparedness	M. Mohlfeld, BfS
14:30-14:50	Current WIPP considerations of reconsolidating salt	C. Herrick, SNL
14:50-15:30	Discussion of key technical issues	Leaders: K. Wieczorek, GRS N. Müller-Hoeppe, DBE TEC
15:30-16:00	Break	
Percolation Issue		
16:00-16:20	Capillary controls on brine percolation in rock salt	M. Hesse, U Texas M. Prodanovic, U Texas
16:20-16:40	Comments of the German Association for Repository Research (DAEF)	T. Popp, IfG W. Minkley, IfG
16:40-17:00	Origin of fluids in salt domes	J. Hammer, BGR G. Zulauf, Uni Frankfurt
17:00-18:00	Discussion—Is percolation a safety issue for a HLW repository?	Leaders: K. Kuhlman, SNL J. Mönig, GRS

Actual, September 23, 2016 SAND2016-5324 O

ACTUAL Technical Agenda

7th US/German Workshop on Salt Repository Research, Design, and Operation

September 9 - Friday

Day 3

Special Topics		
09:00-09:20	Impact of retrieval requirements on repository design	P. Herold, DBE TEC
09:20-09:40	US deep borehole program status	T. Gunter, DOE
09:40-10:00	Basin-scale density-dependent groundwater flow near a salt repository	A. Schneider, GRS K. Kuhlman, SNL
10:00-10:20	Issues on ageing of spent fuel storage systems	K. Sorenson, SNL H. Völzke, BAM
10:20-10:40	Break	
10:40-11:00	Chemistry/Thermodynamic database summary	M. Altmaier, KIT-INE, D. Reed, LANL
11:00-11:20	Announcements: 8th US/German Workshop SALTMECH 2018: https://www.saltmech.com/ 9th US/German Workshop	E. Neeft, COVRA S. Fahland, BGR
11:20-12:00	Wrap-Up (volunteers for chapter assignments for Proceedings)	F. Hansen, SNL W. Steininger, PTKA W. Bollingerfehr, DBE TEC
12:00-13:30	Lunch	

OPTIONAL: On Friday, September 9, those who are interested are invited to the Old Ebbitt Grill (only a few steps from the White House) for a non-hosted dinner. http://www.ebbitt.com/about/history

http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/2016-usgerman-workshop-on-salt-repository-research-design-and-operation/

APPENDIX B: WELCOME ADDRESSES:

Ms. Forinash
Summary of Talking Points for 7th Annual Workshop September 7, 2016

Ms. Forinash welcomed participants on behalf of the Office of Environmental Management within the Department of Energy. She emphasized the importance of salt repositories and the value of international collaboration, with the following observations:

From the earliest days of its national nuclear waste programs, the U.S. has looked to salt formations. The U.S. National Academy of Sciences examined the issue of deep disposal of nuclear waste and concluded that disposal in salt was the geologic medium "promising the most practical immediate solution." That was in 1957. Nearly 60 years later, experience has borne out the wisdom of that recommendation.

Both in the U.S. and in Germany, we've had successful repositories in salt that provide safe isolation for exactly the reasons the Academy named: salt is impermeable, self-sealing, and thermally conductive. From site characterization through the last 15 years of WIPP operation, what we have learned reinforces that the properties of a stable salt formation are exceptionally well-suited to provide the isolation and containment we seek for nuclear waste over centuries. As frustrating as the shut-down of the WIPP has been, the incidents at the facility do not in any way undermine our confidence in the long-term performance of the repository.

As much as we've learned, we continue to improve our understanding of the properties and the behavior of salt. And in this regard, international collaboration is incredibly valuable. The U.S.- Germany workshops have been extremely successful in bringing together our respective scientific communities to support our mutual interest in deep geologic salt repositories for radioactive waste disposal. Such joint efforts are cost-effective ways for researchers to share resources and results that address a wide swath of salt repository issues. This partnership also sustains knowledge preservation, passing down knowledge and documentation over decades.

The topics of the workshop and the results being presented are relevant on a very practical level. It is this work that will feed our understanding of how salt behaves, refine our modeling of repository performance, improve our operating practice, and build confidence in the safety case for radioactive waste disposal. This workshop is a model for the value of international cooperation: shared interests, research, resources, and results.

Mr Wirth

BMWi Address for 7th Annual Workshop September 7, 2016

Ladies and Gentlemen,

On behalf of the Federal Ministry for Economic Affairs and Energy, I would like to welcome you to our seventh U.S.-German Workshop on Salt Repository Research, Design and Operation. Just like its forerunners, this workshop has again been jointly organized by Sandia National Laboratories, DBE Technology, and the Project Management Agency in Karlsruhe. This year, many thanks to Sandia National Laboratories for all of the organizational efforts, and especially to Laura Connolly for all the hard work and her dedication organizing this workshop.

Ladies and Gentlemen,

Our cooperation is based on close personal contacts and excellent relations on the scientific and technological side, which in turn lead to a high level of mutual trust. Therefore, we are deeply saddened that we have lost two important personalities from our midst: Enrique Biurrun from Germany and Abe van Luik from the U.S.

Both had been working in the field of radioactive waste for a very long time and with great dedication. Both colleagues contributed a great deal to our workshops, and were involved in the founding and establishment of the NEA Salt Club in 2012.

With great personal dedication and commitment, they contributed their scientific expertise to our joint research activities. They supported and fostered the solidarity within our research community, transcending borders and continents.

They will always be remembered with great respect.

Ladies and Gentlemen,

It was almost exactly five years ago that the U.S. Department of Energy and the German Federal Ministry for Economic Affairs and Energy signed their Memorandum of Understanding.

In doing so, they stated that they were serious about jointly pursuing research and development on final disposal in rock salt. And beyond that, there are additional issues of common interest.

I am pleased that the Department of Energy is represented here at our workshop. Let me give a special welcome to Ms. Forinash and Ms. Bushman from the Office of Environmental Management, and to Mr. Kotek and Mr. Gunter from the Office of Nuclear Energy.

The fact that this workshop is being attended by you shows us the importance of our bilateral research cooperation for both countries.

This cooperation is still considered highly important, and is greatly appreciated. This is underlined by the fact that some 50 colleagues from United States and Europe have joined us here today.

Once again, salt experts from the U.S., the Netherlands and Germany are attending the workshop. They are taking the opportunity to inform and update one another about the latest developments in their field of research; some activities are the results of joint undertakings.

Besides the usual issues there are also some new topics on the agenda, including questions about containers. Discussions about these topics will be helpful as we contemplate future joint research activities.

Our annual workshop is well-established and has become a sort of flagship for U.S.-German cooperation. Moreover, it is also a sort of initiator for new aspects to be looked at, for instance, the topics of operational safety and container aging. It is also important to mention in this context that participants in this workshop were not only involved in the establishment of the NEA Salt Club, but are also very active members of this body.

Ladies and Gentlemen,

What has changed in Germany since we met in Dresden last September? I'd like to briefly inform you about this and how these changes might possibly influence our work. Let me start with some words about Germany's energy policy, and how it is linked to nuclear waste disposal.

The German energy transition policy is still one of the most important political projects for Germany. We understand the 'energy transition' as a process towards an increased share of renewables in our energy supply system and an improvement in energy efficiency. As you may know, Germany is gradually phasing out nuclear, with the last nuclear power plant to be shut down in 2022. Consequently, it is deemed necessary to ensure that the nuclear waste is adequately disposed of.

Since we last met in Dresden, the regulatory and organizational framework for future nuclear waste management (including disposal) in Germany has been considerably further developed: two independent commissions have completed their work, and their findings are now being implemented in new legislative and organizational measures.

In adopting the 2013 Repository Site Selection Act and by establishing the "Commission on Storage of High-Level Radioactive Waste Material" – the Repository Commission –, Germany paved the way for the siting procedure for a final repository, a procedure that starts with a "white map" and without pre-determined answers.

The Repository Commission compiled its recommendations in a final report. The report was submitted in the middle of this year, as scheduled, to the Bundestag, the

Bundesrat, and the German Government. The recommendations concern organizational and technical matters, as well as important aspects of public participation. The report is key to ensuring a long-term, strategic approach to the disposal of high-level waste in Germany.

In their recommendations, the experts favor disposal in deep geological formations. All three types of host rock are given the same level of attention. As far as rock salt is concerned, the Commission recommends in general to continue research and technology and to advance the state-of-the-art, also addressing the bedded salt formations.

A key point that was subject to lively discussions within the Repository Commission was the new organizational framework concerning responsibilities around final disposal, also having in mind the European Directive.

The new organizational structure mirrors the separation of regulator and implementer. The regulatory body is BfE, the Federal Office for the Safety of Nuclear Waste Management (Bundesamt für kerntechnische Entsorgungssicherheit), and the implementer is BGE, Bundesgesellschaft für Endlagerung, a newly founded state-owned company responsible for final disposal. Both these institutions will be under the jurisdiction of the Federal Ministry of the Environment. The implementer will be formed by merging a department of the Federal Office for Radiation Protection (the former implementing body), Asse GmbH (a limited company), and DBE. This possibly might mean that some of our colleagues may be wearing a new hat when we meet next year.

Ladies and Gentlemen,

The second independent Commission, the “Commission on the financing of the nuclear phase-out”, the KFK Commission, was created by the German Government last October. The objective was to draw up recommendations as to how to organize the financing for the decommissioning and dismantling of German nuclear power plants and for the management of nuclear waste in such a way that companies will be capable of meeting their long-term obligations under nuclear law.

The recommendations were adopted unanimously by the KFK Commission at the end of April. The KFK Commission proposes that the responsibility for the implementation and the financing of the disposal of nuclear waste be merged:

- the nuclear plant operators are to retain responsibility for the implementation and reserves-based financing of the dismantling.
- the state alone is to be responsible for interim storage and final disposal, using a company-financed fund.

The report was examined by the Federal Ministry for Economic Affairs and Energy with the other relevant ministries so that the necessary steps could be taken. The German Government has decided to implement the Commission’s recommendations and to create the appropriate legal basis.

Ladies and Gentlemen,

The Repository Site Selection Act and the recommendations of the Repository Commission also require us to keep developing the state-of-the-art of science and technology. Therefore, scientific work and R&D into disposal will be necessary. This will be supported by international cooperation and the respective expertise.

The Federal Ministry for Economic Affairs and Energy is responsible for not-site-specific project-funded R&D regarding disposal. The Project Management Agency Karlsruhe supports the Ministry. The basis for R&D is the funding concept, ”Research into the Disposal of Radioactive Waste.”

This concept defines the Ministry’s priorities for research and development between 2015 and 2018:

- to intensify the general research into host rocks, i.e. without prioritising a specific type of rock;
- to consider prolonged interim storage, addressing the implications for containers and inventory;
- to consider alternative disposal options other than direct disposal in a mined repository (e.g. very deep boreholes, waste treatment), and finally
- to address socio-technological issues.

Throughout the research concept, conceptual questions should be clarified concerning disposal in bedded rock salt. In this respect the cooperation with the U.S. is very valuable as well and mirrored in the KOSINA R&D project. KOSINA aims at addressing conceptual approaches of this repository concept. For this reason, areas of mutual interest were identified (including the creation of generic models, use of an FEP catalogue developed by Sandia National Laboratories, and a comparison between various numerical simulations using different computer codes).

Furthermore, there are some very important questions to be pointed out around conceptual and long-term safety issues. The WEIMOS project, a flagship project of U.S.-German cooperation addressing these questions, is of great benefit for both countries. Both projects will be on the agenda of this workshop.

In Germany, as mentioned, research conducted into clay and crystalline rock is also to be intensified within our Ministry’s funding concept.

Because international cooperation is considered important for the implementation of the Ministry’s strategy, BMWi plans to continue its commitment to international cooperation or even intensify it (e.g. cooperation in URLs).

Ladies and Gentlemen,

This workshop also serves to promote the technological development in the various areas that are being addressed.

Key issues still important for disposal in rock salt concern questions related to geomechanics will be discussed tomorrow. Other key issues address safety case issues and operational safety questions, the latter being a demanding issue which becomes increasingly important for advanced programs in the licensing phase. Moreover, the topics of sealing and plugging play an important role and will also be discussed.

During the workshop a special session is devoted to the percolation issue. This subject has been discussed among scientists and – as far as Germany is concerned – also within a sort of political frame. However, the political debate was governed less by science and more by agendas. Therefore, this workshop should provide a platform for a good and open scientific discussion. We are looking forward to hearing from our U.S. and German experts on this issue and express our gratitude to the American colleagues from the University of Texas joining us today.

Let me also point out that Friday's "special topics" session will address some very interesting topics with presentations on groundwater modeling, radiochemistry, and the technical requirements necessary in case waste has to be retrieved. Moreover, and of particular interest to Germany because of the Repository Commission's interest, are the issues of container aging (which is important in the context of prolonged interim storage), and very deep borehole disposal.

Ladies and Gentlemen,

We are convinced that our joint research is essential to get a better understanding about the properties of rock salt as well as about conceptual and safety related questions. It is also important to view, reflect on and discuss issues of mutual interest. We feel that it is also essential for BMWi's research concept.

The United States continues to be our number-one international research partner concerning rock salt. We are also pleased that a representative of COVRA from the Netherlands is again attending this workshop. And as far as Germany is concerned, I confirm that we are willing to make our contributions in sharing our expertise on salt to tackle future challenges. The cooperation provides by its synergies an advantage for all national programs of the partners. We can all benefit from the findings, both in scientific and economic terms, and continue our work using the knowledge and expertise of what we have already achieved. This is what makes this cooperation so valuable for all of us – and, by the way, for the Salt Club, which met here yesterday, and the countries involved in it.

Ladies and Gentlemen,

I´d like to emphasize that, seen from a political perspective, rock salt is in Germany still a potential host rock for disposing of radioactive waste and therefore there is still a need for further future 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 workshop.

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS FROM 7TH WORKSHOP

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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 radionuclide chemistry in aqueous media (radionuclide solubility, complex formation, ionic strength effects). Dr. Altmaier is involved in several NEA related activities and is member of the German THEREDA project team. Dr. Altmaier has a strong interest in radioanalytical techniques 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.

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 honour 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.

Volkman Bräuer

Volkmar Bräuer studied geology at the Technical University of Karlsruhe and received his doctorate at the Hanover University. Since 1983 he has been working for the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover. His work focuses on the development of selection and suitability criteria regarding the selection of repository sites. He was project leader for the activities of the BGR at the Grimsel Test Site in Switzerland and conducted the investigations on the identification of repository sites in crystalline rocks in Germany. From 1995 to 1997 Volkmar Bräuer was delegated to the Federal Ministry of Economics and Technology and engaged as expert for nuclear waste management. From 1997 to 2007 he was co-ordinator of the Gorleben project for the disposal of radioactive waste. In 2007 he became head of the department “Engineering Geology, Geotechnology” at the BGR. Since 2009 he is head of the department “Underground space for storage and economic use.”

Stuart A. Buchholz

Mr. Buchholz is the manager of the Materials Testing Laboratory for RESPEC Consulting and Services in Rapid City, SD. 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 10 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

Nancy Buschman, PE, PMP

Nancy is a chemical engineer who worked as a process and project engineer in private industry before joining the Department of Energy (DOE) in 1991. She has overseen programs within the National Nuclear Security Administration, Office of Nuclear Energy, and Office of Environmental Management, particularly in the areas of technology development and nuclear materials and spent nuclear fuel (SNF) management. Nancy's education includes a BS degree in chemical engineering from the University of Maryland and an MS in Technical Management from the Johns Hopkins University. She is a licensed professional engineer, certified project management professional, and federal project director.

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 Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain Project. In 2010 she began her role as a WIPP regulator for the United States 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 (BGR), 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.

Betsy Forinash

Geoff Freeze

Geoff Freeze is an Engineer/Hydrogeologist at Sandia National Laboratories in Albuquerque, New Mexico. Mr. Freeze has 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 United States (US) (at both Yucca Mountain and the Waste Isolation Pilot Plant) and internationally, including 4 years as the Yucca Mountain Project Lead for Features, Events, and Processes (FEP). He is currently the Project Integration Manager for the Deep Borehole Field Test.

His radioactive waste performance assessment modeling experience ranges from the development and application of complex, highly coupled, site-specific, probabilistic system models in a legal/regulatory environment to simplified, generic, deterministic system models supporting FEP screening and scoping studies. His flow and transport modeling experience includes single- and multi-phase, saturated and unsaturated, dual-porosity and discrete fracture implementations, as well as evaluations of alternative remediation techniques.

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.

Mr. Freeze presented at the 3rd US/German Workshop on the topic of Safety Case for Salt Disposal of HLW/SNF and at the 4th and 5th US/German Workshops on the topic of FEPs.

Andy Griffith

Michael Gross

Tim Gunter

Jin Gwo

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. Before joining Sandia in 1988, he established the thermomechanical testing laboratory at RESPEC and earned a PhD at Texas A&M. For more than four decades he contributed significant original research in rock mechanics to the Waste Isolation

Pilot Plant and Yucca Mountain, as well as several multinational programs. The range of this effort included documentation of salt deformation mechanisms, development of salt-based concrete, research on granular salt reconsolidation, panel closure systems, shaft seal system design and analysis, geophysical material properties testing and publication, presentation, and defense of these works in a rigorous regulatory environment. He helped develop and assess performance confirmation programs at WIPP, Yucca Mountain and EU member nations. He participated widely in global repository sciences, IAEA training courses, US/German workshops, and served on the steering committee of the IGSC Salt Club and the Advisory Board for Conferences on the Mechanical Behavior of Salt. Frank was awarded the U.S. Rock Mechanics Applied Research Award. He is a Senior Scientist at Sandia National Laboratories, a registered professional engineer and an ASCE Fellow.

Philipp Herold

Philipp Herold studied mining engineering at Technical University Bergakademie Freiberg (Germany). He graduated in 2011 as mining engineer (M.Sc.). As part of his diploma thesis, he started working in the field of shaft sealing. Upon graduation, Philipp Herold started working as project engineer in the Research and Development Department of DBE TECHNOLOGY GmbH in Peine (Germany). This function covers mining-related tasks connected to the design of radioactive waste repositories, such as the design of repository layouts, sealing elements, equipment selection and design of ventilation systems. Since 2014, he has also been responsible for managing research and development projects.

Courtney Herrick

Marc Hesse

John Kotek

Kristopher Kuhlman

Kristopher Kuhlman is technical staff at Sandia National Laboratories. His research interests include ultra low-permeability rocks and geologic disposal of radioactive waste in mined repositories and boreholes. Kris worked for Sandia at the Waste Isolation Pilot Plant in Carlsbad before his current focus on deep borehole disposal. Kris got a BS in Geological Engineering from Colorado School of Mines and a PhD in Hydrology from University of Arizona.

Tatjana Kühnlenz

Christi Leigh

In October of 2007 Christi began the management of Sandia's Repository Investigations Department where she is still today. While in this assignment, Christi has assumed leadership for the science programs supporting certification of the Waste Isolation Pilot Plant. She is currently leading the salt R&D program funded by the US DOE Office of Fuel Cycle Technologies in the Used Fuel Disposition Campaign. Prior work at SNL focused on performance assessment, probabilistic risk assessment, and decision making for environmental problems in regulatory environments. She has been at SNL for thirty-one years. Beginning in 1989, Christi's emphasis has been in developing the technical basis for radioactive waste disposal, low-level, transuranic and high-level waste. Her technical contributions in the areas of geochemical, hydrological, and contaminant transport issues have supported performance assessments for both Yucca Mountain and the Waste Isolation Pilot Plant. She has also offered her expertise to the DOE on a number of surface soil remediation problems throughout the US.

Christi holds a Bachelors, Masters and PhD in Chemical Engineering from Arizona State University, Stanford University and the University of New Mexico, respectively.

Karl-Heinz Lux

Edward Matteo

Melissa Mills

Melissa Mills is a member of the technical staff at Sandia National Laboratories, and has been involved in several experimental research initiatives in the Nuclear Waste Research and Disposal Organization at SNL for the last 5 years. Contributed projects include thermal and chemical effects on clay minerals for repository design, iodide interaction with clay minerals, and compacted clay pellet percolation and diffusion studies. 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, mineralogical content, pore structure, and substructures by microscopic examination.

Wolfgang Minkley

Matthias Mohlfeld

Jörg Mönig

Jörg Mönig has a degree in Physical Chemistry from the Technical University of Berlin. Since 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.

Nina Müller-Hoeppe

Erika Neeft

Dr. Neeft is the technical coordinator of the Dutch research programme into geological disposal of radioactive waste at the waste management organisation COVRA. 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 IAEA Section Head for Waste and Environmental Safety, in the Division of Radiation, Transport and Waste Safety responsible for the development and promulgation of internationally accepted safety standards, requirements and guides for the 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 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 Sandia National Laboratories, providing leadership for program development initiatives involving all facets of the nuclear fuel cycle. He was responsible for Sandia's Lead Laboratory for Repository Systems program and led Sandia's completion of the post-closure performance assessment portions of the Yucca Mountain License Application. Prior to working on the Yucca Mountain Program, he was a manager for the Waste Isolation Pilot Plant and the National Transuranic Waste Management program. His professional experience spans technical and managerial roles for the US and international programs, including repository development and licensing, national policy development, regulatory framework development, site characterization studies, safety assessments and safety case development, and public confidence.

Teresa Orellana-Perez

Roberto Pabalan

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.

Maša Prodanović has been an associate professor at the Department of Petroleum and Geosystems Engineering, The University of Texas at Austin since September 2016. She holds a Bachelor of Science in Applied Mathematics from the University of Zagreb, Croatia and a PhD in Computational Applied Mathematics from Stony Brook University, New York, USA. She held an assistant professor position 2010-2016, a Research Associate position in the Center for Petroleum and Geosystems Engineering (UT Austin) 2007-2010, and prestigious J. T. Oden Postdoctoral Fellowship at the Institute of Computational Engineering and Sciences 2005-2007, prior to her current post. Her research interests include multiphase flow and image-based porous media characterization especially applied to microfractured media and tight media, pore network models, shale gas flow, particulate flow and formation damage, sediment mechanics, fracturing and ferrohydrodynamics. Most recently, she received NSF CAREER award in 2013, Interpore Procter & Gamble Research Award for Porous Media Research in 2014 as well as SPE Faculty Innovative Teaching Award in 2014. She organized and co-instructed three short courses on image analysis in porous media between 2011 and 2014. Finally, most recently she started Digital Rocks Portal, web-based repository of porous media images and related experimental and simulation data https://www.digitalrocksportal.org/

Donna Reed

Benjamin Redlunn

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 the Waste Isolation Pilot Plant.

Tammy Reynolds

Anke Richter

Anke Schneider

S. David Sevougian

Dr. S. David Sevougian is a principal member of the technical staff at Sandia National Laboratories, 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 spent nuclear fuel, 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.

Paul Shoemaker

Steven Sobolik

Steven Sobolik is a Principal Member of the Technical Staff at Sandia National Laboratories in Albuquerque, New Mexico. He is a mechanical engineer by degree, obtaining his Bachelor's and Master's degrees from Texas A&M University. He began his career performing high-velocity impact tests at the Sandia rocket sled track. For the past twenty years he has specialized in computational and experimental geomechanics, applied to radioactive waste repository projects such as the Yucca Mountain Project; underground oil storage caverns in salt formations for the US Strategic Petroleum Reserve; CO_2 sequestration, wellbore integrity, and other underground storage and geomechanical projects.

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, in particular 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.

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 (BAM). 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 (ESK-AZ), consultant for the IAEA and managing collaboration with several international partners.

Thilo von Berlepsch

Doug Weaver

Doug Weaver is a mechanical engineer with Los Alamos National Laboratory with nearly twenty-five years of experience in repository science and waste management, specifically in the areas of underground operations and test implementation. Doug has managed the underground Test Coordination Office, both at the Yucca Mountain Repository Project in Nevada and currently at the Waste Isolation Pilot Plant in Carlsbad, New Mexico.

Erik Webb

Erik manages the Geoscience Research & Applications Group, the core of Sandia’s geoscience capability with five departments centered around Geotechnology and Engineering, Geophysics and 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.

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, head of geotechnical section.

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 ten 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

Germany`s New Approach for Siting a HLW Repository

Dr. Volkmar Bräuer

7th US/German Workshop on
Salt Repository Research, Design and Operation

Washington, DC

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ABSTRACT

In consequence of a decision of the German government the use of nuclear energy for the industrial generation of electricity will end in 2022 at the latest. Against this background Germany resolved to take a new approach to look for a disposal facility for heat-generating radioactive waste in particular. On the basis of a transparent and scientifically-based procedure, a location is to be sought which guarantees optimal levels of safety for a period of one million years. The legislator stipulated that a "Commission for the Storage of High-level Radioactive Waste" with a pluralistic membership was to define the basic stipulations before the implementation of the actual site selection procedure. The recommendations together with the evaluated Site Selection Act (StandAG) are to be presented to the German Bundestag (national parliament) in 2016, and then to be enacted by parliament. Defining sites for underground exploration is to follow on from the end of surface exploration in 2023. The decision on a site is expected in 2031 after completion of the underground exploration and a comparison of the sites. The subsequent approval process is then expected to take several more years. The commission is of the opinion that the emplacement of high-level radioactive waste at the chosen site with the "best possible safety" will not begin until 2050, insofar as there are no unforeseen delays. The Repository Commission elaborated detailed recommendations on how the selection process should proceed. They are documented in a final report. The site regions to be explored will be identified based on the pre-defined criteria across the whole of the country – based on a white map of Germany. This means that those regions in Germany considered to be worthy of investigation after taking into consideration all of these criteria will only be revealed during the course of this site selection process. The potential host rocks which have been identified are salt, claystone and crystalline rocks.

Phase 1 of the site selection process begins with the exclusion of regions based on the exclusion criteria and minimum requirements. A comparative analysis is then undertaken on the basis of the existing data by applying the assessment criteria and the representative preliminary safety investigations. Surface exploration then takes place in phase 2 (involving drilling and seismic surveys) of those site regions identified in phase 1. This is then followed by underground exploration (constructing a mine and carrying out underground investigations) at those sites selected at the end of phase 2.

An additional need for more research will be required in Germany in future as a result of changes to legal frameworks, and the associated complete restart of the search for a disposal facility. The following thematic changes have arisen compared to the previous research programmes:

- More intense research activity in covering a range of potential host rocks (rock salt, clay stone, crystalline rocks)
- The analysis of longer interim storage of radioactive waste
- Scientific investigations on alternative disposal methods instead of direct disposal
- More intense incorporation of socio-technical issues

In addition to research work focused at a national level, international co-operation activities of German research institutes are also indispensable for disposal facility research. The most important component at the scientific-technical level is the collaboration in international rock laboratories, which is undertaken by Germany in particular because of a shortage of in-situ investigation possibilities within its own borders. Apart from geoscientific-technical research activities, it is also indispensable to implement socio-technical issues, which make it possible to transparently present and explain the current scientific understanding of technical and social issues to interested and critical members of the general public and all stakeholders.

Safety Case: German Approach [from ISIBEL to KOSINA]

Jens Wolf[1]

7th US/German Workshop on
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ABSTRACT

During the last decade the concept of the Safety Case has been internationally established. The Safety Case is a compilation of evidence, analyses and arguments that quantify and substantiate a claim that a repository will be safe. The Safety Case evolves stepwise from a preliminary stage into a more and more comprehensive stage. In Germany the idea of the Safety Case for the disposal of HLW has been discussed and developed in the context of R&D projects. Typical questions of Safety Case R&D are high-level analyses such as: How to achieve safety? How to demonstrate safety? How to manage uncertainties? How to communicate safety?

Starting from the general German regulatory requirements for the disposal of HLW, a methodological approach has been developed in several R&D projects, e.g. ISIBEL, that allows the derivation of a safety concept for a repository for domal salt. The safety concept is based on the safe containment of radioactive waste in a containment-providing rock zone (CRZ). On the basis of a few guiding principles, specific objectives were devised, which were used to identify strategic measures. These measures provide the basis for the detailed design and layout of the repository. A scenario development methodology was developed, which is an important tool for the management of uncertainties and forms the basis for the safety assessment. Each scenario is described in detail by FEP and their characteristics. Key elements of the safety assessment are the integrity proofs for the geological and geotechnical barriers and the analysis of the backfill compaction. The potential releases of radionuclides from the CRZ in the derived scenarios were evaluated against radiological safety indicators.

The most recent R&D work on Safety Case issues is the project KOSINA concerning the HLW disposal in bedded salt in Germany. In a first step a safety concept for a repository in bedded salt was established and compared to the safety concept for domal salt repositories. The presentation gives an introduction to the Safety Case R&D in Germany including recent results of the ISIBEL and KOSINA projects.

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WIPP and the Safety Case – A Regulator's Perspective

Kathleen Economy

7th US/German Workshop on
Salt Repository Research, Design, and Operation

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ABSTRACT

The United States Environmental Protection Agency (EPA) is the regulator of the Waste Isolation Pilot Plant (WIPP). The EPA certified WIPP in 1998, and recertifies WIPP every five years. A challenge in the recertification evaluation is to determine whether parameters and assumptions adopted in past certifications are acceptable based on an increased knowledge base. Since the initial certification there is an increased knowledgebase of our understanding of the behavior of salt that has been collected over the past twenty years. The Agency is re-evaluating those assumptions and parameters values adopted in the 1990's and determining whether they are aligned with this current understanding.

Because of this larger knowledge base, especially related to the behavior of salt post-excavation, there is a higher level of confidence in determining repository post-closure initial conditions and conditions outward to approximately 500 years. The Agency believes it is important to align Performance Assessment inputs parameters that are representative of these near-term conditions, then project outward to capture the uncertainties over the 10,000 year period. Aligning input parameters boosts the level of confidence in the predictions of long-term repository performance.

Joint US-German FEPs Catalog

S. David Sevougian*, Geoff Freeze*, Michael Gross**, Kris Kuhlman*, Christi Leigh*
Jens Wolf***, Dieter Buhmann***, and Jörg Mönig***
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ABSTRACT

This presentation describes a new organizational structure for the FEPs that characterize the potential post-closure performance of a deep geologic repository for spent nuclear fuel and high-level radioactive waste. FEPs are traditionally organized using a classification scheme that is based on two overlapping sets of categories: features (e.g., waste form, waste package, backfill, host rock, etc.) and multi-physics processes (e.g., thermal, chemical, mechanical, hydrologic). The categories are overlapping in the sense that a specific FEP (e.g., flow through the waste package) may be classified both by a feature category (e.g., waste package) and by a process category (e.g., hydrologic). As a result, related FEPs are not always mapped to the same category and it can be difficult to group and/or find all related FEPs within a FEP list. The new FEP organizational structure is built around a two-dimensional FEP classification matrix and is based on the concept that a FEP is typically a process or event acting upon or within a feature. The two-dimensional structure of the FEP matrix makes it easier to identify groups of related FEPs and thereby better inform post-closure 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 United States 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 either crystalline or argillaceous formations. Recent efforts have focused on a more logical organization and naming of individual FEPs within a given coupled-process category. For example, new thermal-hydrologic FEPs are generally organized by the nature of the driving force. This would include flow processes arising from bulk fluid pressure differences versus flow processes arising from capillary processes versus flow processes arising from gravity. Each individual FEP is then subdivided into “associated processes,” which represent those processes that are individually considered when constructing a predictive model for repository system performance, such as wicking, free convection, thin-film flow, fracture-matrix interactions, etc. An electronic database (www.saltfep.org), tied to the new FEP matrix structure, is being developed by GRS to facilitate FEP identification, documentation, analysis, and screening.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04- 94AL85000. This work is supported by DOE Office of Nuclear Energy, Office of Used Nuclear Fuel Disposition. The presentation associated with this abstract is SAND2016-8441C.

NEA/IAEA Workshop on Operational Safety

Wilhelm Bollingerfehr

7th US/German Workshop on
Salt Repository Research, Design, and Operation

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ABSTRACT

The NEA and IAEA held a joint *Workshop on Operational Safety of Geological Repositories* to evaluate the state of the art in operational safety at the OECD conference centre in Paris in July 2016. The purposes of the workshop were to (i) explore how implementers address operational safety in developing geological repositories for radioactive waste disposal, (ii), identify effective and practical design alternatives used to achieve operational safety in geological repositories, (iii), evaluate the adequacy and comprehensiveness of the existing regulatory framework guiding implementers in addressing operational safety in geological repositories and (iv), identify areas and topics that require further work. The 3-day-workshop comprised presentations in the morning, followed by small group discussions in the afternoon with concluding summaries afterwards. Implementers and regulators gave insights on their approaches to dealing with operational safety from a range of programmes. The programmes included those at an early stage of planning, where operational considerations are rather theoretical, as well as more advanced programmes, where operational safety is an immediate and pressing concern. Practical experience on how to deal with operational hazards is now available as well. The workshop revealed important challenges and questions in a number of areas. Examples are:

- Regulatory environment: demonstrating compliance with a wide range of relevant regulations, coordinating the work of multiple regulatory bodies, and resolving the current lack of international guidance specifically focused on the operational safety of geological repositories
- System design and controls: dealing with possible conflicts in requirements, (e.g. between fire safety requirements and provision of a good work environment during normal operations)
- Operational safety assessment and risk management: investigating the possibility to develop standardised high-level approaches, (e.g. to fire risk management), better justifying certain key model assumptions (e.g. regarding the temperatures and durations of fires)
- Monitoring and compliance control: clarifying regulatory expectations regarding monitoring at each licencing stage, and demonstrating and maintaining the reliability of monitoring equipment,

First Results of the KOSINA-Project: Technical Concepts, Geological Models and Numerical Modeling

Tatjana Kühnlenz & KOSINA-Team

7th US/German Workshop on
Salt Repository Research, Design and Operation

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ABSTRACT

In 2013 the German Government restarted the siting process for a HRW repository in Germany. The evaluation of all types of host rocks based on actual geological data is one of the most important elements of this process.

On behalf of the Federal Ministry for Economic Affairs and Energy (BMWi), the research & development project with the title "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" (German acronym: KOSINA) was launched in 2015 in order to investigate the host rock *bedded salt*. The main goal of the project is the development of a technical site-independent concept as well as a safety and safety demonstration concept for a repository for heat generating waste and spent fuel on the basis of generic, geological 3d models. These models were developed for two types of bedded formations: type "flat-bedded salt formation" and type "salt pillow."

All available geological data for bedded salt formations in Germany were evaluated, whereby the first results of the BASAL project ("Distribution and properties of flat-bedded salt formations in Germany;" 2014 – 2019) were included. This data was brought together with the minimum requirements regarding depth and thickness of geological barriers resulting in generic geological profiles, which represented the basis for the geological 3d models. For further characterization of the geomechanical integrity of a repository based on the 3d models, THM numerical calculations will be carried out in the future.

Two technical repository designs were provided: drift disposal of POLLUX® casks and horizontal borehole disposal of BSK (BSK-H) for flat-bedded salt formations as well as vertical borehole disposal of steel canisters "BSK" (BSK-V) type and direct disposal of transport and storage casks in short horizontal boreholes for salt pillow.

KOSINA project provides a technical-scientific basis for the safety oriented evaluation of repository systems in different host rocks according to the German site selection act and allows comparing safety of repository systems in different host rocks.

WIPP Recovery and Lessons Learned

Tammy R. Reynolds
7th US/German Workshop on
Salt Repository Research, Design, and Operation
Washington, DC
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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) facility mission is to provide a safe and permanent disposal location for government-owned transuranic (TRU) and TRU mixed wastes. The current WIPP mission includes the disposal of both contact handled waste (i.e., waste with a radiation level of less than 200 millirem per hour at the surface of the waste container) and RH waste (i.e., waste with a radiation level of equal to or greater than 200 millirem per hour but less than 1,000 rem per our) in the underground repository.

The United States Department of Energy (US DOE) was authorized by Public Law in 1979 to provide a research and development facility for demonstrating the safe permanent disposal of TRU wastes from national defense activities and program of the US, exempted from regulation by the US Nuclear Regulatory Commission. Construction of the WIPP site started in the early 1980s. WIPP began receipt and disposal of contact handled waste in March 1999, and RH waste in January 2007. The WIPP facility is classified as a Hazard Category 2 DOE Nonreactor Nuclear Facility.

On February 5, 2014, a fire occurred in the underground involving a salt haul truck. The event was investigated by a DOE appointed Accident Investigation Team, with issuance of report, U.S. Department of Energy Accident Investigation Report, Underground Salt Haul Truck Fire at the Waste Isolation Pilot Plant, February 5, 2014 on March 13, 2014.

On February 14, 2014, a radioactive release event occurred in the underground due to a chemical exothermic reaction in a drum noncompliant with the WIPP Waste Acceptance Criteria, involving a small release to the environment. The event was investigated by a DOE appointed Accident Investigation Team in two phases with issuance of reports, Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014 (Phase I) on April 22, 2014, and Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014 (Phase II) on April 16, 2015.

Recovery activities to allow the WIPP mission to resume have been ongoing since 2014 and are in the final stages. The recovery effort has included corrective actions and lessons learned to address infrastructure, programmatic and cultural changes necessary to prevent recurrence of events.

The Past Dutch Disposal Concepts

Erika A.C. Neeft, PhD

Ewoud V. Verhoef, PhD

7th US/German Workshop on Salt Repository Research, Design and Operation

Washington, DC, September 7-9, 2016

ABSTRACT

In the Netherlands, the research on geological disposal of radioactive waste started in the seventies of the previous century. The primary focus of investigations was on the disposal in rock salt. The goal is to progressively refine the disposal concept in successive research programs over the next decades. To do so, it is important to identify the similarities and differences between the past and present and understand how these developed over time. This presentation compares the disposal concepts of the past four decades and identifies the lessons learned using five questions:

1) Which types of waste were intended to be disposed of?
2) How is the geological disposal facility envisaged to be constructed?
3) How is the waste suggested to be emplaced?
4) How is the suggested geological disposal facility suggested to be closed?
5) How has the Dutch parliament / government responded to the disposal concepts?

The end-point management of the type of waste may provide some understanding of the investigated disposal concepts.

End-point management techniques considered during the different research programs

Type of waste	HLW	ILW	LLW
Before 1982	CSD-V to be disposed (not yet produced) SRRF sent back to US	To be disposed for those not suitable for ocean disposal	Ocean disposal
1982-1992; 1st program Disposal on Land OPLA	CSD-V to be disposed (not yet produced) SRRF sent back to US	To be disposed in a geological disposal facility (storage at least 100 years)	
1995-2001; 2nd program Commission Disposal Radioactive Waste CORA	CSD-V to be disposed (production started) SSRF to be disposed	To be disposed in a geological disposal facility (storage at least 100 years)	
2011-2016; 3rd program Research program into geological disposal of radioactive waste OPERA	CSD-V to be disposed SSRF to be disposed (storage ≥ 100 years)	To be disposed in a geological disposal facility if disposed in the Netherlands (storage at least 100 years).	
	Dutch participation in the ERDO-working group		

Abbreviations are Dutch acronyms of the titles of the research programs, H/I/LLW High/Intermediate/Low Level Waste, CSD-V vitrified HLW waste i.e. nuclear power waste processed in la Hague (France) or Sellafield (England), SRRF spent research reactor fuel, ERDO European Repository Development Organization

COVRA is the Dutch waste management organization (Central Organization for Radioactive Waste). COVRA collects waste, processes waste, stores waste for a period of at least 100 years and implements its eventual disposal. Since 2002, COVRA is a state-owned enterprise. and coordinates the Dutch research into geological disposal of radioactive waste since 2009.

The past Dutch disposal concepts	Waste investigated to be disposed in rock salt	Points of departure concept facility	Construction facility	Emplacement of waste	Closure disposal rooms	Reference	Response government / parliament	Reference
Before 1982	CSD-V 3500 MWe	-Domal salt -Top dome ≥ 250 m Earth'surface -facility surrounded by 200 m rock salt -disposal depth HLW: 800 m -vertical disposal galleries till 300 m in length	Switch method excavation from dissolution to dry drilling to limit corrosion equipment	-Free fall -Wire	Filling galleries with mixture of salt, clay and fly ash Plug: granulate bentonite Seal: salt-concrete & steel cover plate	Hamstra (1981) EUR7151 Hamstra (1985) EUR9566	Start OPLA; coordination Dutch geological survey	
	LILW 3500 MWe							
1982-1992 OPLA	Three different nuclear power scenarios	-facility in domal, pillow and bedded salt.	'conventional mining technique'	Road-like vehicles	-crushed salt and 'suitable material'	OPLA overview reports available in Dutch (1989) & (1993)	-a.o. disposal of HLW waste by making stacking of CSD-V	Government report in Dutch (1987)
		Boreholes with a length from 2000 to 2500 m in domal salt		Brine filled borehole to reduce impact in fall	-creep of salt		-Requirement waste to be retrievable	Parliament document in Dutch (1993)
1995-2001 CORA	CSD-V	-disposal depth 800 m -short horizontal disposal galleries to dispose 1 container	'conventional mining technique'	Road-like vehicles	-'suitable material'	CORA reports most available in Dutch (2001)	Retrievability of waste is possible	Parliament document in Dutch (2002)
2011-2016 OPERA	All Dutch waste	Not determined	Selection of Dutch research OPLA and CORA available in English Hart (2015) OPERA-PU-NRG211A/B				Coordination COVRA	

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Joint Project on Constitutive Models: Conclusions from Phases I – III and Introduction of Project WEIMOS

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ABSTRACT

Well-tested constitutive models and calculation procedures are required for reliable numerical simulations performed for the design, stability analysis, and evaluation of the long-term behavior of underground repositories for radioactive wastes in rock salt. A main goal of the calculations is to check and prove the long-term integrity of the geological barrier.

In three joint projects between 2004 and 2016, constitutive models for the thermo-mechanical behavior of rock salt were tested and compared by the following partners: From Germany: Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (BGR, project I); Dr. Andreas Hampel, Scientific Consultant, Mainz; Institut für Gebirgsmechanik GmbH (IfG), Leipzig; Karlsruher Institut für Technologie (KIT); Leibniz Universität Hannover (LUH); Technische Universität Clausthal (TUC); Technische Universität Braunschweig (TUBS, project III); from the United States: Sandia National Laboratories, Albuquerque and Carlsbad, NM, (project III).

In these studies, numerous recalculations of systematic laboratory tests and simulations of selected underground structures were performed in order to check the ability of the involved models to describe reliably the deformation phenomena in rock salt – transient and steady-state creep, evolution of damage and dilatancy (volumetric strains), creep failure and short-term strength, post-failure behavior and residual strength – and their dependences of in-situ relevant boundary conditions – stresses, temperatures, and deformation rates – in a wide range.

The partners performed the calculations successfully and the results were in good agreement with each other and with experimental results from the laboratory and from in-situ measurements. This demonstrates the applicability of the involved models and confirms that the partners do have appropriate tools for model calculations.

The studies have also revealed needs for the further development of the models in four topics:

- Deformation behavior at small deviatoric stresses
- Influence of temperature and stress state on the damage reduction
- Deformation behavior resulting from tensile stresses
- Influence of inhomogeneities (layer boundaries, interfaces) on deformation

These subjects are explored experimentally and theoretically in the new joint project WEIMOS (English title: "Joint project: Further development and qualification of the rock mechanical modeling for a HLW disposal in rock salt", period: April 1st, 2016 – March 31st, 2019) of the partners Dr. Hampel, IfG Leipzig, LU Hannover, TU Braunschweig, TU Clausthal, and Sandia National Laboratories.

Reinvestigation into Closure Predictions of Room D at the Waste Isolation Pilot Plant

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ABSTRACT

Room D was an *in situ*, isothermal, underground experiment conducted at the Waste Isolation Pilot Plant between 1984 and 1991. The room was carefully and redundantly instrumented to measure horizontal and vertical closure immediately upon excavation and for several years thereafter. Early finite-element simulations of salt creep around Room D under predicted vertical closure by 4.5×, causing investigators to explore a series of changes to the way Room D was modeled. Discrepancies between simulations and measurements were resolved through a series of adjustments to model parameters, which were openly acknowledged in published reports.

Interest in Room D has been rekindled recently by the U.S./German Joint Project III and Project WEIMOS, which seek to improve predictions of rock salt constitutive models. Joint Project participants calibrate their models solely against laboratory tests, and benchmark the models against underground experiments, such as room D. This presentation describes updating legacy Room D simulations to today's computational standards by rectifying several numerical issues. Subsequently, the constitutive model used in previous modeling is recalibrated against a suite of new laboratory creep experiments on salt extracted from the repository horizon of the Waste Isolation Pilot Plant. Simulations with the new, laboratory-based calibration under predict Room D vertical closure by 3.1×. A list of potential improvements is discussed.

Sandia National Laboratories is a multi-mission laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2016-8559 A.

Further Important Topics in Rock Salt Geomechanics

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ABSTRACT

At the 5th US/German Workshop 2014 the three main salt related topics

(1) how salt deforms in the long term
(2) integrity analysis of the rock salt barrier
(3) consolidation of crushed salt

have been identified in order to demonstrate the geomechanical integrity of the salt barrier for repositories in salt formations. As research continues in the US as well as in Germany the progress and recent results are compiled and discussed jointly in the framework of the US/German workshop. Additionally, issues still pending are returned to mind and it is checked whether new topics arose that may worth to be put on the agenda. The general progress will be illustrated by presenting new results and further topics.

To improve understanding how salt behaves the long term experiments first creep experiments at low deviatoric stresses were established and are running for more than 1 year now. Additionally, a high resolution creep test rig is under construction in order to improve the preciseness of strain measurement about a factor of 1000. It is aimed at to close the gap between strain rates achieved in laboratory and the natural strain rates existing due to salt uplift.

Considering the integrity analysis, as a new topic, the question was posed whether hydro-mechanical induced failure modes II or III exceeding the hydro-mechanical induced failure mode I – i. e. violating the fluid pressure criterion – may exist. Hypothetically, failure modes II and III were derived their relevance in practice – however - is an open question. In addition, percolation, as a physical process of fluid flow, is discussed regarding the underlying mechanisms and possible integrity criteria.

Regarding the consolidation of crushed salt, the consolidation state of backfill in the TSDE-test field was re-investigated after 15 y in the framework of the Asse site investigations. The porosity of the very dry backfill was further reduced reflecting the magnitude of the drift convergence. The influence of humidity and temperature on the consolidation ability of crushed backfill was investigated by laboratory tests performed within the Repoperm II Project.

Importance of Small Deviatoric Stresses on the Creep of Rock Salt

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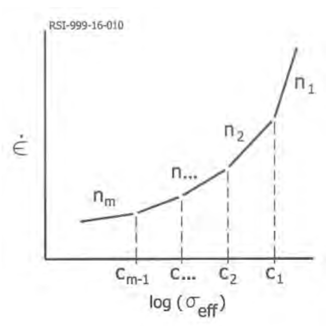
ABSTRACT

Creep is recognized as rock salt's primary deformation mechanism based on many years' of underground observations in salt and potash mines and laboratory testing. A common aspect of these observations, however, is that the measured creep deformations (rates) typically resulted from relative large rock stresses – whether in underground or in the laboratory. Because the preponderance of data are creep rates at these large stresses, the creep laws developed from the data are representative for large stresses, but the creep laws might not be suitable for small stresses. In general, this was not considered a problem until well-controlled field studies of structures in rock salt with pre-test and post-test numerical modeling of those field studies consistently under-predicted the measured behavior. A culprit in producing the too-small calculated response is that the commonly-used creep laws fail to predict the significant creep at small deviatoric stresses. Consequently, too-small structural responses are calculated. The prevailing argument has been that most of the creep deformation in a structure surely results because of the faster creep in the high-stress regions, and that ignoring or under-predicting slow creep in the lower-stress regions is inconsequential. That prevailing argument is wrong for one simple reason: on a volume basis, the vast majority of most salt structures has small stresses, and the cumulative effect of this large volume dominates or at least influences the structural response.

Since the stress distribution around the structure depends on the active creep mechanisms, a complex multi-mechanism creep can be simplified by using a piece-wise linear (or multilinear segmented) representation. A general solution was developed for multilinear creep law with three or more power-law segments, which allows easy estimation of the influence for particular combinations of different stress exponents. For example, creep strain rates as a function of a low-, multiple intermediate-, and a high-stress regime are hypothetically illustrated in figure. Using an analytical solution for stress distributions around a circular opening (open wellbore or cavern) for a multilinear segmented creep law reveals a factor of 10 increase in volumetric closure rate when including four creep-law segments with progressively smaller stress exponents but larger coefficients compared to a single segment with the same largest stress exponent and a smallest coefficient. In retrospect, such a result is mandatory even in a qualitative sense. The principle of strain compatibility requires that as an element of salt creeps "toward" the opening, another element of salt must creep into the formerly occupied location. In other words, the deformation caused by creep cannot create any voids or change in the volume of salt. Nearest the opening, the effective stresses are greatest; farther from the opening, the effective stress is smaller; however, the volume of salt with smaller effective stresses is vastly greater than the volume of salt with larger effective stresses. In an axisymmetric situation, the "radius-squared deformation dependency" must be the same for each area. If not, either a void in the salt would develop or the volume of salt would need to change, and neither is permissible in pure creep.



A Comparison of Salt Cavern and Repository Modeling

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ABSTRACT

The US-German Workshops have focused their efforts on developing a thorough understanding of salt repository design, analysis, operations, and long-term predictions. A necessary component of these efforts is predictive modeling of the mechanical behavior of the repository during the operational period and long-term. Validation of these models requires comparison with available stress and closure data from field measurements, such as from WIPP Rooms B & D. In the development of these models, salt mechanical properties such as creep, strength, and dilatancy envelopes are based on values obtained from laboratory tests on a number of samples from the site. However, regardless of the choice of creep model or the number of laboratory samples tested, there is inevitably some discrepancy between model results with observed behavior that requires either some modification of the conceptual model (e.g., the addition of slip along clay seams) or some "parameter adjustment" to obtain better agreement. It is incumbent on the modelers to carefully examine discrepancies between behavior predicted by models and that observed at full-scale.

Repository modeling might benefit from similar experience and applications to oil-storage caverns in domal salt. This discussion describes an evolution of geomechanical modeling of cavern mechanical behavior. Salt cavern geomechanical modeling began as a tool to predict surface subsidence and cavern volume closure over periods of 20 years or more. Early analyses used a simple steady-state creep model with a reduced elastic modulus to simulate transient response. Simplified salt dome and cavern geometric models were thought to be sufficient for such analyses. Subsequently, more cavern-specific and operational requirements were placed on the application of cavern modeling, such as identifying cavern geometries with high potential for dilatant cracking, evaluating effects on casings due to transient workover operations, and predicting cavern creep response when adjacent caverns experience workovers. As a result, cavern modelers have upgraded creep models, mesh geometries, and material representations based on known features at each site. In addition, the heterogeneous nature of cavern volume closure at each site has required attempts to calibrate predicted cavern behavior by adjusting material parameters around each cavern, using 35+ years of cavern volume closure and subsidence data. These practices have improved the applicability of cavern modeling to operational concerns, and have reduced uncertainty in predicted results.

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Fluid Dynamic Processes within a Closed Repository with or without Long-Term Monitoring

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ABSTRACT

Regarding the disposal of high-level radioactive waste within a repository in deep geological formations, different concepts are discussed in the international community. These concepts are not only different because of different availability of host rock formations in different nations, but also due to different demands on a long-term monitoring option to check the repository's behaviour over time. In Germany, according to its final report, the “Endlagerkommission” prefers a repository in deep geological formations, but reversibility of decisions as well as retrievability of waste canisters implied by significant improvements of scientific knowledge and technology or by an unexpected development of the repository system should be possible for future generations. A long-term monitoring option should be implemented into the repository concept to provide data about the time-dependent physical as well as the chemical situation within the repository system.

A long-term monitoring could be performed only within special observation parts of the repository, like it is considered in the Swiss concept, but in this case there will not be any data available about the situation within the main part of the repository system. Due to this, a long-term monitoring of at least preselected representative parts of the main repository or even of every single emplacement drift seems to be more suitable. This second approach is investigated in the framework of the ENTRIA-project for the drift emplacement concept, analyzing the influence of a long-term monitoring not only on the repository system's load-bearing behaviour during operational phase and during a limited monitoring phase afterwards by project partner TU Braunschweig, but also on the fluid dynamic processes as well as on barrier integrity within the emplacement drifts on the smaller scale and the whole repository system on the bigger scale by Chair in Waste Disposal and Geomechanics of Clausthal University of Technology.

For analysis of the time- and space-dependent development of fluid dynamic processes occurring in the totally backfilled emplacement level as well as in the rest of a repository system with or without implementation of a long-term monitoring option built in a salt rock formation based physical modelling and numerical simulation, a complex simulation tool has been developed at Chair in Waste Disposal and Geomechanics of Clausthal University of Technology within the framework of the ENTRIA-project.

Closure of the Teutschenthal Backfill Mine - Challenge for a Geomechanical Safety Concept -

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ABSTRACT

Underground disposal of hazardous waste (UTD) offers the possibility of permanent and safe disposal, particularly for so-called conventional wastes (with a high proportion of toxic water-soluble materials and heavy metals). In Germany the 'TA Abfall' (Technical Instructions on Waste) only allows the construction and operation of underground disposals in salt formations. The unique host rock properties of salt rocks enable a fast and total inclusion / encapsulation of the waste and its hazardous constituents without any further barriers needed (in the best case). Furthermore, the utilization of non-mining wastes in salt mines is common for backfilling of unstable underground openings (UTV). The experiences gained from both mining applications in the past may act as industrial analogues giving useful practical information on aspects such as the design of tunnel backfills, plugs and seals for construction of radioactive waste repositories.

As prerequisite, both for UTD and UTV, a site-specific safety assessment of the random conditions (e.g. geological barrier, hydrology) has to be performed to verify that the waste will be separated from the biosphere permanently and reliably. If the used salt rock formation shows any deficits (e.g. homogeneity, thickness) properties of the host rock might become offset by means of a so-called multi-barrier system, consisting e.g. of geotechnical shaft and drift seals.

As an example with special challenges regarding the geological and mining random conditions the special situation of former potash salt mine Teutschenthal will be presented. Due to the risk of rock bursts backfilling measures with hazardous waste are being performed by the company GTS (Grube Teutschenthal Sicherungs GmbH & Co. KG) in the mined carnallite areas since 1992. Because most of the originally more than 15 mio. m^3 underground openings are successfully backfilled the remaining stabilization period is around 10 y. Currently the planning run for the decommissioning of the mine consisting of a sophisticated safety concept. This paper provides a comprehensive overview of the current status and geotechnical closure concepts.

DOPAS: Full-Scale Demonstration of the Feasibility and Performance of Plugs and Seals – German Contribution: CH/HM Coupled Behaviour of Shaft Sealing Materials

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ABSTRACT

THE EC-cofinanced DOPAS project includes design, implementation and assessment of five experiments on plugs and seals. Three large-scale experiments are performed in crystalline rock by SKB (Sweden), POSIVA (Finland) and SURAO/CTU (Czech Republic), one performed by ANDRA (France) addresses a seal in clay rock. The fifth (German) contribution includes lab experiments and performance assessment studies related to salt. In this frame, the investigation programme of GRS addresses sealing materials planned to be used in the shaft seals. The issues addressed comprise the chemical-hydraulic (CH) and the hydro-mechanical (HM) behaviour of cement based sealing materials in rock salt. A third topic, the hydro-mechanical behaviour of claystone-bentonite-mixture as seal material, is not discussed here.

Samples of rock salt and salt concrete were obtained from an existing drift seal element finished in 1992 and underwent testing with respect to long-term deformation and damage behaviour. In the meantime, the CH behaviour of sorel concrete (MgO-based concrete) samples prepared in the laboratory was investigated by corrosion and diffusion experiments. In particular, advection experiments with NaCl and $MgCl_2$-saturated brines were performed. $MgCl_2$-saturated brine is corrosive for salt concrete, while NaCl brine is corrosive for sorel concrete. When sorel concrete is subjected to NaCl brine, corrosion leads to an expected increase in permeability after 7 – 60 days, however, afterwards no additionally permeability increase is observed. The interpretation is that the solution passes the sample fast enough that the brine in the already corroded concrete is not replaced, which protects the material farther away from the pathways. A major part of the experiments is dedicated to the investigation of the combined system of plug, contact zone (the main pathway) and surrounding (damaged) rock salt. Hollow salt cylinders equipped with salt concrete cores were used for this. Samples are subjected to radial load and axial flow (gas or brine). At dry conditions, reconsolidation is slow, while a fast reduction of permeability is observed, if brine is present and the seal element is intact.

In one of the experiments, the sample is subjected to radial load and axial flow with NaCl and afterwards $MgCl_2$-saturated solution. In the first phase (with NaCl solution), permeability decreases with time due to creep of the salt and closing of the contact zone. In the second phase, the solution is replaced by corrosive $MgCl_2$-saturated brine, which leads first to a permeability decrease because of brucite precipitation. The associated pH decrease to 8-9, however, causes decomposition of portlandite and CSH phases and leads to permeability increase in the longer term.

Future work includes dismantling of the samples and microscopic inspection for pathways.

Shaft Seals for HLW Repositories

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ABSTRACT

The R&D project "Shaft sealing systems for final repositories for high-level waste (ELSA) – Phase 2: Concept design for shaft seals and testing of functional elements of shaft seals," which is funded by the Federal Ministry for Economic Affairs and Energy (BMWi), was initiated to develop shaft sealing concepts for the two host rock options rock salt and claystone. These concepts are to be modular in design so that they can be adapted to suit the eventual site conditions. As no decision has yet been made on the choice of site for the final disposal of high-level waste and spent fuel, generic shaft sealing concepts have been developed based on currently existing host-rock data. Diversity and redundancy are basic design requirements for shaft sealing of repositories for high-level waste and spent fuel. Bitumen/asphalt will fulfill these basical requirements, in addition to clay-based sealing elements, such as binare mixtures of bentonite. Within the ELSA projcet, two already existing conceptual designs of bitumen/asphalt seals were tested in-situ and one new asphalt sealing system was developed and tested. All tests showed that sealing systems made of bitumen/asphalt lead to a permeability close to initial host rock permeability. Especially soft bitumen penetrates the EDZ and fills cracks, which was shown by a microstructure analysis of the removed bitumen seals. Additional, in-situ tests were realized for MgO-concrete and mixtures of crushed salt and clay. The in-situ tests of dynamic compaction of mixtures made of crushed salt and clay demonstrate the suitability of this technology for sealing construction. In a next step, the conventional equipment has to be modified for conditions inside a shaft. The use of MgO-concrete and mixtures of crushed salt and clay is limited to rock salt. Bimodal bentonite seals promissie functionally independent of the type of host rock. Sealing elements made of conventional binare bentonite mixtures and equipotential layers were tested in semi-scale tests, too.

Asse II Mine – Retrieval of Waste Taking into Account the Best Possible Emergency Preparedness

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ABSTRACT

The Asse II salt mine near Wolfenbüttel (Germany) is an approximately 100-year-old potash and salt mine. In early times the former operator used the Asse II mine as a “research mine” for the disposal of radioactive waste in salt formations. At the beginning of 2009, the Federal Office for Radiation Protection (BfS) took over operatorship for the Asse II mine. According to a comparison of possible options for the closure of the Asse II mine, the retrieving of the radioactive waste is, according to current knowledge, the only option for a safe decommissioning. Therefore, the decommissioning should take place after retrieving the radioactive waste from the facility.

Retrieving according to § 57 b AtG requires by law the immediate and parallel conduction of retrieval measures. Necessary are an interim storage facility for the recovered waste, a new shaft and technology for waste recovery. Investigation for the new shaft started in 2014, retrieval planning for all types of low-level and medium-level radioactive waste started in 2015. As it is important to gain relevant data for the planning of retrieval, the exploration and testing phase at one chamber has been continued in 2016.

Today, the Asse II mine faces two major problems: On the one hand, brines enter the mine, on the other hand the stability of the mine openings is at risk. Therefore, the BfS has developed actions for an emergency plan for the Asse II mine. Parallel to the retrieval measures - to improve the mine’s stability and protect the emplacement chambers as well as to minimise the consequences of potential flooding – the mine is stabilised by backfilling remaining cavities with concrete. Additionally, further measures to reduce the radiological consequences of flooding are scheduled.

The emergency plan is maintained and updated on a regular basis. For this purpose, an accompanying technical examination is carried out on the basis of calculations; experts refer to an "analysis of consequences." Challenging aspects of these examinations are the enormous amounts of interactions in regard to content (analysing and updating site conditions) and structure of the whole project. The Asse II mine is a complex project and, generally spoken, impacts of complex projects have to be analysed from a system perspective. With its examination, BfS aims to optimise the developed actions for an emergency plan of the Asse II mine without adversely affecting the retrievabily.

Parameter Selections Associated with Modeling WIPP's ROM Salt Panel Closure System

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, is a United States Department of Energy geological repository for the permanent disposal of defense-related transuranic waste. The radioactive waste is emplaced in rooms excavated in the Salado Formation, a Permian-aged bedded salt formation, at a depth of 2150 ft (655 m) below the ground surface.

In 2011, a new closure system design was proposed to close off the filled waste disposal panels. The proposed panel closure system, referred to as the WIPP Panel Closure (WPC), is to consist of a minimum of 100 feet of compacted run-of-mine (ROM) salt sandwiched between two barriers. The barriers will be either two standard mine ventilation bulkheads or one standard bulkhead and one block wall, if the block wall was previously installed. The proposed WPC design called for emplacing three distinct horizontal layers of ROM salt at different levels of compaction ranging from 85% to 70% of the in situ density of the Salado salt formation.

Nuclear Waste Partnership LLC (NWP), who performs the day-to-day operations at WIPP including its mining and maintenance, attempted to construct the WPC in an unused section of a 12.5 ft high drift. Due to the size of the intake and exhaust panel drifts and the equipment currently available at WIPP, or which could be obtained by renting or leasing, the proposed design was modified from three distinct layers to either two or no layers to be able to construct the closures. NWP constructed three different prototype panel closures: (1) having a 4 ft lower layer of ROM salt compacted by roller with a 8.5 ft upper layer of ROM salt compacted by push plate, to which 1% water by weight was added to both layers; (2) being constructed in the same manner as the first case, but with no added water; and (3) consisting of essentially uncompacted ROM salt being pushed tight against the back by push plate, having no layering or added water. Field sampling and laboratory testing was conducted on the emplaced salt layers to determine their moisture content and density. In addition, grain size analyses were performed on the ROM salt.

Previous modeling efforts of the creep and compaction of the salt surrounding the rooms and the ROM salt making up the panel closures were performed without knowledge of the important parameters water content; grain size; initial density of the layers; layer thicknesses; and, in the case of the prototype demonstration closures, the geometry. These parameters have been determined and are presented. In the future, the WIPP Crushed Salt model developed by Callahan (1999) will be used to model the ROM salt. The WIPP Crushed Salt model is more advanced than the models used in previous modeling attempts. Our goal is to produce realistic baseline calculations of actual ROM salt panel closures that can be used as a guide for present and future ROM salt applications in WIPP.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2016-8664A

Capillary Controls on Brine Percolation in Rock Salt

Marc Hesse and Masha Prodanovic

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ABSTRACT

The ability the microstructure in rock salt to evolve to minimize the surface energy of the pore-space exerts an important control on brine percolation. The behavior is especially interesting under conditions when brine is wetting the grain boundaries and the pore network percolates at very low porosities, below the transport threshold in typical porous media. We present pore-scale simulations of texturally equilibrated pore spaces in real polycrystalline materials.

This allows us to probe the basic physical properties of these materials, such as percolation and trapping thresholds as well as permeability-porosity relationships. Laboratory experiments in NaCl-H2O system are consistent with the computed percolation thresholds. Field data from hydrocarbon exploration wells in rock salt show that fluid commonly invades the lower section of the salt domes. This is consistent with laboratory measurements that show that brine begins to wet the salt grain boundaries with increasing pressure and temperature and theoretical arguments suggesting this would lead to fluid invasion. In several salt domes, however, fluid have percolated to shallower depths, apparently overcoming a substantial percolation threshold. This is likely due to the shear deformation in salt domes, which is not accounted for in theory and experiments.

Comments of the German Association for Repository Research (DAEF)

Till Popp, Wolfgang Minkley -- Institute for Geomechanics (IfG)

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ABSTRACT

On 30.11.2015 the article, “Deformation-assisted fluid percolation in rock salt” by Ghanbarzadeh, S. et al. was published in the journal Science. This item was taken up in Germany by the media and was presented as new technical knowledge which may contradict the suitability of salt as a host rock for radioactive waste. The DAEF prepared a brief statement with the present opinion, to discuss the various theses and the reliability of conclusions made in the above-mentioned paper. The main outcome of the DAEF-paper is presented as part of discussion in the breakout session.

Firstly, as a general statement, we believe, based on our long-lasting experience of research on salt, that it’s a fact that salt is usually tight. Thus, salt is the most suitable geological barrier for radioactive waste repositories, as just might be demonstrated by the occurrence of hydrocarbon accumulations in salt. The tightness of salt results mainly from its low porosity (and permeability) generated during burial diagenesis. Due to (e,g. dislocation or humidity-assisted) salt creep, favored by increasing temperature and pressure with depth mechanical stresses are nearly isostatic and, therefore, acting external fluid pressures are usually lower than the minimal stress, which is a prerequisite for salt barrier integrity.

From the engineering point of view, the processes and conditions, where salt can lose its integrity, described as percolation threshold, are well known. Two mechanisms are assumed as relevant for performance assessment (Minkley & Popp, 2010):

(1) deviatoric stresses inducing growth and connection of inter-crystalline pores as well as transcrystalline cracks – assessed by the dilatancy criterion; and

(2) fluid pressures causing hydraulic opening of cracks and grain boundaries and their interconnection – in practice assessed by the minimum stress criterion.

Here a third loss-of-tightness mechanism for salt is suggested based on the static pore-scale theory. The thesis is that salt will become permeable at greater depth (e.g. lower than 3000 m depth). The scientific basis results from the work of Lewis & Holness (1996), who observed the formation of topological connected brine-filled pores and triple-junction pores in halite/water aggregates at respective PT-conditions. As a pity, from our knowledge, no natural salt from that depths was investigated confirming the textural observations made on synthetic salt.

Thus, the first question arises, **“Are the realized experimental test conditions, relevant for natural salt?”**

As a fundamental critique, the authors used only small synthetic samples (around 150 mg table salt with uniform single halite-crystals, whereby 7 - 15 mg water is added). This corresponds to a saturated water-filled porosity in the order of 7 to 15% which is quite high and unrealistic for natural salt conditions.

The second question is **“How can we explain the occurrence of hydro-carbons in salt?”**

The answer could be very simple; hydrocarbons are a typical feature of salt formations, due to formation of organic-rich evaporitic mudstones during burial diagenesis. Therefore, it has to be demonstrated that the observed hydrocarbons have a different stratigraphic origin than the surrounding salt.

The third comment is that “**The main statements about high permeability of salt rocks are derived only from pore-space simulations, and not supported by real permeability measurements”.**

IfG performed preliminary measurements on natural salt cores in the relevant PT-field (p = 95 MPa, T = 120°C). We were not able to measure any gas flow (injection pressure up to 10 MPa) but the measurements need to be verified.

At the state of knowledge we believe that the impact of the dihedral angle on salt integrity at repository conditions may be low, but we suggest additional investigations to improve the understanding of these processes and to solve the uncertainties, i.e.

(1) to repeat the hot-pressing tests with lower water contents, until the order of <1% and to perform the respective texture investigations. There is probably a fluid content threshold where – due to missing water - no connecting pores may be generated, independently from the PT-conditions (typically existing in a repository for radioactive waste). This would allow solving the debate about natural salt permeability.

(2) to perform permeability tests on natural salt samples at the respective PT-conditions.

Origin and Microdistribution of Fluids in Salt Domes

Jörg Hammer[1] & Gernold Zulauf[2]

7th US/German Workshop on
Salt Repository Research, Design and Operation

Washington, DC

September 7-9, 2016

ABSTRACT

Salt diapirs/domes are well known for their barrier properties and isolation capability to segregate hazardous waste (chemical-toxic and radioactive) permanently away from the biosphere. The long term tightness of rock salt might be demonstrated by the occurrence of hydrocarbon accumulations in salt. Macro-/microstructural studies of the "Hauptsalz" (z2HS, Staßfurt unit, Zechstein, Upper Permian) in the Gorleben salt dome show an interrupted, heterogeneous distribution of hydrocarbons. They appear mostly in the form of streaks, dispersed clouds and isolated clusters. Microscopic studies and computed tomography suggest that hydrocarbons are located 1) along grain boundaries of halite and/or anhydrite crystals, 2) in newly formed artificial microcracks due to drilling and sample preparation, 3) in cleavage-parallel microcapillary tubes within anhydrite crystals and 4) rarely in micro-porous parts of the Hauptsalz. Halite crystals with primary, intracrystalline inclusions of hydrocarbons were only rarely observed.

The quantification of hydrocarbons (C1 to C40) for 210 Hauptsalz samples reveal a background concentration of < 1 mg/kgrock. 64% of the samples have a hydrocarbon content < 1 mg/kg (i.e. 1 ppm or 0.0001 wt.-%). 70 samples show concentrations between 1 mg/kg and 50 mg/kg (average 2.66 mg/kg). 5 samples show outlier values up to 443 mg/kg (0.0443 wt.-%).

Analyses of triterpenoid and other biomarkers detected in the hydrocarbon mixtures from liquid hydrocarbon occurrences in the Hauptsalz and in nearby potential source rocks (samples were taken from borehole Gorleben Z1) point to the Staßfurt carbonate (z2SK) as source rocks of most or all of the hydrocarbons. The hydrocarbons are mostly autochthonous Zechstein products from thermal alteration of the organic matter of the Staßfurt carbonate (organic-rich evaporitic mudstones). Because of the very low permeability of halitic rocks under lithostatic pressure, hydrocarbons can only migrate into and inside evaporites if open fractures are present or diffusion processes occur. In early phases of halotectonic salt uprise, temporarily elevated permeability could have been caused by uprise-related deformation and accompanied by a release of brines and hydrocarbons from the Staßfurt carbonate into the overlaying Hauptsalz, which was subsequently deformed and reworked. The hydrocarbons are then trapped within the salt rocks as a result of deformation-related and healing processes. Subsequently, the hydrocarbons are dragged along or relocated within the salt structure during the further upward salt movement and salt creep.

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[1] *Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany*

[2] *Institute of Geoscience, Goethe University Frankfurt, Frankfurt/Main, Germany*

Impact of Retrieval Requirements on Repository Design

Philipp Herold, Sabine Dörr, Eric Kuate Simo, Wilhelm Bollingerfehr, Wolfgang Filbert

7th US/German Workshop on
Salt Repository Research, Design and Operation

Washington, DC

September 7-9, 2016

ABSTRACT

In 2010, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety issued the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" (BMU, 2010). Since then, retrievability is a design criterion and a requirement for the licensing of HLW and spent fuel repository in Germany. All repository concepts have to ensure that retrieval of the waste containers is possible. In Germany, retrievability "… is the planned technical option for removing emplaced radioactive waste containers from the repository mine" (BMU, 2010) and must be possible during the operating period of a repository, which ends with the sealing of the shafts. The safety requirements also stipulate that the number of mine openings be kept to a minimum and that they be backfilled and sealed as soon as possible. Taking into account these design criteria, DBE TECHNOLOGY GmbH considers the so-called "re-mining" strategy as most suitable for the retrieval of waste containers. Emplacement of the waste containers and sealing of the mine openings is to be carried out as designed in the existing concepts, however, for retrieval, i.e. the removal of the waste containers from the repository, the already backfilled and sealed mine openings will be excavated again. Based on this strategy, DBE TECHNOLOGY GmbH investigated the operational processes during retrieval, the necessary mine layout and technical equipment as well as the expected underground conditions for the two disposal options in rock salt – drift disposal of POLLUX® casks and borehole disposal of spent fuel canisters (BSK).

Basin-Scale Density-Dependent Groundwater Flow near a Salt Repository

Kristopher L. Kuhlman, Sandia National Laboratories (SNL)

Anke Schneider, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

7th US/German Workshop on
Salt Repository Research, Design and Operation

Washington, DC

September 7-9, 2016

ABSTRACT

Basin-scale groundwater flow and solute transport modeling in the geological units surrounding a salt repository are typically important parts of the safety case for radioactive waste disposal in salt. Because salt is highly soluble, aquifers surrounding the repository present a significant potential failure mechanism in salt. The dissolution of bedded salt could occur by laterally migrating dissolution fronts by inter-salt-bed sedimentary aquifers or by vertically circulating groundwater.

Ongoing collaboration between GRS (d^3f) and Sandia (PFLOTRAN) compares and extends our existing numerical groundwater flow and solute transport models to improve conceptualization and numerical implementation of regional groundwater flow simulations near repositories. Our efforts include reimplementation and extension of the WIPP basin-scale groundwater model, from 1996. The collaboration began by identifying key features missing from existing models (density dependent flow and mesh element types). Several features have since been implemented, most notably solute concentration-dependent fluid density in PFLOTRAN.

Initial model comparison has been conducted, and issues and complications have been identified. The modeling comparison and collaboration continues. This work will lead to an updated regional groundwater flow and chemistry model for the WIPP area, and improved understanding of the issued in previous and future regional groundwater models for either bedded or domal salt surrounding a repository.

Sandia National Laboratories is a multi-mission laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2016-9236 A.

Issues on Aging of Spent Fuel Storage Systems

Holger Völzke, Bundesanstalt für Materialforschung und –prüfung (BAM)
Ken B. Sorenson, Sandia National Laboratories (SNL)

7th US/German Workshop on
Salt Repository Research, Design and Operation

Washington, DC

September 7-9, 2016

ABSTRACT

The Bundesanstalt für Materialforschung und –prüfung (BAM) and Sandia National Laboratories (SNL) entered into a Memorandum of Understanding (MOU) in September 2012 to foster technical collaborations in the areas associated with the backend of the commercial nuclear fuel cycle. Specifically, the focus is on packaging, transportation, and storage of commercial spent nuclear fuel. The institutes meet about twice each year, alternating between institutes. This provides the opportunity for staff members from the host organization more exposure to technical issues that are of concern internationally and to collaborate with technical experts working on similar problems.

Since 2012, the focus of the meetings has been on technical issues associated with extended dry storage and subsequent transportation of commercial spent fuel. Topics range from hydride effects on cladding integrity, spent fuel response during Normal Conditions of Transport, finite element analyses of fuel and cask response to accident conditions, bolt and seal behavior over extended periods of time, and corrosion associated with bolts, metallic seals, and stainless steel canisters.

This MOU has provided an effective leverage for technical collaboration. For example, SNL is funding (through DOE), Savannah River National Laboratories (SRNL) to look at bolt and seal degradation issues. SRNL has an MOU with BAM to collaborate on bolt and seal degradation during extended storage. Likewise, Sandia and BAM are collaborating with the EC Joint Research Center on an International Nuclear Energy Research Initiative to investigate spent fuel behavior when subjected to mechanical loadings. This important work will provide insight into failure mechanisms, as well as spent fuel release fractions, given a breach of the cladding wall.

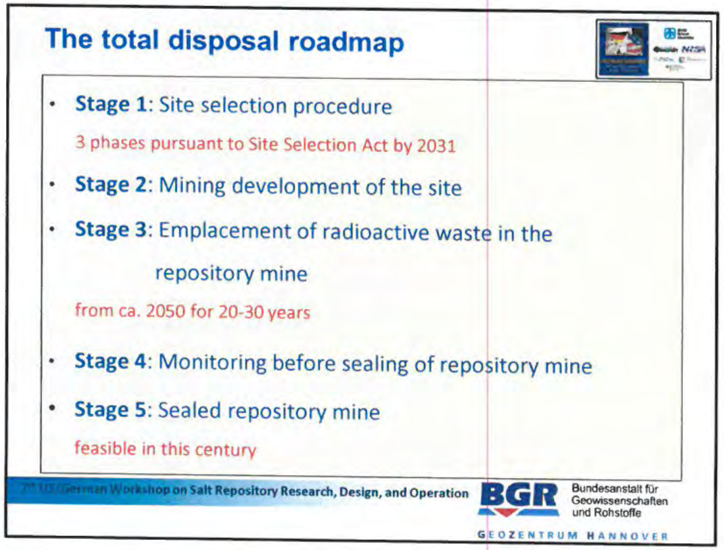
This presentation provides an overview of high ranked technical issues associated with extended storage and subsequent transportation, as well as the work underway at BAM and SNL that are addressing these issues.

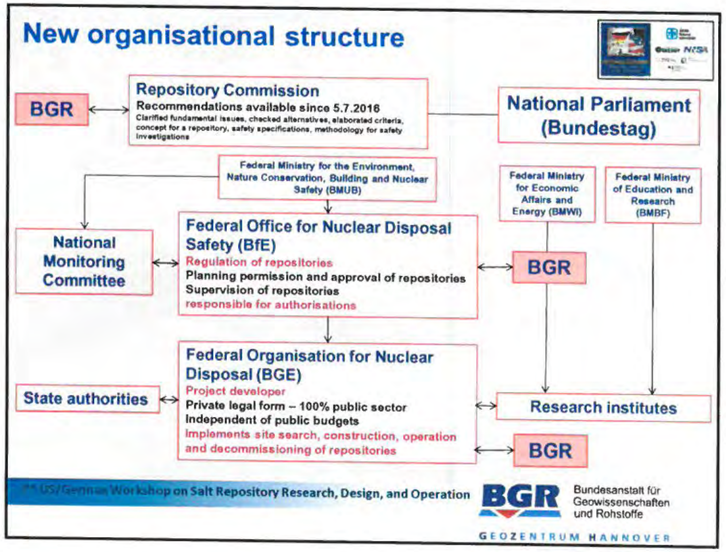
Sandia National Laboratories is a multi-mission laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2016-8274 A

APPENDIX F: PRESENTATIONS


7th US/German Workshop on Salt Repository Research, Design, and Operation
Germany`s new approach for siting a nuclear waste repository
Dr. Volkmar Bräuer
Federal Institute for Geosciences and Natural Resources
BGR, Hannover Germany
www.bgr.bund.de
Washington, DC
September 7-9, 2016
US GERMAN WORKSHOP
ENERGY
NNSA
7th US/German Workshop on Salt Repository Research, Design, and Operation
BGR
Bundesanstalt für Geowissenschaften und Rohstoffe


April 9, 2013 was a historic day:
The German Federal Government and the Federal States agreed for the first time on a new site selection for a nuclear waste repository in Germany!
7th US/German Workshop on Salt Repository Research, Design, and Operation
BGR
Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER


The total disposal roadmap
Stage 1: Site selection procedure
3 phases pursuant to Site Selection Act by 2031
Stage 2: Mining development of the site
Stage 3: Emplacement of radioactive waste in the repository mine
from ca. 2050 for 20-30 years
Stage 4: Monitoring before sealing of repository mine
Stage 5: Sealed repository mine
feasible in this century
7th US/German Workshop on Salt Repository Research, Design, and Operation
BGR
Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER


New organisational structure
BGR
Repository Commission
Recommendations available since 5.7.2016
Clarified fundamental issues, checked alternatives, elaborated criteria, concept for a repository, safety specifications, methodology for safety investigations
National Parliament (Bundestag)
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)
Federal Ministry for Economic Affairs and Energy (BMWi)
Federal Ministry of Education and Research (BMBF)
National Monitoring Committee
Federal Office for Nuclear Disposal Safety (BfE)
Regulation of repositories
Planning permission and approval of repositories
Supervision of repositories
responsible for authorisations
BGR
Federal Organisation for Nuclear Disposal (BGE)
Project developer
Private legal form – 100% public sector
Independent of public budgets
Implements site search, construction, operation and decommissioning of repositories
State authorities
Research institutes
BGR
7th US/German Workshop on Salt Repository Research, Design, and Operation
BGR
Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

The total disposal roadmap

- **Stage 1**: Site selection procedure
  3 phases pursuant to Site Selection Act by 2031
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  feasible in this century

US/German Workshop on Salt Repository Research, Design, and Operation
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

New Site Selection Act (StandAG) Time schedule (Stage 1)

Repository Commission (ended in 2016)

Phase 1: Exclusion of regions and comparative analysis
Definition of sites for surface exploration

Phase 2: Surface exploration by end 2023
Definition of sites for underground exploration

Phase 3: Underground exploration and Environmental Impact Assessment by 2031
Site comparison and final site selection

US/German Workshop on Salt Repository Research, Design, and Operation
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

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Site comparison and final site selection

US/German Workshop on Salt Repository Research, Design, and Operation
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
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Repository Commission (1)

Repository Commission "Storage of high-level radioactive waste"

34 members:

8 (representatives of Bundesländer (German states), 8 (members of the Bundestag)

8 (scientists), 8 (representatives of civil society), 1+1 (Chairperson) (groundwork done by: scientific institutions such as BGR)

General Objectives:

Analyse and assess fundamental issues, elaborate criteria and recommendations, evaluate alternatives for final disposal, reporting on a consensus basis, min. 2/3 majority

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Repository Commission (2)

Working basis:

GEOLOGY = safety for long periods of time

- with the best possible safety for the storage of high-level radioactive waste in particular
- ensuring the best possible safety for a period of one million years
- assessing the host rocks – rock salt, claystone and crystalline rocks in a scientifically based, neutral selection procedure based on a "blank map" of Germany

Repository Commission (2)

Working basis:

GEOLOGY = safety for long periods of time

- with the best possible safety for the storage of high-level radioactive waste in particular
- ensuring the best possible safety for a period of one million years
- assessing the host rocks – rock salt, claystone and crystalline rocks in a scientifically based, neutral selection procedure based on a "blank map" of Germany

Repository Commission (3)

Time schedule

1. The commission submitted recommendations to the Bundestag, Bundesrat and the German government on July 5th 2016
2. German Bundestag evaluates, and if necessary, redetermines the Site Selection Act on the basis of the report
3. Final decision expected in 2017

Commission findings (1)

General Objective

Define site region and then a site which demonstrates the best possible safety to isolate the waste for a time period of one million years

GEOLOGY = Safety for long periods of time

- Storage in deep geological formations
- "Best possible site" in a neutral procedure
- Criteria are the key guides for the procedure
- Additional research necessary, e.g. for containers
- Repository mine with retrievability/recovery is a new concept
- Self-critical system (reversibility of decisions, e.g. to correct errors)

Commission findings (2)
Geoscientific Criteria

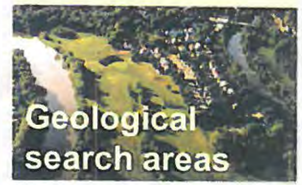
Criteria:
1. Exclusion criteria
e.g. volcanic activity

2. Minimum requirements
e.g. depth of effective isolating rock zone

3. Weighing criteria
e.g. no or only slow transport by groundwater at the level of the repository

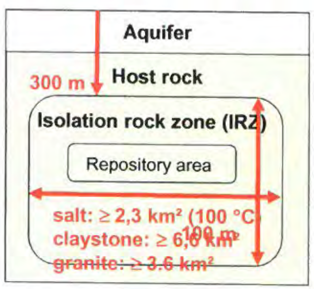
Stage 1
Phase 1: Step 1
1. Exclusion criteria geoscientific

Target:
Identification of
geological search areas



Large-scale vertical movements
Active fault zones
Mining activity
Seismic activity
Volcanic activity
Groundwater age

Stage 1
Phase 1: Step 1
2. Minimum requirements geoscientific



Host rock = Barrier rock

Rock permeability: < 10^{-10} m/s
Minimum thickness: 100 m
(crystalline rock can be less)
Minimum depth: 300 m
and as deep as possible Erosion or decompaction in case of claystone, in case of salt + 300 m salt layer above IRZ
Minimum area for realisation:
Salt: 200 °C: 1.3 km²; 100 °C: 2.3 km²
Claystone: 100 °C: 6.6 km²
Granite: 100 °C: 3.6 km²
Integrity of IRZ maintained for 1 million years

Criteria in practise: Permeability

Permeability measurements by BGR in claystone in Mont Terri (Switzerland)

Data on this criterion are available for various host rocks. Attention is given here to where and how the criterion was determined.

Permeability (k)		Rock salt	Opalinus Clay	Granite (unfractured)
Laboratory:		k < 10^{-21} m²	k < 10^{-19} m²	ca. 10^{-20} m²
In-situ:	"undisturbed" rock	k < 10^{-20} m²	k < 10^{-19} m²	k < 10^{-18} m²
	Excavation disturbed zone	k < 10^{-14} m²	k < 10^{-16} m² to 10^{-13} m²	k < 10^{-15} m²

Data source: BGR

Stage 1

Phase 1: Step **2**

3. Weighing criteria geoscientific

Selection of partial areas with particularly favourable geological conditions

Data from BGR and Services of Federal States (Länder)

Geoscientific weighing

Groups of criteria:

1: Quality of ability to isolate and reliability of evidence

2: Verifying isolation capacity

3: Other safety relevant properties

Stage 1

Phase 1: Step **3**

3. Weighing criteria Geoscientific and planning scientific

Identification and selection of site regions for exploration from the surface

Regional data from BGR and Federal States (Länder)

Geoscientific weighing criteria

Representative preliminary safety investigations

Planning scientific weighing criteria

Stage 1

Phase 1: Step **3**

3. Weighing criteria Geoscientific and planning scientific

Identification and selection of site regions for exploration from the surface

Regional data from BGR and Federal States (Länder)

Geoscientific weighing criteria

Representative preliminary safety investigations

Planning scientific weighing criteria

Planning scientific criteria

competing uses or conflicts of interest which relate differently to
- surface (shaft or ramp) and
- underground

Competing interests need to be taken into consideration! Therefore, no minimum requirements and exclusion criteria.

- **Weighing group 1** (surface planning aspects): Protection of people and human health
- **Weighing group 2** (surface and underground planning aspects): Protection of unique natural and cultural heritage from irreversible damage
- **Weighing group 3** (surface and underground planning aspects): other competing uses and infrastructure

Stage 1

Phase 2:
Surface exploration

Proceedings, criteria, assessments

Determining sites for underground exploration

Geoscientific criteria

Further-developed preliminary safety investigations

Socio-economic potential analyses

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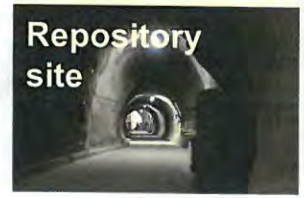
Stage 1

Phase 3
Underground exploration

Proceedings, criteria, assessments

Determine site



Geoscientific criteria

Site-specific test criteria
(= exclusion criteria)
still to be defined
and exploration programmes

Comprehensive preliminary safety investigations,
comparative safety investigations

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Requirements for research and technological development

The commission is of the opinion that research on repositories in Germany has a good foundation, and provides a good basis for redefining the focus of research activities in the years to come.
Gaps in knowledge that could hinder the new selection process should be closed, for instance:

- Three host rock types with appropriate repository concepts,
- Container development,
- Safety and verification concepts,
- Setting up arrangements to correct errors, including retrieval of the casks during the operating phase and recovery of the casks after closure,
- Safety-related verification for containers and inventories for a longer period of interim storage,
- Accompanying research on participation and acceptance in a democratic constitutional state,
- Interdisciplinary and transdisciplinary approaches for cooperation of technical and non-technical disciplines with societal players.

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Conclusions

- **There is no ideal host rock!**
  Claystones, rock salt and crystalline rocks are being investigated internationally as potential host rocks.
  The crucial aspect is a favourable overall geological setting.
- **The geological conditions in Germany are well studied,** the host rocks rock salt, claystone and crystalline rocks are regionally present.
- **Good exploration methods are available.**
- **Research results on the characterisation of host rocks in international cooperation projects are necessary**
- **The search for a site in Germany can begin!**

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Safety Case: German Approach - from ISIBEL to KOSINA

Jens Wolf
GRS gGmbH

7th US/German Workshop on Salt Repository Research, Design, and Operation

Washington, DC, September 7-9, 2016

Safety Case

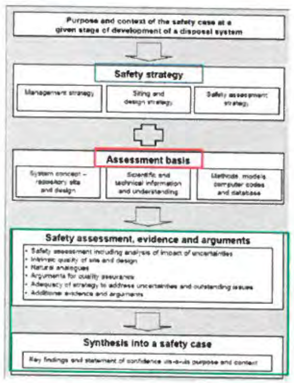
The safety case is the **collection of scientific, technical, administrative and managerial arguments** and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility.

(...)

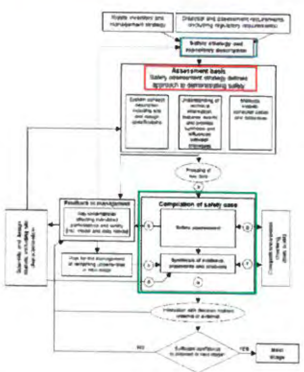
The safety case and supporting safety assessment provide the basis for demonstration of safety and for licensing. They will **evolve** with the development of the disposal facility, and will assist and guide decisions on siting, design and operations.

Source: IAEA SSG-23

Safety Case: Nature and Purpose

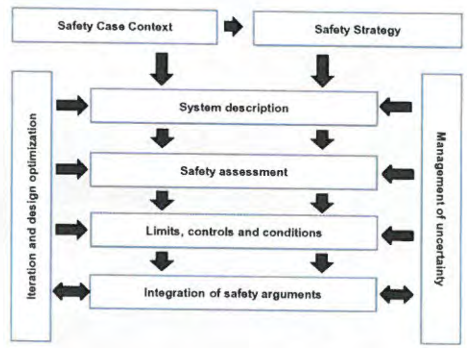


Source: NEA No. 3679, 2004



Source: NEA No. 78121, 2013

Elements of the Safety Case



Source: IAEA SSG-23

Safety Case

Preliminary Safety Case ➡ **Comprehensive Safety Case**

German Safety Case Approach has been developed in R&D projects dealing with the following questions:

- How to achieve safety?
  → Safety strategy (OS/PCS)
- How to demonstrate safety?
  → Safety assessment
- How to manage uncertainties?
  → Management of uncertainties
- How to communicate safety?
  → Integration of safety arguments

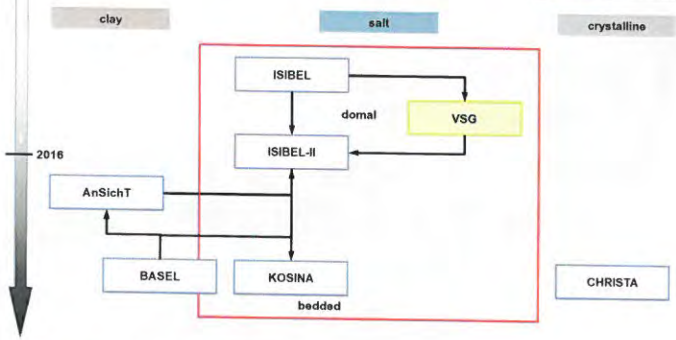
} **Safety Case R&D**

Elements of Safety Case R&D

R&D in Germany

Source: IAEA SSG-23

Safety Case: R&D in Germany



X R&D BMWi

+ support international cooperation (NEA/IAEA)

Safety Strategy

How to achieve safety?

Regulations / **Geology / Repository Concept**

- Protection Goals
- Safety Principles / Safety Functions
- Guiding Principles
- Design Requirements
- (...)

Objectives ↔ Measures

→ How to demonstrate safety?

Safety concept: Domal salt (VSG)

Requirement A:
The stored waste packages ought to be quickly and as close as possible enclosed by rock salt in conjunction with the geotechnical barriers (containment).

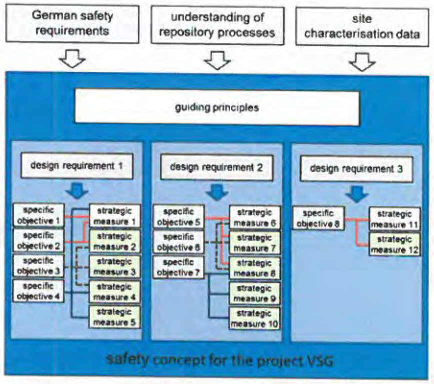
Requirement B:
The containment providing rock zone remains intact (geological and geotechnical barriers) and is not altered by internal or external events and processes (integrity / freedom from maintenance)

Requirement C:
A recriticality must be excluded at every stage of the repository evolution (criticality exclusion)

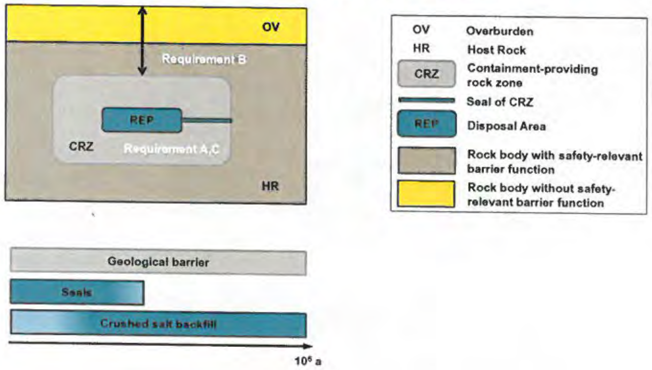
→ Specific objectives (14 principal goals)

→ Strategic measures (17 design specifications and technical measures)

Safety concept



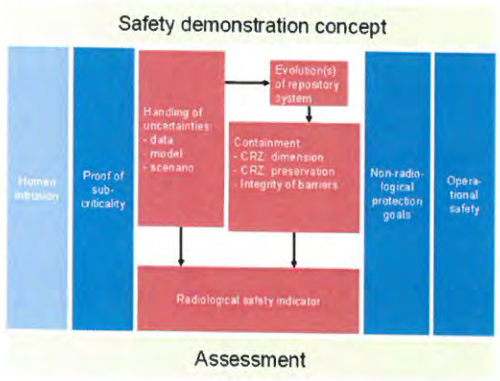
Safety concept: Containment-providing rock zone



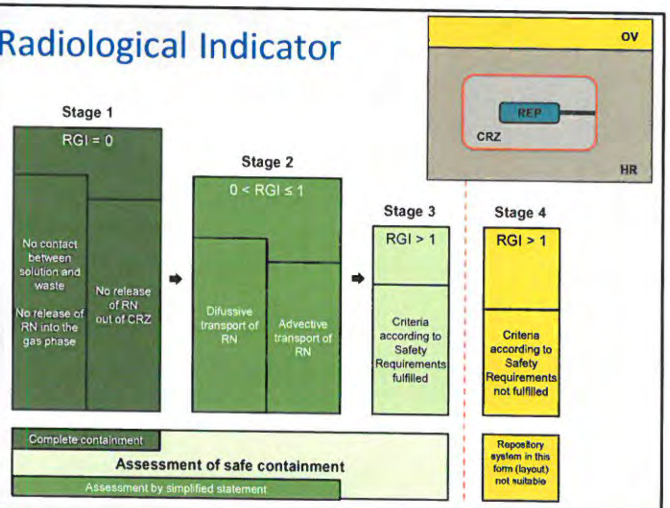
Management of Uncertainties

- Scenario uncertainties
  - ➡ Scenario analysis (FEP, scenario development)
- Data and parameter uncertainties
  - ➡ Uncertainty and sensitivity analysis
- Model uncertainties
  - ➡ Benchmarking, uncertainty and sensitivity analysis

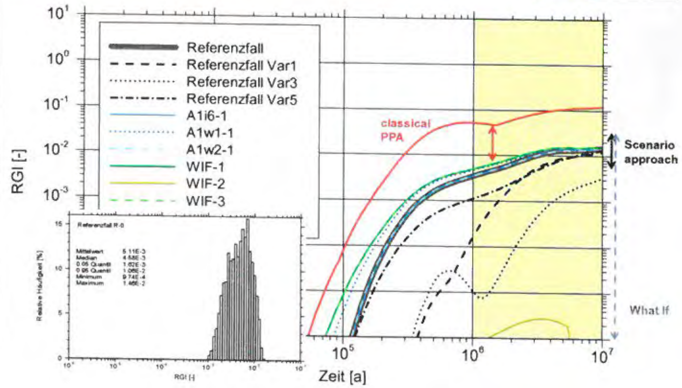
Demonstration concept



Radiological Indicator



Radiological consequences



Integration of Arguments

- Performance assessment (radiological consequences) still main argument
- Complementary safety and performance indicators
  NEA/RWM/R(2012)7: Indicators in the Safety Case
- Natural analogues
  NEA/RWM/R(2013)10: Natural Analogues for Safety Cases of Repositories in Rock Salt, Salt Club Workshop Proceedings 2013
  NAWG, http://www.natural-analogues.com/

Safety concept: Bedded salt (KOSINA)

Requirement A:
The stored waste packages ought to be quickly and as close as possible enclosed by rock salt in conjunction with the geotechnical barriers (containment).

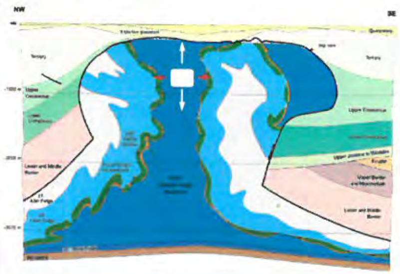
Requirement B:
The containment providing rock zone remains intact (geological and geotechnical barriers) and is not altered by internal or external events and processes (integrity / freedom from maintenance)

Requirement C:
A recriticality must be excluded at every stage of the repository evolution (criticality exclusion)

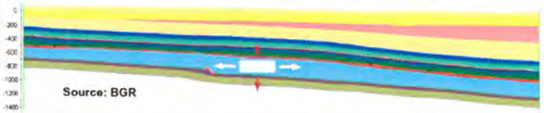
→ Specific objectives (14 principal goals)

→ Strategic measures (**17 design specifications and technical measures**)

From domal to bedded salt



Source: BGR



Source: BGR

Guiding principles ✓
Design requirements ✓
Specific objectives ✓
≠ Strategic measures

Domal vs bedded salt

Domal salt	Bedded salt	Safety and Demonstration Concept
vertical extent	horizontally layered, thickness rock salt ≤ 200 m	Different safety margins Underlying layers CRZ-concept Integrity analysis host rock - temperature criteria - dilatancy Vertical boreholes Shaft seals
Lateral inhomogeneous geology	horizontal extent	Different safety margins CRZ-concept Disposal area Drift seals / Drift disposal

National focus on Safety Case R&D

- FEP and scenarios
- Safety concept / Demonstration concept
- Integrity of geological and geotechnical barriers
  - Geomechanical behaviour of rock salt
  - Geomechanical behaviour of crushed salt
  - Transport processes in crushed salt
- Uncertainty and sensitivity analysis
- Operational safety
- Operational safety vs. Long-term safety

Supported by:
Federal Ministry of Economics and Energy
on the basis of a decision by the German Bundestag

Discussion of key technical issues

Jens Wolf
GRS gGmbH
7th US/German Workshop on Salt Repository Research, Design, and Operation
Washington, DC, September 7-9, 2016

Int. Focus on Safety Case R&D [EC, IAEA, NEA since 2010]

- Forum on Stakeholder Confidence
- Socio-Technical Challenges for Implementing Geological Disposal
- Records, Knowledge Preservation and Memory (RK&M)
- Implementing Public Participation Approaches
- Monitoring
- Full Scale Demonstration of Plugs and Seals
- Implementing sustainable education programmes
- Biosphere Research
- Operational safety
- (...)

Discussion of key technical issues

Statements to discuss:

- Safety Case needs should lead R&D
- Safety assessment is the main element of the safety case (SSG-23 4.4)
- Status of national programs is diverging
  → Different R&D needs
- Safety Case R&D:
  - How to achieve safety?
  - **How to demonstrate safety?**
  - **How to manage uncertainties?**
  - How to communicate safety?

PAMINA (2008)
MeSA (2012)
SCS (2013), next 2018
GEOSAF

Discussion of key technical issues

Important topics such as

- Uncertainty and sensitivity analysis
- Scenario development
- Model development / Benchmarks
- Additional arguments (indicators, analogues)

are **not adequately addressed in international activities**

7th US/German Workshop on Salt Repository Research, Design, and Operation

Nature of the WIPP Safety Case Carlsbad, New Mexico, USA

Paul Shoemaker
Sandia National Laboratories/Carlsbad

Washington, DC
September 7-9, 2016

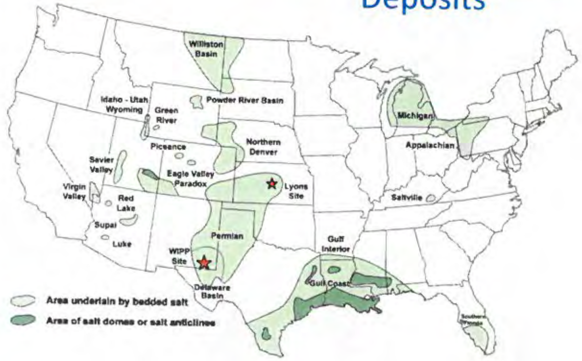
WIPP Background – Why Salt?

Bedded Salt, Chosen Purposefully, for the Siting of the US Defense Nuclear Wastes

- Salt can be mined easily
- Salt is known to close under the pressure of overlying beds, and therefore will consolidate around the waste and isolate it in place
- Salt is essentially impermeable
- Fractures in salt are self healing
- Salt that has existed underground for millions of years will almost certainly remain stable for millions of years into the future
- Salt has a relatively high thermal conductivity
- Wide geographic distribution (many potential sites)

1

WIPP Background – US Salt Deposits



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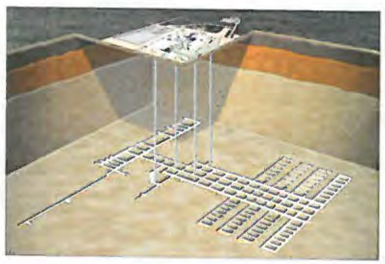
WIPP Background – Repository Layout



- 2,150 feet deep
- Eight disposal panels
- Four vertical shafts
- Filtered ventilation
- North Experimental Area
- Meant for the permanent disposal of defense-related transuranic radioactive waste

3

Long-Term Regulatory Requirements

- 40 CFR Part 191
  - Generally applicable to permanent geologic repositories for the disposal of radioactive waste
    - Not WIPP-specific, included HLW, SNF, & TRU
- 40 CFR Part 194
  - WIPP-specific certification criteria

The Regulations: Limits Long-Term Releases

40 CFR 191 Subpart B

- Conservative
- Uses defense-in-depth approach
- Primarily a *release* standard, but releases are based on estimated doses caused by a hypothetical in-situ uranium ore body
  - *Quite unique, and quite clever* – basing maximum allowable disposal risks on those posed by unmined nuclear raw material

The Regulations: Limits Long-Term Releases

40 CFR 191.13

(a)Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

- Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
- Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

(b) Performance assessments need not provide complete assurance that the requirements of § 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with § 191.13(a) will be achieved.

NOTE: In developing the standard, EPA did its own modeling of a hypothetical geologic repository using a standard source term (waste expected from 100,000 metric tons of reactor fuel). The releases from that generic repository were predicted to cause roughly the same health risks (premature cancer deaths) as an unmined uranium ore body, needed to produce the same 100,000 metric tons of reactor fuel. The values in Table A, Appendix 1, are a way to normalize releases to this standard source term, taking into account that not all radionuclides are created equal, in terms of their ability to negatively impact human health.

The Regulations: Redundant Elements of Safety

40 CFR Part 191.14

" § 191.14 To provide the confidence needed for long-term compliance with the requirements of 191.13,..."

six qualitative *"assurance requirements"* were included to provide *additional confidence* that the containment requirements would be met, given the substantial uncertainties inherent in predictions of repository performance over 10,000 years

1. Active Institutional Controls
2. Monitoring
3. Passive Institutional Controls
4. Engineered Barriers
5. Consideration of the Presence of Resources
6. Removal of Waste

The Regulations: Conservative Aspects/Assumptions

40 CFR Part 191

- Assumes inadvertent human intrusion *will happen,* and these releases must be included, even though deep drilling is hardly considered an "inadvertent" endeavor; additionally, even though passive institutional controls (long-term markers) will be employed, they are assumed to be ineffective.*

* WIPP certification criteria allow for credit to be taken for PIC effectiveness, but EPA has allowed credit only during active controls (100 years after closure)

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The Regulations: Other Key Features

40 CFR Part 191

- 10,000 year performance period
  - A period of 10,000 years was considered long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. This period was considered short enough so that major geologic changes would be unlikely and repository performance might be reasonably projected.
- Demonstration of compliance based on a probabilistic assessment of risk
- Demonstration of a "reasonable expectation" that compliance with the release limits will be achieved
  - Due to long time-period of evaluation, redundant safety considerations, and inherent uncertainties in such predictions, only a "reasonable expectation" is required

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The WIPP Safety Case

- Features, Events, and Processes (FEPs) were identified using all available resources and databases
- Scenario development process was done iteratively and reviewed broadly before finalization
- Performance Assessment (PA) parameters were scrutinized and based on either experimental data, expert judgment, or expert elicitation. These processes were all governed by a thorough and documented Quality Assurance Program.
- Final conceptual models were Peer Reviewed by Independent Peer Panel and documented as part of the Compliance Certification Application (CCA 1996)

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The WIPP Safety Case

- As with our governing regulation, the WIPP safety case is conservative
- Conservatism is employed as a means to deal with uncertainty, especially over the 10,000 year regulatory period of interest
  - 10,000 years is short compared to a 1 million year regulatory framework, but
  - It's still a long time (twice the time that has elapsed from the founding of Troy to today)
- Conceptual models containing conservatisms are used to demonstrate WIPP's compliance with containment requirements; these conceptual models have been judged to be adequate

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The WIPP Safety Case

- Undisturbed (base case)
- Disturbed Scenarios
  - An accidental deep borehole intercepts the repository and a deeper hypothetical zone of pressurized brine beneath the repository (results in releases of cuttings, cavings, and spallings, but also may serve to saturate the repository hundreds or thousands of years later) (E1 Scenario)
  - An accidental deep borehole intercepts only the repository (results in releases of cuttings, cavings, and spallings) (E2 Scenario)
  - An accidental deep borehole intercepts the repository that was previously intercepted by a borehole that also intercepted a zone of pressurized brine (results in cuttings, cavings, spallings, and direct brine release [DBR]) (E1E2 Scenario)
  - Mining occurs in potash-bearing units above the repository resulting in subsidence, disruption, and increased transmissivity of saturated zones

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The WIPP Safety Case

Human Intrusion Scenario Conservatism Example

- Assumes that current drilling rate in area persists into the future for 10,000 years
  - Ignores inevitable depletion and resulting reduction in drilling rate
  - Provides for multiple and compound intrusion scenarios
  - Ignores the high probability of "rediscovering" the existence of the repository and updating human knowledge base of the repository's existence

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The WIPP Safety Case

- Formal PA calculations have demonstrated compliance for each certification and recertification submittal
  - Compliance Certification Application – 1996
  - Compliance Recertification Application – 2004
  - Compliance Recertification Application – 2009
  - Compliance Recertification Application – 2014
- Parameter input changes have been made with each regulatory cycle, but performance predictions remain fairly consistent
- Results have repeatedly shown that cumulative releases from WIPP over the next 10,000 years will fall below the applicable regulatory limits

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The WIPP Safety Case

Future Treatment of Conservatisms

- Perhaps some conservatisms could be reduced in order to be more "realistic," however . . .
  - What some consider "realistic" others may not, especially when those "realisms" are extended over 10,000 years
  - Pursuit of "realism" may not be worth the effort from either a regulatory or a stakeholder communication perspective, if injecting "realism" into a given conceptual model has no appreciable effect on the projected performance of the repository

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Conclusion

- WIPP's steadfast compliance position is due in equal parts to:
  - A thoughtful and protective regulatory standard
  - A rigorous and robust Safety Case
  - An excellent host site
- Looking toward the future, it may be that one or more of the conceptual models foundational to the WIPP safety case will be modified in order to reduce uncertainty
  - These modifications will be undertaken at appropriate times within the regulatory cycle
  - They will be tested through rigorous peer review before being implemented

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Back-Up Slides

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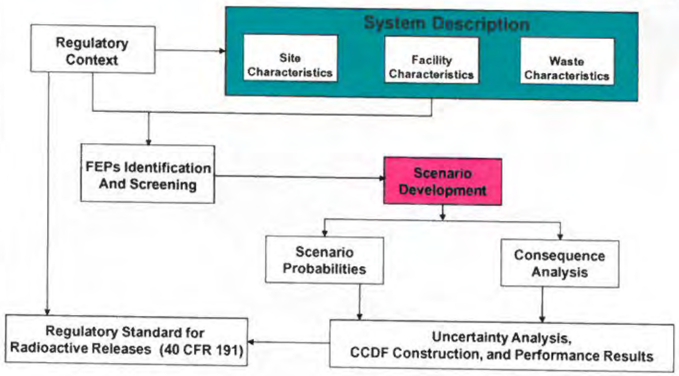
PA Methodology



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Notes/Backup

EPA Development of the Release Standard (1985)

The EPA modeled the performance of potential repositories for SNF and HLW in several geologic media. Radionuclide releases over 10,000 years were projected. Very general models of environmental transport and a linear, non-threshold dose-effect relationship were used to relate these releases to the incidence of premature cancer deaths they might cause. For the various geologic media, these assessments indicated that disposal of the wastes from 100,000 metric tons of reactor fuel would cause a population risk ranging from no more than about ten to a little more than one hundred premature deaths during 10,000 years, assuming that the then-existing provisions of 10 CFR Part 60 regarding engineered barriers were met.

The EPA also evaluated the health risks from the unmined uranium ore needed to produce 100,000 metric tons of reactor fuel. Population risks ranging between 10 and 100,000 premature cancer deaths over 10,000 years were associated with this quantity of in-situ uranium ore, depending upon analytical assumptions used in the evaluation.

Limiting radionuclide releases to levels associated with no more than 1,000 premature cancer deaths over 10,000 years from disposal of the wastes from 100,000 metric tons of reactor fuel satisfied two important objectives. First, it provided a level of protection that appeared reasonably achievable by applying the various options being considered within the national program for commercial wastes. Second, such a limitation would keep risks to future populations at acceptably small levels, because it appeared to limit risks to no more than the midpoint of the range of estimated *risks that future generations would have been exposed to if the uranium ore had never been mined.*

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Notes/Backup

EPA Deliberations on "Reasonable Expectation" - 1985

The containment requirements call for a *reasonable expectation* that the various quantitative tests be met. This phrase reflects the fact that unequivocal numerical proof of compliance is neither necessary nor likely to be obtained. A similar qualitative test, *reasonable assurance*, is used with NRC regulations. Although the EPA's intent is similar, the NRC phrase was not used in 40 CFR Part 191 because *reasonable assurance* is associated with a level of confidence that may not be appropriate for the very long-term projections that are called for by 40 CFR 191.13.

Joint US-German FEPs Catalog

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

7th US/German Workshop on Salt Repository Research, Design, and Operation
Washington, DC
September 7-9, 2016

Outline

- Feature, Event, and Process (FEP) Analysis Overview / Review
- Objectives / Motivation for new FEPs Catalog
- Update on Collaborative Results
  - Revisions to FEPs Matrix
  - New Structure/Organization for FEPs and their Associated Processes
- NEA Salt Club
- Future Work
  - Participants
    - SNL: Geoff Freeze, David Sevougian, Michael Gross, Christi Leigh, Kris Kuhlman
      - DOE Used Fuel Disposition (UFD) Campaign
      - Waste Isolation Pilot Plant (WIPP)
    - GRS: Jens Wolf, Dieter Buhmann, Jörg Mönig
      - Gorleben (VSG) – domal salt
      - KOSINA – bedded salt

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FEP Analysis Overview

- A FEP is a Process or Event acting upon or within Feature(s)
- FEP Identification
  - Develop and classify a comprehensive list of FEPs potentially relevant to long-term repository performance
- FEP Screening
  - Specify a subset of important FEPs that individually, or in combination, that contribute to long-term repository performance
- Scenario Development and Screening
  - Identify and screen scenarios (i.e., combinations/sequences of FEPs)
    - Nominal/reference, disruptive/alternative

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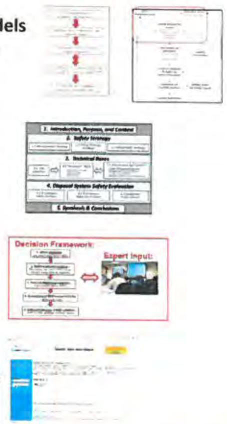
Use of FEPs in Repository Development

- Construction of scenarios and models
  - Important processes and events (safety affecting)
  - Completeness of model
- Post-closure safety case
  - Organization of remaining "issues" and uncertainties
  - Completeness check
- RD&D prioritization
  - Organization/planning and allocation of resources (personnel, financial, etc.) to reduce future uncertainties and add confidence
- Database structuring
  - Linkages between models, scenarios, and RD&D needs



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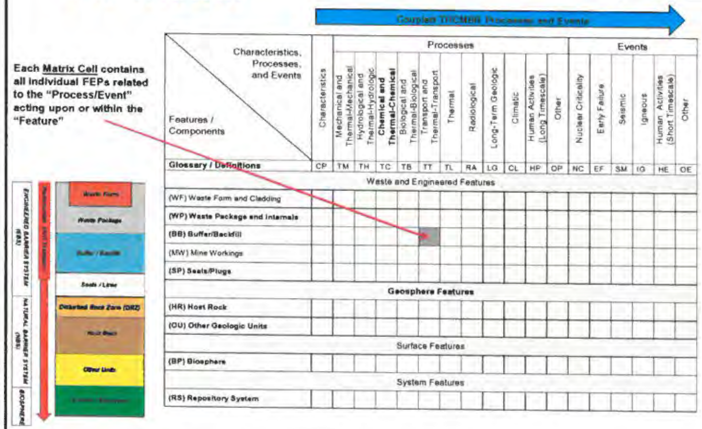
Objectives/Motivation for SNL/GRS FEPs Collaboration

- **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
  - **Review FEP identification and analysis approaches**
    - Adopted FEP Matrix approach: improves transparency and reduces redundancy
    - Restructure FEPs list to improve transparency
- **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

Typical (NEA-like) individual FEPs

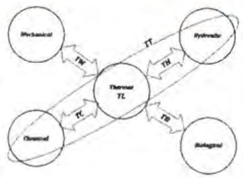
UFD FEP Number	Description	Associated Processes	Screening Recommendation for a Generic Salt Site
2.0.00.00	2. DISPOSAL SYSTEM FACTORS		
2.1.00.00	1. WASTES AND ENGINEERED FEATURES		
2.1.03.00	1.03. WASTE CONTAINER		
2.1.03.02	**General Corrosion of Waste Packages**	- Dry-air oxidation in anoxic condition - Humid-air corrosion in anoxic condition - Aqueous phase corrosion in anoxic condition - Passive film formation and stability - Chemistry of brine contacting WP - Salt deliquescence - Hydrogen gas buildup - Effect of close contact with salt undergoing creep deformation	Included for presence of corrosion products and for gas generation by anaerobic corrosion. Evaluate for impact on water chemistry using corrosion rates and failure rates and gas generation rates for carbon steel overpack. Excluded for waste package as a long-term hydrologic barrier because we do not need to take credit for the package once salt encapsulates the waste.
2.1.03.08	**Evolution of Flow Pathways in Waste Packages**	- Evolution of physical form of waste package degradation - Plugging of cracks in waste packages	Excluded because we do not need to take credit for the detailed flow pathways once salt encapsulates the waste
2.1.08.00	1.08. HYDROLOGIC PROCESSES		
2.1.08.02	**Flow In and Through Waste Packages**	- Saturated / Unsaturated flow - Movement as thin films or droplets	Included
2.1.08.03	**Flow in Backfill**	- Saturated / Unsaturated flow - Fracture / Matrix flow – fracture flow does not occur in crushed salt - Preferential flow pathway as crushed salt backfill undergoes consolidation	Included
2.1.08.04	**Flow Through Seals**	- Saturated / Unsaturated flow - Fracture / Matrix flow - Gas transport (in UFD, Appendix A list) - Preferential flows in non-salt portion - Brine formation by salt deliquescence	Included

FEP Matrix



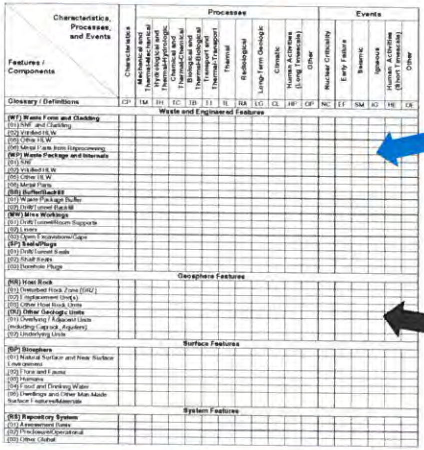
Summary of FEP Matrix Approach

- **Two-dimensional FEP organizational structure:**
  - Matrix Rows = Feature (and Component) Categories
  - Matrix Columns = Process and Event Categories
- **Thermal-centric organization of the processes and process coupling**
- **FEP Identification "Numbering" Scheme**
  - Developed a new alpha-numeric identification scheme indicating where a FEP is mapped in the FEP Matrix (row and column)
    - More descriptive than strictly numeric identifiers
    - Can still be traced to NEA Database numbering
      - BB.02.CP.01 Backfill Materials (Characteristic FEP)
      - BB.02.TM.01 Mechanical Effects on Backfill or from Backfill
      - BB.02.TM.02 Thermal-Mechanical Effects on Backfill or from Backfill
      - HR.02.TH.01 Flow Through the DRZ
      - SP.02.TC.01 Chemical Interaction of Groundwater with Shaft Seals



Describes/catalogs the physical-chemical properties of a feature or component

Full FEP Matrix



U.S.
~200 UFD Bedded Salt FEPs (Sevougian et al. 2012)

- Modified from generic FEPs (Freeze et al. 2011) to be more salt-specific
- Derived from NEA FEP Database (1999, 2006)
- Cross-checked against WIPP FEP catalogue (DOE 2009)

Germany
~100 Gorleben VSG FEPs (Wolf et al. 2012a,b)

- Derived from NEA FEP Database (1999, 2006)
- Specific to a salt dome in Northern Germany

Combined Salt FEPs (2015)

- **25 Examples of matrix-based FEPs:**
  - Derived from initial US and German FEPs
  - Focus on FEPs which emphasize differences between bedded and domal salt

- **Screening occurs at the "associated process" level!**

Table 3-1. Screening decisions for HR.02.TH.01 - Flow Through the DRZ

ID	Description of Associated Process	Screening Decision	
		Bedded Salt	Domal Salt
A	**Single-phase flow** (saturated and/or unsaturated)	Evaluate	Included
B	**Multi-phase flow** (e.g., gas/liquid)	Included	Evaluate
C	**Fracture flow and/or matrix flow**	Evaluate	Evaluate
D	**Evolution of flow pathways** through the DRZ, especially by healing/ sealing of the DRZ	Likely Included	Likely Included

- **Extensive Documentation in Sevougian et al. (2015)**
  - FEP Descriptions
  - Preliminary, generic screening
- **Many more FEPs still to be created**

Recent Developments (2016)

- **FEPs matrix redesigned at a joint meeting in DC in February to be generally applicable to any mined concept, i.e., any host rock**
  - By changing the features/components (rows of the matrix) to be more general, e.g.,
    - "Bedded or domal salt" component under the Host Rock (HR) feature changed to "Emplacement Unit(s)"
    - "Pressurized brine reservoir(s)" component under the Other Geologic Units (OU) feature changed to "Underlying Units"
  - By changing the various individual FEPs which appear in the FEPs matrix cells to be less "salt-centric" and more general
- **New organization and formulation of individual FEPs by using a more logical structure for associated processes**
  - Eliminates some redundancy among FEPs (e.g., some of the old feature-related FEPs can be combined with old process-related FEPs)
  - Allow for an easier initial completeness check for each FEPs matrix cell
  - Screening (i.e., inclusion/exclusion in PA model and/or scenario development) continues to be managed at the associated process level, rather than the higher FEPs level!

New TH FEPs and Associated Processes

- FEPs themselves (e.g., HR.00.TH.01) tend to be formulated around driving *forces* or "loading"
- Associated processes tend to formulated as *responses* to the driving forces
- First six FEPs do not specifically include temperature (heat or energy) effects
- Last FEP (.07) includes coupled thermal-hydrological flow processes:
  - technically brine-inclusion decrepitation and/or migration could go here, too

HR.00.TH.01 Pressure-driven Darcy flow in fractures and porous media
- 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.00.TH.02 Capillarity-dominated Darcy flow
- A. Wicking and absorption (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.00.TH.03 Gravity- and density-dominated flow
- A. Free convection due to density variation (temperature and salinity effects)
- B. Infiltration, imbibition, and drainage
- C. Dripping and ponding

HR.00.TH.04 Adsorption-dominated flow (water held by electrostatic, van der Waals, and hydration forces)
- A. Thin-film flow below residual saturation (i.e., near liquid dryout)
- B. Hygroscopy (equilibration of solid phase with humidity)
- C. Immobile water in nano-pores or small-aperture fractures

HR.00.TH.05 Diffusion and dispersion in miscible phases
- A. Vapor diffusion in air phase
- B. Dissolved gas diffusion in liquid phase

HR.00.TH.06 Non-Darcy flow in fractures and porous media
- A. High Reynolds number gas or liquid flow in large-aperture fractures
- B. Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flowpaths
- C. Threshold gradient flow in low-permeability matrix
- D. Decrepitation, creation (during reconsolidation), and migration of fluid inclusions

HR.00.TH.07 Thermal-Hydrological effects
- 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, freezing, and sublimation)
- E. Release of water from hydrated minerals during heating

New RN Transport FEPs and Associated Processes

- **New transport FEPs organized a bit differently than new TH FEPs:**
  - Organized primarily by material phase, instead of "driving force"
  - Other organizational structures could be considered but this one seems reasonably complete from a model-building perspective
- **For any set of FEPs, the level of "discretization" of both FEPs and associated processes is somewhat arbitrary:**
  - Strive for a reasonable level of discretization as might be conceived when building a process model or a PA model, but not too highly discretized
  - Competing "goals": completeness for licensing (i.e., greater discretization) but more "rolled-up" (i.e., less discretization) for model building.

RS.00.TT.01 Transport of Dissolved Radionuclides in the Liquid Phase
A. Advection
B. Dispersion
C. Diffusion
D. Matrix Diffusion
E. Intra-aqueous Complexation
F. Isotopic Dilution (mixing of radioisotopes and stable isotopes)
G. Dilution by Mixing of Groundwaters

RS.00.TT.02 Interaction of Dissolved Radionuclides with Stationary Phases (Rock Matrix, Fracture Surfaces)
A. Reversible/Irreversible Physical Sorption
B. Surface Complexation
C. Ion Exchange
D. Precipitation/Dissolution

RS.00.TT.03 Interaction of Dissolved Radionuclides with other Mobile Phases (Colloids, Gas Phase)
A. Reversible/Irreversible Physical Sorption
B. Surface Complexation
C. Ion Exchange
D. Precipitation/Dissolution
E. Partitioning

RS.00.TT.04 Coupled Process Effects on Transport of Dissolved Radionuclides

RS.00.TT.05 Transport of Radionuclides in the Gas Phase
A. Advection
B. Diffusion

RS.00.TT.06 Formation of Colloids
A. Intrinsic Colloids*
B. Pseudo-colloids*

RS.00.TT.07 Transport of Radionuclides on Colloids
A. Advection of Colloids
B. Dispersion of Colloids
C. Diffusion of Colloids
D. Matrix Diffusion of Colloids
E. Stability/Flocculation of Colloids (mechanical stability, chemical stability)
F. Filtration of Colloids (physical filtration, electrostatic filtration)
G. Dilution by Mixing of Groundwaters

RS.00.TT.08 Interaction of Colloids with Other Phases (Rock Matrix, Fracture Surfaces)
A. Reversible/Irreversible Physical Sorption of Colloid Particles onto Stationary Phases
B. Sorption of Colloids at Air-Water Interface

*FEPs .07 and .08 may need to be screened separately for intrinsic vs. pseudo-colloids

SaltFEP Database Project

Future Work

- **Salt FEP Catalogue**
  - Continuation of matrix-based FEP identification and documentation
  - Both countries are in a pre-site-selection stage
    - Generic FEPs only, hard to screen without a site or design
  - Filling out the entire matrix with fully described FEPs requires significant resources
    - Maybe just identify FEP names?
  - Advanced electronic FEP Database
- **NEA Participation**
  - Need to identify "Product" for Salt Club
  - Complete NEA FEP Database beta testing

Acknowledgements

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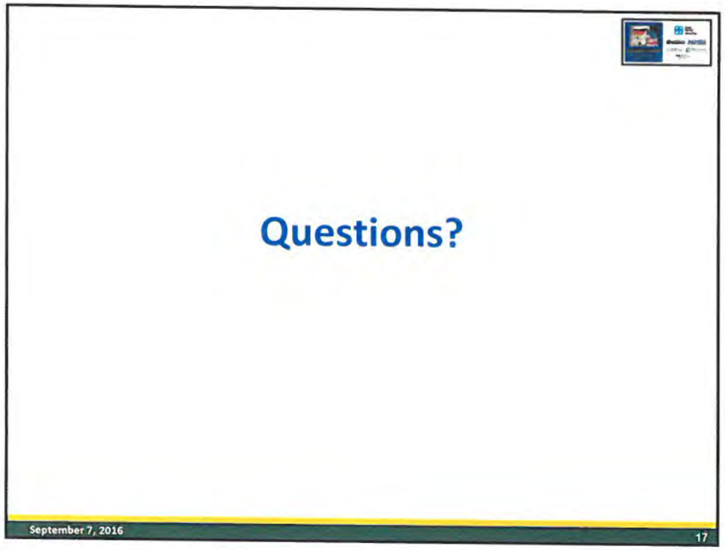
Federal Ministry of Economics and Energy

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

on the basis of a decision by the German Bundestag


Questions?
September 7, 2016
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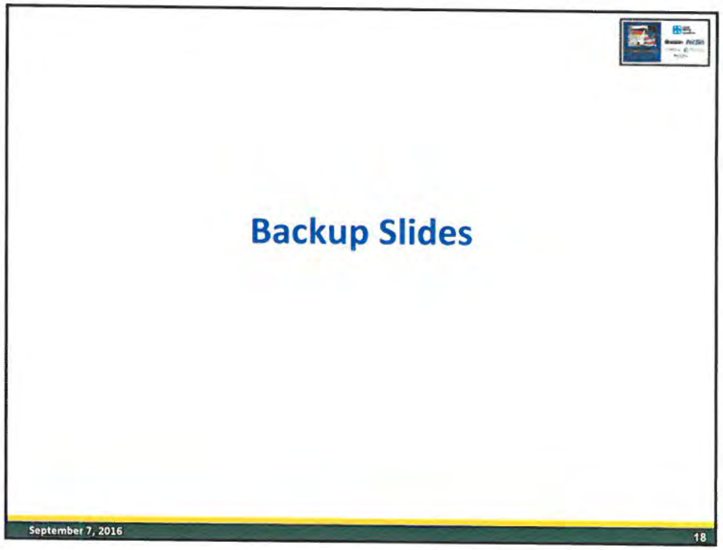
Backup Slides
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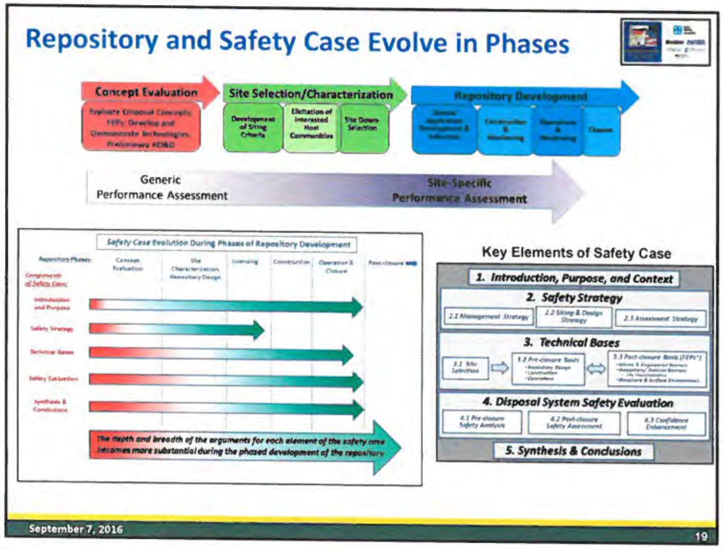
Repository and Safety Case Evolve in Phases
Concept Evaluation
Site Selection/Characterization
Development of Siting Criteria
Elicitation of Interested Host Communities
Site Down Selection
Repository Development
Construction & Monitoring
Operations & Monitoring
Closure
Generic
Performance Assessment
Site-Specific
Performance Assessment
Safety Case Evolution During Phases of Repository Development
Key Elements of Safety Case
1. Introduction, Purpose, and Context
2. Safety Strategy
2.1 Management Strategy
2.2 Siting & Design Strategy
2.3 Assessment Strategy
3. Technical Bases
3.1 Site Selection
3.2 Pre-closure Basis
3.3 Post-closure Basis (FEPs*)
4. Disposal System Safety Evaluation
4.1 Pre-closure Safety Analysis
4.2 Post-closure Safety Assessment
4.3 Confidence Enhancement
5. Synthesis & Conclusions
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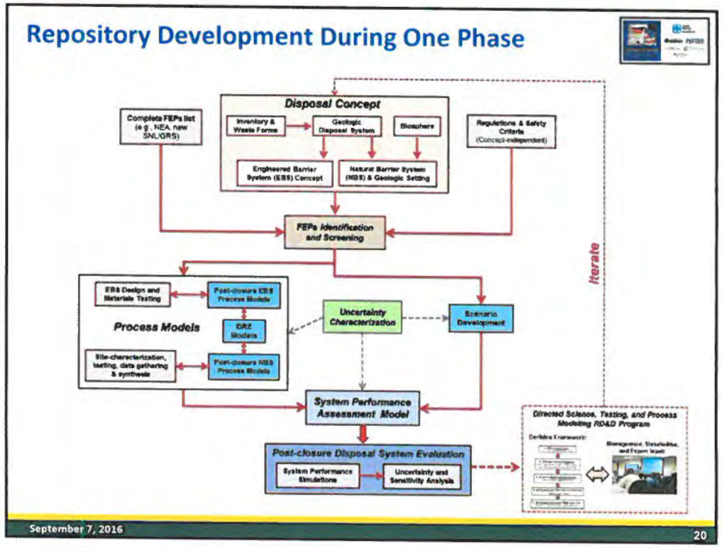
Repository Development During One Phase
Complete FEPs list (e.g., NEA, new SNL/GRS)
Disposal Concept
Inventory & Waste Forms
Geologic Disposal System
Biosphere
Engineered Barrier System (EBS) Concept
Natural Barrier System (NBS) & Geologic Setting
Regulations & Safety Criteria (Concept-independent)
FEPs Identification and Screening
EBS Design and Materials Testing
Post-closure EBS Process Models
Process Models
DRZ Models
Site-characterization, testing, data gathering & synthesis
Post-closure NBS Process Models
Uncertainty Characterization
Scenario Development
System Performance Assessment Model
Post-closure Disposal System Evaluation
System Performance Simulations
Uncertainty and Sensitivity Analysis
Directed Science, Testing, and Process Modeling RD&D Program
Iterate
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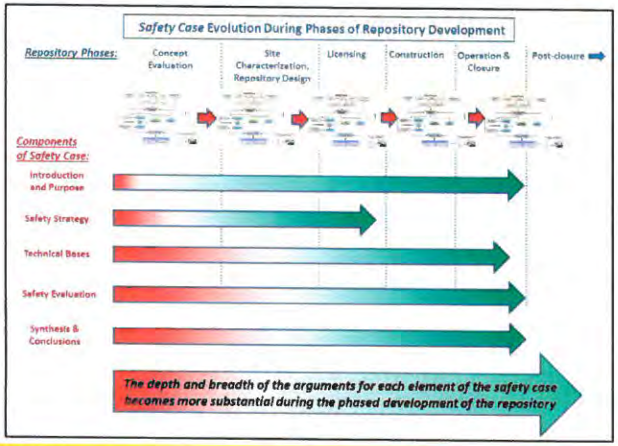
Iteration/Evolution of Phases



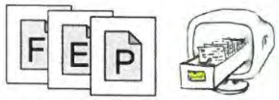
New Associated Processes for TC FEPs

- **Set of TC FEPs has not yet been redefined (as was the case with TH and TT FEPs)**
- **Associated processes for any C or TC FEPs were designed as a comprehensive list that might be applicable to any feature/component:**

(A) Speciation
(B) Oxidation/reduction processes, reaction kinetics
(C) Dissolution, reaction kinetics
(D) Precipitation, inclusion in secondary phase, reaction kinetics
(E) Formation and filtration of colloids
(F) Effect of sorption
(G) Solubility of radionuclides and other species
(H) Thermal-chemical interactions with WP/MW/BB/seal components, including chemical effects on fluid density
(I) Thermal-chemical interaction with corrosion products, including effects on fluid density
(J) Thermal-chemical Interaction with intruding fluids, including effects on fluid density
(K) Interaction with gas phase
(L) Osmotic stress and osmotic binding

NEA Participation – Salt Club

- **Produce a FEP Catalogue for use by all NEA Salt Club members**
  - Countries with potential interest in salt repositories
- **Deliverable due at end of current Salt Club Mandate Period (2014-16)**
  - Full Salt FEP Catalogue will not be complete
  - Deliverable content TBD

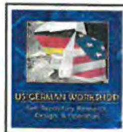


NEA Participation – FEP Database

- **US and German participation in the NEA FEP Task Group Meeting**
  - Presentation of Salt FEPs Approach and Content
- **Inform the pending update to the NEA International FEP database (completion date is TBD)**
  - Existing NEA FEPs
  - Capability for user uploading of new FEP lists
- **Currently beta testing web-based Version 0.3**

Discussion of Key Technical Issues Re: Components of the Safety Case

S. David Sevougian,
Robert J. MacKinnon
Sandia National Laboratories
Wilhelm Bollingerfehr
DBE Technology GmbH



7th US/German Workshop on Salt Repository Research, Design, and Operation
Washington, DC
September 7-9, 2016

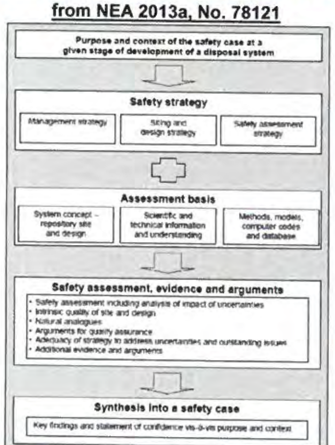
Typical Components of a Safety Case

1. **Introduction, Purpose, and Context**
2. **Safety Strategy**
   - 2.1 Management Strategy
   - 2.2 Siting & Design Strategy
   - 2.3 Assessment Strategy
3. **Technical Bases (or Assessment Basis)**
   - 3.1 Site Selection
   - 3.2 Pre-closure Basis
     - Repository Design
     - Construction
     - Operations
   - 3.3 Post-closure Basis (FEPs*)
     - Waste & Engineered Barriers
     - Geosphere/Natural Barriers
       - Site Characterization
     - Biosphere & Surface Environment
4. **Disposal System Safety Assessment**
   - 4.1 Pre-closure Safety Analysis
   - 4.2 Post-closure Safety Assessment
   - 4.3 Confidence Enhancement
5. **Synthesis & Conclusions**

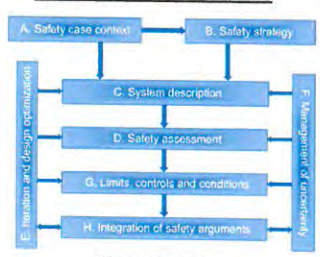
*FEP = Feature, Event, or Process

Components of Safety Case – Other Examples

from NEA 2013a, No. 78121



from IAEA 2012, No. SSG-23



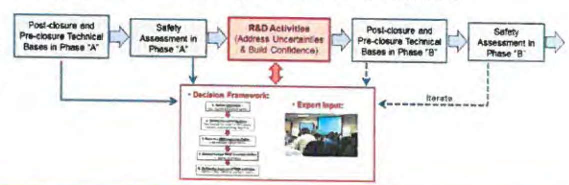
Evolution and Iteration of the Safety Case

- Safety case and safety confidence *evolve* with the different phases of repository development, **via RD&D activities**

Repository Phases:

- *Iteration* of two major elements of the safety case—***technical bases*** and ***safety assessment***—guides RD&D activities:

Iteration: (across phases)



Safety Understanding Evolves Through "Issue Resolution"

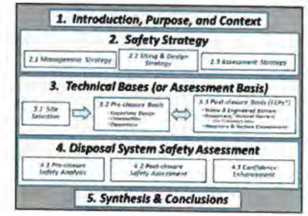
- **In a safety or licensing case, *all* outstanding issues* must ultimately be addressed with technical arguments and evidence****
  - During most phases of the safety case, limited resources ($,) requires prioritization of issues and the associated RD&D activities to resolve them
  - Set of remaining issues ("uncertainties") is based on inferences from the existing technical knowledge base — including lab, field, and *in situ* testing, as well as prior performance assessment modeling and process modeling
- **Typical issue "categories":**
  - Feature/process issues (FEPs)—"technical bases"
  - Modeling issues
  - Confidence-building issues
  - *In-situ* design/operations/testing issues

* Information need or knowledge gap.

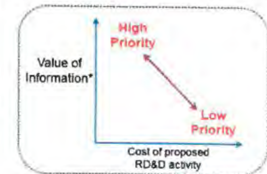
** An existing broad technical basis for either a generic repository or a site-specific repository implies a reduced set of high importance issues (also depends on program phase).

Prioritizing RD&D Activities

- **RD&D activities prioritized by** →
  1. *Importance* to components of the *safety case*: safety assessment, technical bases, confidence-building
  2. Potential to reduce key *uncertainties*
  3. Other factors (e.g., *cost*, maturity or TRL of activity, redundancies, synergies)



- **Prioritization process can be formalized**
  1. Identify a set of objectives and associated metrics, including
     - Value of information, maturity (TRL), cost, etc.
  2. Evaluate each RD&D activity using the metrics
  3. Define a "utility function" to combine the metric scores
  4. Compare utilities ("rankings") of the RD&D activities



* = Func (sensitivity of performance to the information obtained, uncertainty reduction potential (TRL))

A Simplifying Assumption

- **Prioritize each proposed RD&D *activity* by evaluating the importance of the corresponding RD&D *issue* that the activity is designed to address:***
  - Example *issue* (FEP): "Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects"
  - Example *activity*: Single heater test
  - A metric designed to evaluate the importance of a particular RD&D *issue* to the safety case is a "proxy metric" for measuring the importance of the corresponding *activity*
  - Only rigorous if there is a one-to-one correspondence between issues and activities
    - There can be more than one activity to resolve an issue (e.g., lab test or *in situ* URL test; or two types of measurement techniques)
    - Can be more than one issue resolved by a single "activity"
    - Need to evaluate the importance of *issue-activity pairs*

*see Sevougian et al. 2013

RD&D Prioritization Methodology

- **Method:** Use standard decision analysis methodology to facilitate prioritization (similar to systems engineering methods):

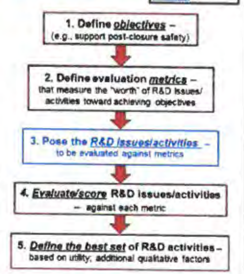
1. **Define *objectives*** – (e.g., support post-closure safety)
2. **Define evaluation *metrics*** – that measure the "worth" of R&D issues/activities toward achieving objectives ← e.g., define post-closure *safety functions** (e.g., containment, limited releases, isolation)
3. **Pose the *R&D issues/activities*** – to be evaluated against metrics
4. ***Evaluate/score* R&D issues/activities** – against each metric
5. ***Define the best set* of R&D activities** – based on utility; additional qualitative factors

➢ **Safety case context:** base the objectives on elements of the safety case

*see Sevougian and MacKinnon 2014

Step 3. Pose the RD&D Issues

- Potential post-closure RD&D issues taken from FEPs catalogue (completeness)—e.g., DOE (2012)
- ***Important*** remaining RD&D issues based on the existing technical knowledge base— derived from lab, field, and *in situ* testing, as well as prior performance assessment modeling, process modeling, and uncertainty characterization
- Example for generic salt repositories: phenomena related to heat-generating waste given special consideration, e.g.,
  - Creep closure accelerated by elevated temperatures
  - Crushed salt backfill reconsolidation for elevated temperatures
  - Material property changes coupled to fluid movement enhanced by thermal-hydrologic-mechanical (THM) processes



Salt RD&D Feature/Process Issues

- 30 feature/process ("FEPs") issues were identified and given "pre-workshop" importance ratings—11 rated as "H"—then evaluated by experts during a DOE-NE/EM workshop, March 2013, in Albuquerque, NM
- Based on *nominal scenario* evolution and high heat load assumption – see Sevougian et al. 2013
- Two breakout groups (pre-closure and post-closure) reconsidered ratings, making a few changes

Salt RD&D Technical Issue	Issue Importance Rating
Wastes and Engineered Features (EBS) Feature/Process Issues	
1. Inventory and WP Loading	M (= I,P)
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)
5. Mechanical response of backfill	H (= D,P)
6. Impact of mechanical loading on performance of the WP	H (= D,P)
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)
8. Corrosion performance of the waste package	M = (I,P)
9. Mechanical and chemical degradation of the waste forms	L (= D,S)
10. Brine flow through waste package	L (= D,S)
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)
12. Radionuclide solubility in the waste package and EBS	L (= D,S)
13. Radionuclide transport in the waste package and EBS	L (= D,S)

Salt RD&D Technical Issue	Issue Importance Rating
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues	
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)
17. The formation and evolution of the EDZ	H (= D,P)
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)
19. Chemical characteristics of brine in the host rock	L (= I,S)
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)
22. Radionuclide transport in the host rock and EDZ	L (= D,S)
Repository System (EBS and Geosphere combined) Feature/Process Issues	
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)
24. Buoyancy of the waste packages	L (= W,P)
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)
28. Performance of seal system	H (= D,P)
29. Performance of ground support	L = (W,P,S)
30. Performance and effects of ventilation	M (= I,P)

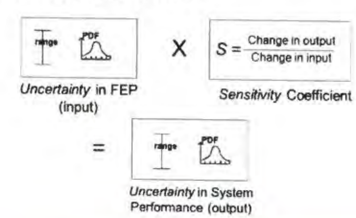
Post-Workshop RD&D Activity Proposals

Table 7-1 Summary of RD&D Test Proposals Questionnaires Received after the Salt RD&D Integration Workshop

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation
Primarily *in situ*, large-scale field testing (with modeling)			
H-1	Clay Seam Shear Testing	In situ tests in the new URL; Laboratory tests; Constitutive modeling; International collaborations	Frank Hansen (SNL)
H-2	Single Heater Test	Generic in situ tests in the new URL; international collaborations; Modeling prediction and validation	Frank Hansen (SNL), Carlos Jove-Colon (SNL)
H-3	Large Scale Seal Test	In situ tests in the new URL; international collaborations; Modeling; Lab—ACI concrete testing	Frank Hansen (SNL)
H-4	Salt Defense Disposal Investigations (SDDI) Thermal Test	In situ thermal test; Laboratory tests; THM and THMC model validation	Doug Weaver (LANL)
H-5	Water migration tracer test during the proposed SDDI experiment	In situ field test with lab analysis, including pre-, during, and post-test transport modeling	Philip Stauffer (LANL), Florie Caporuscio (LANL), Paul Reimus (LANL), Ernest Hardin (SNL)
Laboratory testing, followed by *in situ* testing (with modeling)			
H-6	Salt Decrepitation Effects	Laboratory tests initially; borehole & in situ field testing later; THM process and constitutive modeling	Kris Kuhlman (SNL)
H-7	Development of an Integrated Geophysical Imaging System for Field-Scale Monitoring of Brine Migration and Mechanical Alteration in Salt Repositories	Laboratory tests; Field testing at LBNL Geophysical Measurement Facility (GMF); (no modeling initially but later some pre-test modeling)	T.M. Daley, Y. Wu, J. Birkholzer, and J.B. Ajo-Franklin (LBNL)
Laboratory testing, followed by *in situ* testing (no modeling)			
H-8	Geophysical and acoustical monitoring of fluid migration and fracture evolution for WIPP salt thermal tests	Initial lab sensitivity experiments; followed by in situ field tests at WIPP during SDDI thermal tests (no modeling)	Peter Roberts (LANL)
H-9	In situ and laboratory testing of moisture monitoring methods	Laboratory tests; in situ field tests (no simulation modeling mentioned)	Dan Levitt (LANL)
Laboratory testing (with modeling)			
H-10	Thermo-Hydro-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay on Permeability and Brine Migration in Salt at High Temperatures and Pressures	Complex THMC laboratory experiments; coupled process modeling to predict/interpret the results	Tim Kneafsey and Seiji Nakagawa (LBNL)
Laboratory testing (no modeling)			
H-11	Long-term steel corrosion analyses from Room A1/B ex-entry	Laboratory test; no simulation modeling mentioned	Pat Brady (SNL)
H-12	Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography	Laboratory tests (no simulation modeling)	Hongwu Xu (LANL), Jonathan Ajo-Franklin (LBL)
H-13	Validation of constitutive models and parameterization of unsaturated brine flow in intact and crushed salt	Laboratory test (no simulation modeling)	Kris Kuhlman (SNL), Beatriz Mesona (SNL)
H-14	Stability of Polyhalite in the Salado Formation	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)
H-15	Stability of hydrous phases (correnste, bassanite) in the Salado Formation	Laboratory test (applicable for SDDI waste emplacement studies)— (no simulation modeling)	Florie Caporuscio (LANL)
H-16	Use of ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) to map and quantify brine content in an undisturbed salt core	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)
H-17	Elevated-Temperature Measurements of Plutonium (III) and Neodymium(III) Solubility in Low to Moderate Ionic Strength Aqueous Solutions	Laboratory tests (no modeling)	Jonathan Icenhower and David Shuh (LBNL); Donald Reed (LANL)
H-18	Laboratory Study on the Long-term Porosity and Permeability Reduction in Salt Backfill Under Elevated Temperature Conditions	Laboratory tests (no modeling)	Tim Kneafsey and Seiji Nakagawa (LBNL)
Modeling and simulation studies only (no physical tests)			
H-19	Mechanistic modeling of brine and vapor movement	Theoretical and modeling study	Qinjun Kang (LANL)
H-20	THM Optimization of Preclosure Repository Design	Coupled process modeling	Jonny Rutqvist and Laura Blanco-Martin (LBNL); Phil Stauffer and Florie Caporuscio (LANL)
H-21	Benchmarking Simulations for THM Behavior of Rock Salt	THM(C) benchmark modeling—model-to-model comparisons for a simplified repository, for a lab/field THM experiment, and for the planned SDDI test	Jonny Rutqvist and Jens Birkholzer (LBNL); Phil Stauffer and Bruce Robinson (LANL); Carlos Jove-Colon, Kristopher Kuhlman, and Ernest Hardin (SNL)
H-22	THM Model of Salt Rock Microstructural Damage and Healing	Mechanistic microstructure modeling of coupled processes in salt	Dasuke Asahina and Jim Houseworth (LBNL)
H-23	Brine Migration in Salt: Review and Constitutive Model Development	Constitutive models	Jim Houseworth, Jonny Rutqvist, Hui-Hai Liu, Jens Birkholzer (LBNL)

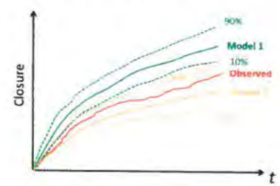
Effect of Uncertainty and/or TRL

- **Previous evaluation of issue significance was mostly based on their importance to system performance or safety:**
  - How *sensitive* is the system to the given issue or FEP?
- **Just as critical to any RD&D funding decision is our current state of knowledge (TRL) regarding the issue or FEP, i.e., *uncertainty* reduction potential**

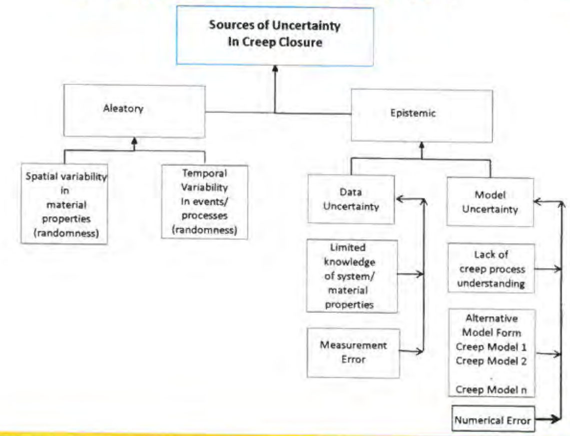


Potential Focus Topic for Today

- *Uncertainty characterization for THM processes and models*
- How can we know how uncertainty in THM models affects *post-closure* system performance (e.g., total dose), in order to know how much additional RD&D is necessary?
- How to characterize uncertainty in model input parameters?
- Which constitutive model or how many models are needed to encompass potential behavior?



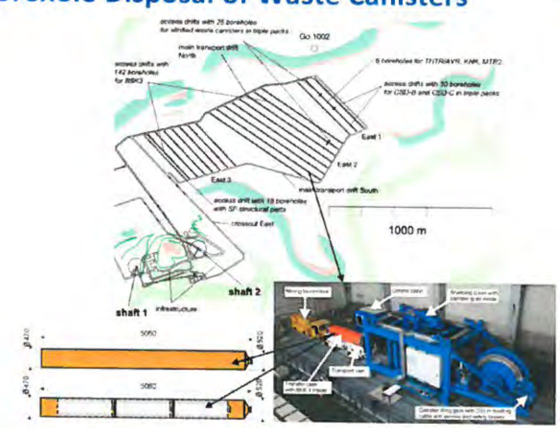
Uncertainty in Creep Closure of Emplacement Drifts in Salt



Operational Safety

- Operational Safety is a substantial part of the Safety Case for a HLW/SF-Repository
- Events with possible impacts on operating activities that could endanger operational safety have to be systematically analyzed and evaluated
- Safety of Technical systems and components has to be demonstrated (reliability, safety and robustness)

Example Repository Design: Borehole Disposal of Waste Canisters



Regulatory Framework in Germany

- Atomic Energy Act
- Radiation Protection Ordinance
- Federal Mining Act
- Safety Requirements Governing the Final Disposal of Heat-Generating Waste (BMU, 2010)
  - "A **comprehensive safety case** shall be documented for all **operating states of the final repository**, including the surface facilities. In particular, facility-specific safety analyses shall be conducted for emplacement operation and decommissioning...." and
  - "For the safety of the final repository in the operating phase including decommissioning, the reliability and robustness of safety functions within the final repository must be proven..... **For the operating phase**, moreover, **a four-level safety concept** should be planned..."

Defense in Depth Concept

- **Four-level safety concept:**
  - **level 1: Normal Operation:** measures prevent the occurrence of operational failures
  - **level 2: Anomalous Operation:** measures prevent the occurrence of design basis accidents
  - **level 3: Design Basis Accidents:** measures control design basis accidents
  - **level 4: Beyond Design Basis Accidents/Incidents:** measures reduce probability or limit environmental impacts

Radiological Operational Safety

- **Radiological Protection Goal:**
  - safe confinement of radioactive substances
- **Deterministic Safety Analysis**
  - Demonstration of completeness
    - » complete list of all possible incidents and accidents
  - Compilation of significant events
    - » internally and externally initiated
  - Identification of design-basis incidents
    - » analysis of most serious consequences of events/combinations of events on relevant subsystems
  - Demonstration of adequate damage prevention measures
    - » by means of detailed analysis of such incidents

Radiological Operational Safety

- **Radiological Protection Goal:**
  - safe confinement of radioactive substances
- **Probabilistic Safety Analysis**
  - no regulatory provisions to perform a PSA prior to licensing application
  - according to the "Guide Probabilistic Safety Analysis" the results of a PSA are:
    - » supplement to the deterministic safety assessment
    - » form a basis to determine the necessity and urgency of safety improvements
    - » enables a balanced plant concept with regard to safety issues

Conventional Operational Safety in a Repository Mine

- Safety related issues governed by numerous sectional implementation regulations in the German Federal Mining Act
- Events with possible impacts on operating activities that could endanger operational safety:
  - rock mechanical impacts
    - (e.g. cross section reduction, loose material, inclination of floor, etc.)
  - inflow of brine and natural gases
  - failure of ventilation system
  - failure of power supply
  - fire within the facility
  - derailing of a loaded cart

Conventional Operational Safety in a Repository Mine

- Rock mechanical impacts (e.g. cross section reduction, loose material, inclination of floor, etc.)
  - controllable (by means of observation, removal of loose material, etc.)
- Inflow of brine and natural gases
  - both have to be investigated site specific;
  - may be ruled out or
  - volume and potential effects on operational safety to be assessed

Conventional Operational Safety in a Repository Mine

- failure of ventilation system
- failure of power supply
- fire within the facility
- derailing of a loaded cart

➢ For the Reference Disposal Concept : (HLW- and SF-Repository in a Salt Dome)
  - all these 4 events deem to be controllable,
  - thus do not result in safety risks,
  - but safe operation has to be demonstrated

Open Discussion

Questions:

1. Is Operational Safety as important as Long Term Safety?
2. How is Operational Safety linked to Long-term Safety and vice versa? Give examples
3. To what extend are the tools developed and standardized for both safety analysis (OS and LTS)?
4. Is the FEP-methodology applicable for OS as well?
5. How is ongoing RD&D work dealing with these questions?

Open Discussion

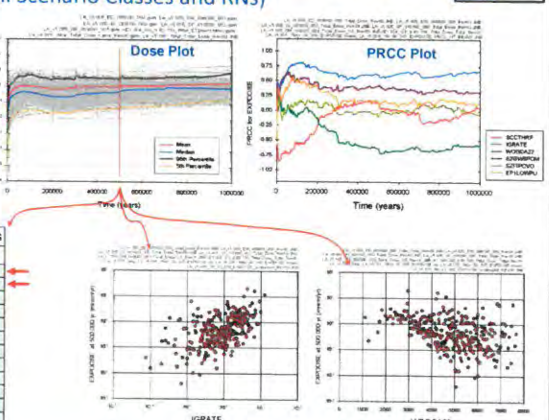
Backup Slides

Uncertainty in YM Total Expected Dose
(Sum over All Scenario Classes and RNs)

IGRATE – Frequency of igneous events

WDGCA22 – Temperature dependence in A22 corrosion rate

SZGWSPDM – Uncert factor for groundwater specific discharge rate



EXPDOSE: 500,000 Years

Variable	R^2	SRRC
IGRATE	0.29	0.54
WDGCA22	0.46	−0.38
SZGWSPDM	0.53	0.24
EP1LOWNU	0.56	0.19
MICNP237	0.59	0.16
EP1LOWPU	0.61	0.17
SZCONCOL	0.64	0.15
SZFISPVO	0.66	0.15
INFIL	0.67	0.11
GOESITED	0.68	−0.10
SZKDCSVO	0.69	−0.10
HFOSITED	0.69	−0.09
SZDIFCVO	0.70	−0.09

Some Aspects of Uncertainty Characterization

- **Nature of uncertainty: aleatory (inherent randomness) vs. epistemic (lack of knowledge)**
- **Sources of model and prediction uncertainty, e.g.:**
  - Parameter (input) uncertainty (epistemic)
  - Model structural uncertainty (epistemic—lack of knowledge of true physics)
  - Experiment or data measurement uncertainty (aleatory or variability)
  - Numerical approximation uncertainties, arising from spatial-temporal discretization error, statistical sampling error, iterative convergence error
- **How to upscale data (from lab to field; from core data to numerical grid blocks)—how to handle associated variance reduction**
- **Methods to fit uncertainty distributions to dense data sets**
  - Mechanistic considerations when choosing probability distribution type
- **How to fit uncertainty distributions to sparse data sets**
  - Maximum entropy
  - How/when to use expert elicitation (i.e., subjective uncertainty assessment)?

NEA/IAEA Workshop on Operational Safety:
- Summary of Presentations and Discussions -

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH

Washington, DC
September 7-9, 2016

Contents

- Background
- Objectives of the Workshop
- Workshop Format
- Workshop Summary and Future Challenges

Background

For decades, geological disposal programmes

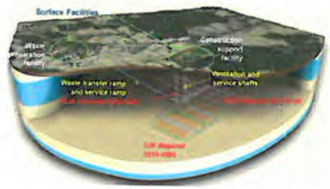
- ➢ focussed on long-term safety,

As programmes have matured:

- ➢ aspects related to engineering feasibility and operational safety have received increasing attention.
- ➢ It has become apparent that operating a repository safelty for many decades is a challenging undertaking,
- ➢ as is demonstrating operational safety at a level of detail adequate to license such operations.

Common Disposal Concepts

- Deep geological repositories will be sited, designed, constructed, operated and closed to isolate RW from the accessible biosphere;
- Surface operations are as important as activities in the underground (UG); infrastructure like shafts and/or ramps that connects the UG with the surface;



- Deep geological repositories may remain operational for long period (up to 100 yrs), may be expanded if needed;
- ALARA and the defence-in-depth strategy along with engineered barriers are often applied to minimize exposure risks.

Repository Operations

- **Surface facilities:** typical processes include waste acceptance, encapsulation of conditioned waste; inspection, and canister preparation / acceptance for transfer to UG disposal;
- **Ready packages** are transferred in shielded transfer cask;
- **Emplacement** of disposal canisters in UG boreholes or cells;
- **Exposure** to workers and the public **during the operational phase** is likely similar as in other nuclear facilities.

Shielded driver cabin – locomotive (Ondraf/Niras)

Motivation for a Common Workshop

Both the NEA and the IAEA have long recognised the importance of operational safety. Projects and work initiatives have been carried out with different work scopes and objectives to address various operational safety issues. For instance,

- The NEA IGSC created the Expert Group on Operational Safety (EGOS) in 2013 to develop the best operating practices and the optimal design provisions of geological repositories.
- IAEA had launched the GEOSAF Project in 2008 (a forum to exchange ideas and experience on the development and review of safety cases for geological disposal facilities).
- Consequentially a common workshop was initiated to share information and experiences (NEA-OECD-headquarters in Paris, July 2016)

Objectives of the Workshop

- Explore how implementers address operational safety in developing geological repositories for radioactive waste disposal,
- Identify effective and practical design alternatives used to achieve operational safety in geological repositories,
- Evaluate the adequacy and comprehensiveness of the existing regulatory framework guiding implementers in addressing operational safety in geological repositories and
- Identify areas and topics that require further work.

Workshop Format

The workshop focuses on **three key topics**:

1) **technical design aspects,** e.g. fire risk management, on-site transportation and emplacement;

2) **repository regulatory framework and requirements**; and

3) **radiological protection** issues in DGR,

each one consisting of introducing presentations followed by small group discussions (guided by specific questions).

- *45 Participants from 15 countries attended the Workshop, and representatives from NEA and IAEA*

Worshop Summary and Future Challenges

1. Regulatory Environment
2. System design and Controls
3. Operational safety assessment and risk management
4. Monitoring and compliance control
5. Safety Culture

1. Regulatory Environment

- Demonstrating compliance with a wide range of relevant regulations and coordinating the work of multiple regulatory bodies, and
- Building and adapting a regulatory system with clear responsibilities of all involved regulatory bodies. It is also crucial to maintain regulatory competence;
- Resolving the current lack of international guidance specifically focussed on the operational safety of geological repositories and investigating the possibility of integrating harmonising national regulations;
- Preparing for an emergency situation.

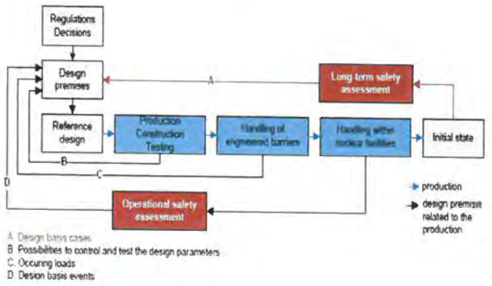
2. System Design and Controls 1/2

- dealing, e.g. through the development of waste acceptance criteria, with the often wide range of waste types that can arise over periods of decades, some of which give rise to specific safety concerns (e.g. produce gases)
- striking a suitable balance between prevention of incidents and accidents on the one hand and detection/mitigation on the other,
- including "resilience" in design, i.e. the ability to respond / recover effectively in the event of an incident or accident,

2. System Design and Controls 2/2

- managing possible conflicts in safety requirements (e.g. between fire safety requirements and provision of a good working environment during normal operations when planning ventilation systems) and, more generally, between construction/operational safety and long-term safety, and
- implementing a system of change management during the operational period, (must be properly documented for transparency and also they can give rise to unforeseen operational safety issues.

Example: System Design and Controls



Iterative process of design development, with feedback from operational and long-term safety assessments to design requirements or premises, (as envisioned by SKB and Posiva)

3. Operational Safety Assessment and Risk Management

- investigating the possibility to develop standardised high-level approaches, e.g. to fire risk management,
- better justifying certain key model assumptions, e.g. regarding the temperature and duration of fires,
- ensuring waste retrieval operations, if needed, can be carried out safely in such a way that guarantees safeguards and security, and
- promoting completeness in evaluating risks or hazards and the ranges of potential consequences.

4. Monitoring and Compliance Control 1/2

- clarifying regulatory expectations on monitoring at each licencing stage,
- demonstrating and maintaining the reliability of monitoring equipment,
- clarifying the extent to which equipment for monitoring during the operational phase needs to be removed,
- identifying the role, nature and conditions for post-operational monitoring,

4. Monitoring and Compliance Control 2/2

- developing “safety envelopes” that define the ranges of parameter values that are consistent with safety,
- clarifying what actions to take if parameter values that are monitored are outside their respective safety envelopes (including circumstances in which waste packages should be retrieved), and
- clarifying the roles of underground research laboratories and “pilot facilities” with regard to monitoring .

5. Safety Culture

- maintaining the main focus of the organization on safety over a period of many decades (e.g. continual support from management, maintaining staff competence, preserving corporate memory, etc),
- ensuring that schedules and cost concerns do not compromise safety,
- resolving possible cultural differences between construction personnel (miners) and operations personnel, and
- demonstrating an adequate safety culture to stakeholders.

Acknowlegements

Many Thanks to:

- NEA and IAEA as initiators and organizers of the workshop
- Workshop Programme Committee
- Chairpersons and rapporteurs
- Participants for presentations and discussions
- Paul Smith: Draft summary report

First results of the KOSINA-project: technical concepts and geological and numerical modeling

T. Kühnlenz & KOSINA-Team
BGR, DBE TEC, GRS, IfG

Washington, DC
September 7-9, 2016

Background

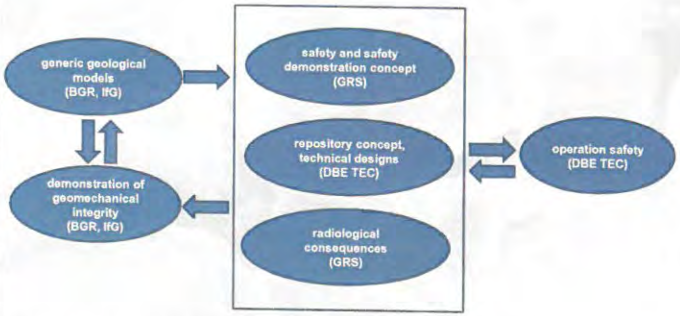
- **2013** – The German Repository Site Selection Act
- **1960 – 2014** - main focus of salt studies - salt diapirs
  →Necessity of additional geological data for bedded salt formations
  →BGR-Projekt **BASAL** → distribution and characterization of flat bedded salt formations
- **April 2015** - R&D-projekt:

  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)

Organisations involved:

- *German Company for Construction and Operation of Waste Repositories (DBE TEC)*
- *Company for Safety of constructions and reactors (GRS)*
- *Institute for geomechanics (IfG)*
- *Federal Institute for Geosciences and Mineral Ressources (BGR)*

Objectives

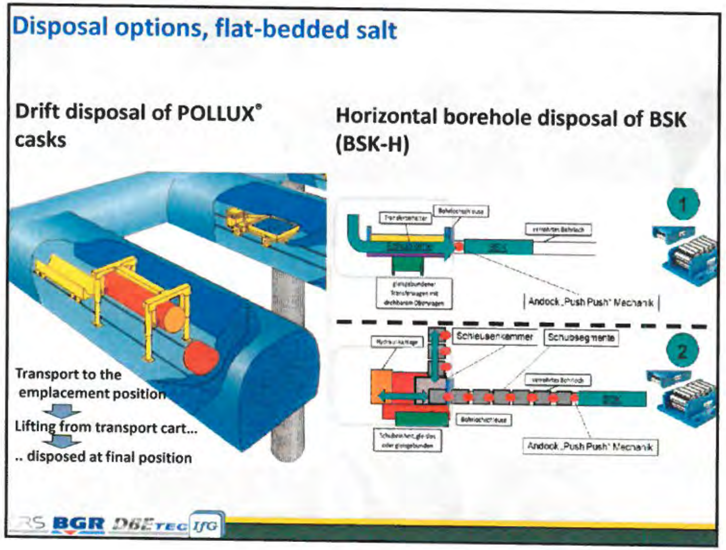


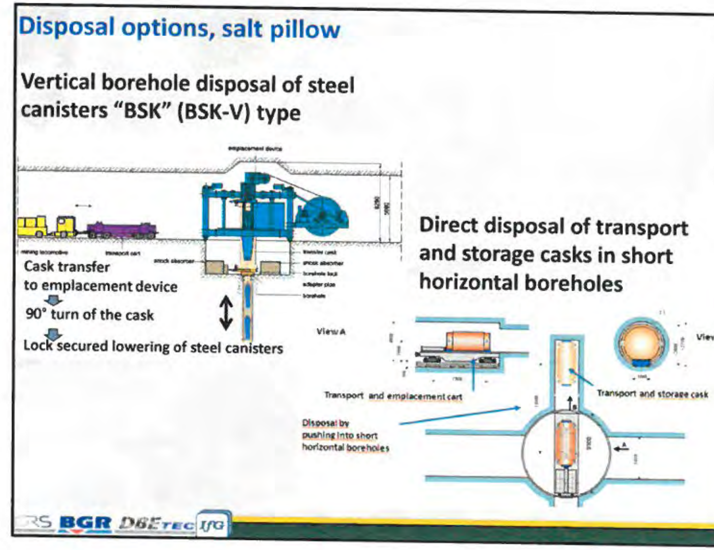
➢ provide a technical-scientific basis for the safety oriented evaluation of repository systems in different host rocks according to the German site selection law

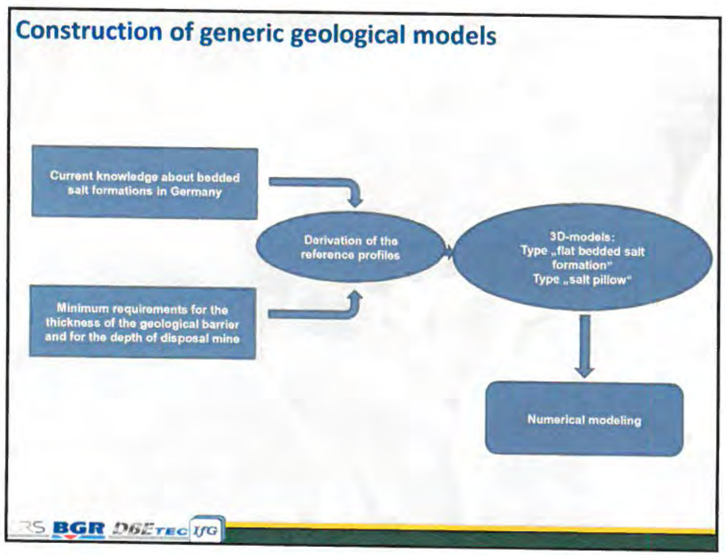
Development of technical concepts

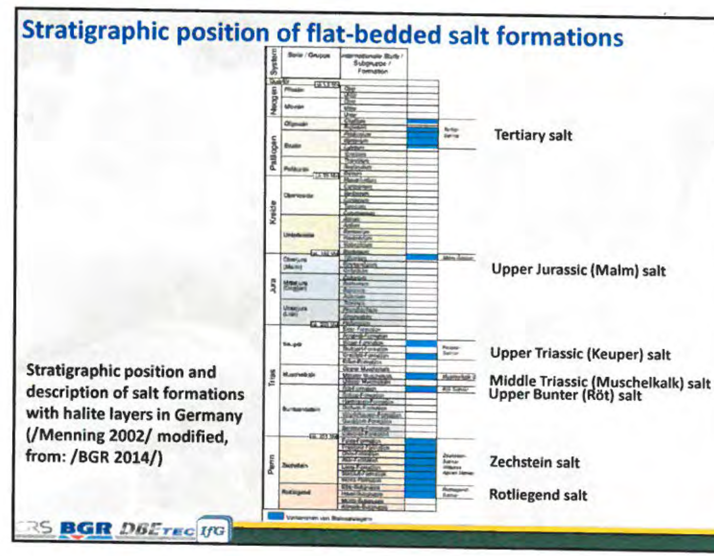
having regard to the topics:

- Recoverability
- Effects of increased temporary storage periods
- Transport and operation technique
- Disposal and recoverability technique
- Backfill and sealing technique


Disposal options, flat-bedded salt
Drift disposal of POLLUX® casks
Horizontal borehole disposal of BSK (BSK-H)
Transport to the emplacement position
Lifting from transport cart...
.. disposed at final position
Andock „Push Push" Mechanik
Schleusenkammer
Schubsegmente
Andock „Push Push" Mechanik
1
2
BGR DBE TEC IfG


Disposal options, salt pillow
Vertical borehole disposal of steel canisters "BSK" (BSK-V) type
Cask transfer to emplacement device
90° turn of the cask
Lock secured lowering of steel canisters
Direct disposal of transport and storage casks in short horizontal boreholes
View A
View B
Transport and emplacement cart
Transport and storage cask
Disposal by pushing into short horizontal boreholes
BGR DBE TEC IfG

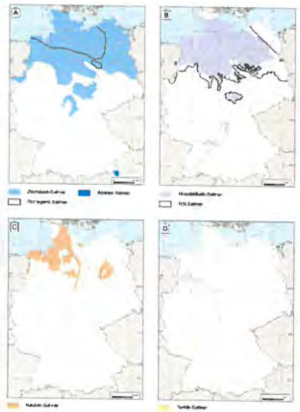

Construction of generic geological models
Current knowledge about bedded salt formations in Germany
Minimum requirements for the thickness of the geological barrier and for the depth of disposal mine
Derivation of the reference profiles
3D-models:
Type „flat bedded salt formation"
Type „salt pillow"
Numerical modeling
BGR DBE TEC IfG


Stratigraphic position of flat-bedded salt formations
Tertiary salt
Upper Jurassic (Malm) salt
Upper Triassic (Keuper) salt
Middle Triassic (Muschelkalk) salt
Upper Bunter (Röt) salt
Zechstein salt
Rotliegend salt
Stratigraphic position and description of salt formations with halite layers in Germany (/Menning 2002/ modified, from: /BGR 2014/)
BGR DBE TEC IfG

On-shore-distribution of flat-bedded salt formations

Rotliegend
Zechstein

Bunter (Röt)
Muschelkalk



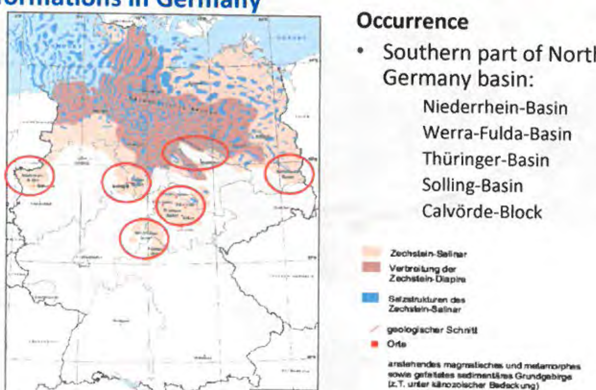
Keuper (Trias)

Jurassic (Malm)
Tertiary

Minimum requirements

- Criteria or minimum requirements → derivation of the data from still existing studies (AkEnd 2002, BGR 2004, Hammer et al. 2009, IfG 2010)
  - Depth of repository mine between 500 m and 1.000 m below surface
  - Thickness of the storage horizon thicker than 100 m

Distribution of flat-bedded Zechstein (upper Permian) salt formations in Germany

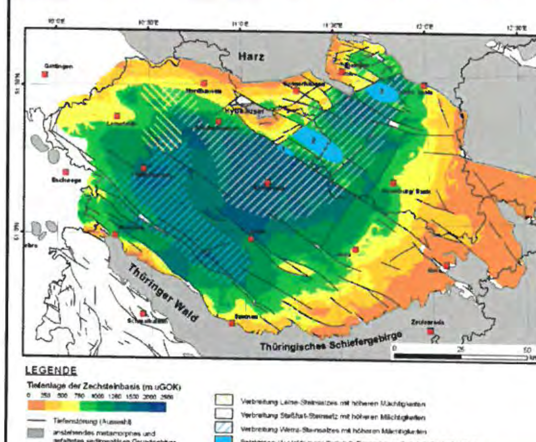


Occurrence

- Southern part of Northern Germany basin:
  - Niederrhein-Basin
  - Werra-Fulda-Basin
  - Thüringer-Basin
  - Solling-Basin
  - Calvörde-Block

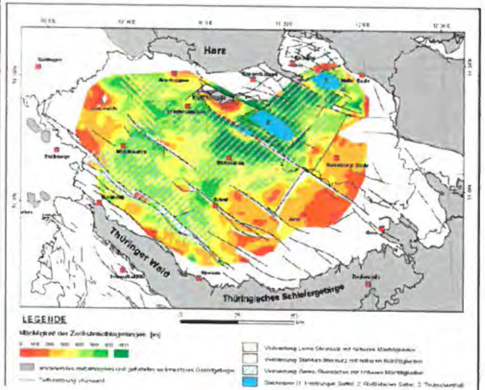
Schematic on-shore-distribution of halite-composed Zechstein salt in Germany (according to: KULICK ET AL. 1984, FREUDENBERGER & SCHWERD 1996, KRULL ET AL. 2004); Distribution of Zechstein salt structures (according to: REINHOLD ET AL. (2008))

Depth of Zechstein basin - Thuringian Basin



- margin of basin → close to surface
- center of basin → 2000 m (Zander & Huckriede 2011)

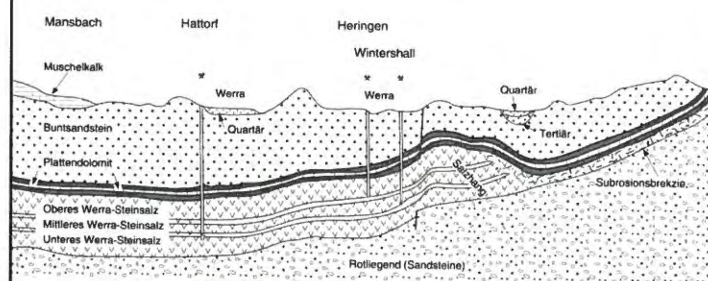
Thickness of Zechstein – Thuringian basin



– Staßfurt-Formation:

→ high thickness in the NE (up to 500 m in the salt structures)
→Inclusions of up to 20 m thick Kaliflöz Staßfurt

Geological section Werra-Fulda Basin



- Werra-Formation→ thickness up to 220 m
- Top of Zechstein salt layers in a depth of 600 m to 1000 m (Ahorner & Sobisch 1988)

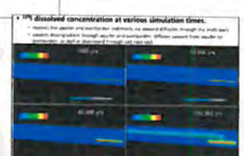
Specific characteristic of flat-bedded salt layers

Layer inclination

Profile in SW-Thuringia

Author: Hoppe (1958)

WIPP

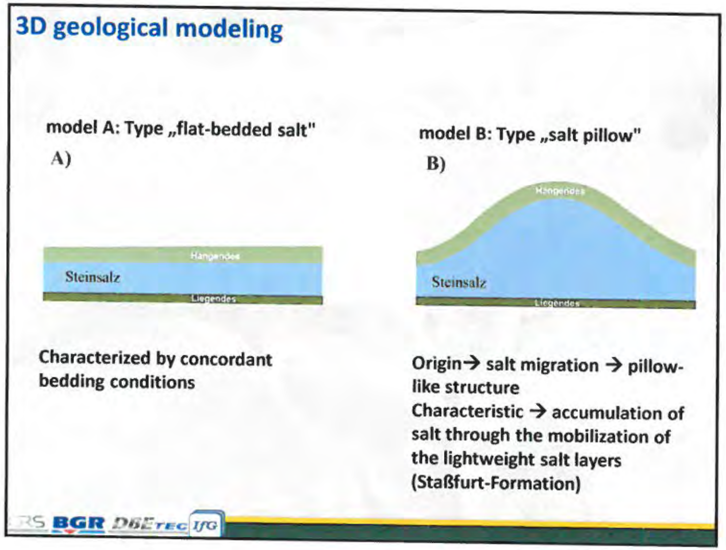


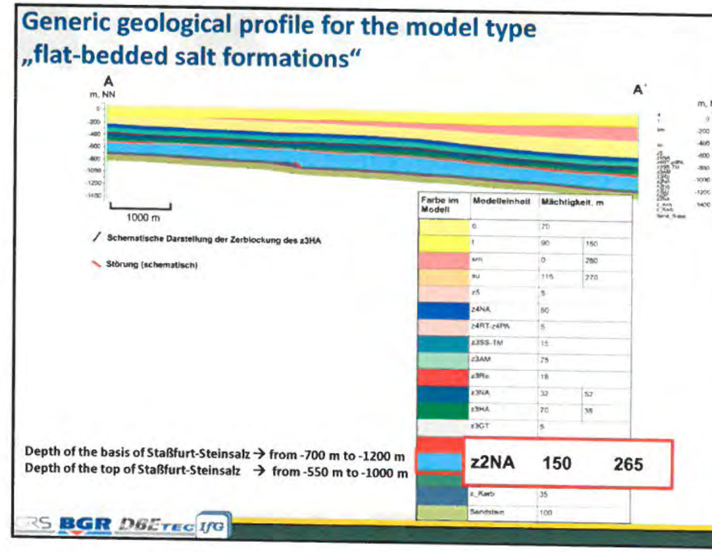
S. David Sevougian, PhD Sandia National Laboratories. PFLOTRAN: Coupled THM Simulations. In: 6th US/German Workshop on Salt Repository Research, Design and Operation.

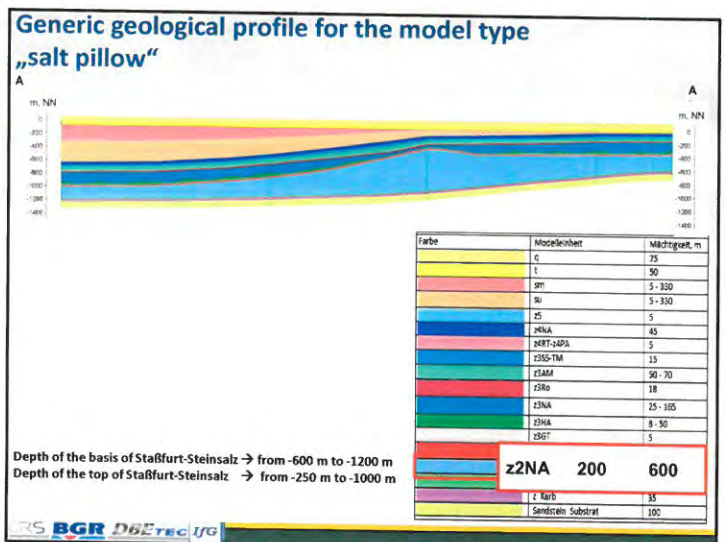
Geological sequences for the reference profile

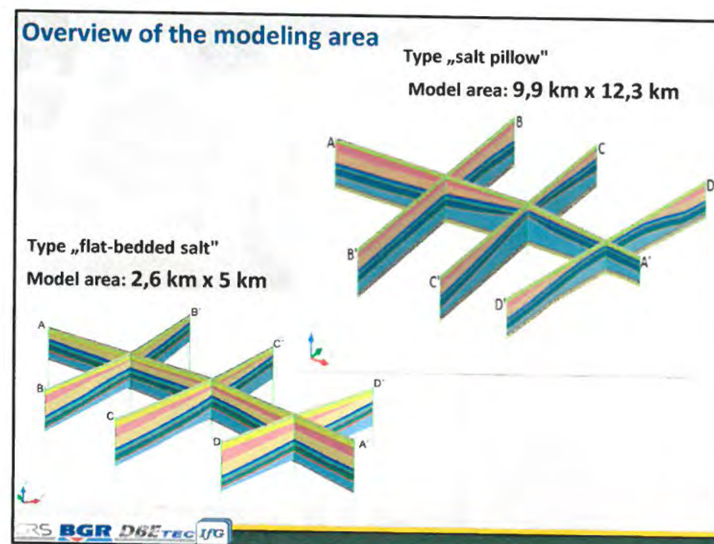
Overburden	q t sm su	Quartär Tertiär mittlerer Buntsandstein unterer Buntsandstein	
Ohre-Folge	z5	Ohre-Sedimente	Host rock
Aller-Folge	z4NA z4RT-z4PA	Aller-Steinsalz Roter Salzton/Pegmatitanhydrit	Host rock
Leine-Folge	z3SS-TM z3AM z3RO z3NA z3HA z3GT	Schwadensalz/Tonmittelsalz Anhydritmittelsalz Kaliflöz Ronnenberg Leine-Steinsalz Hauptanhydrit Grauer Salzton	Host rock
Staßfurt-Folge	z2SF	Kaliflöz Staßfurt	Host rock
Staßfurt-Folge	z2NA	Staßfurt-Steinsalz storage horizon	Host rock
Underlying beds		z_Anhydrit z_Karbonat	Host rock
Underlying beds		Sandstone	

- **Host rocks →** Zechstein (z1, z2, z3,z4,z5-z7)
- **Storage horizon →** Staßfurt-Hauptsalz (z2HS)

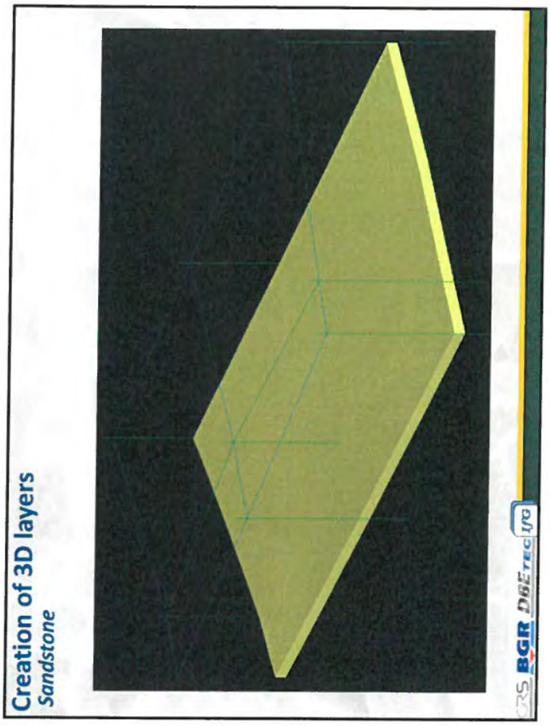

3D geological modeling
model A: Type „flat-bedded salt"
A)
Hangendes
Steinsalz
Liegendes
Characterized by concordant bedding conditions
model B: Type „salt pillow"
B)
Hangendes
Steinsalz
Liegendes
Origin→ salt migration → pillow-like structure
Characteristic → accumulation of salt through the mobilization of the lightweight salt layers (Staßfurt-Formation)
BGR DBETEC IfG

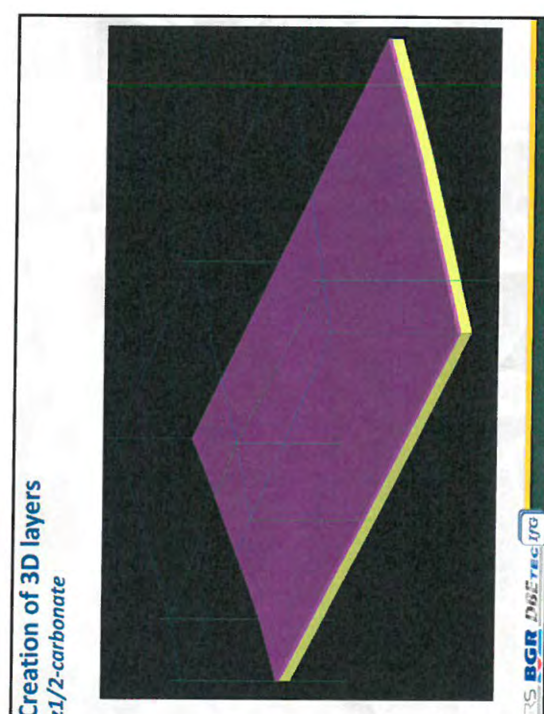

Generic geological profile for the model type „flat-bedded salt formations"
A
A'
m, NN
1000 m
Schematische Darstellung der Zerblockung des z3HA
Störung (schematisch)
Farbe im Modell
Modelleinheit
Mächtigkeit, m
z2NA 150 265
Depth of the basis of Staßfurt-Steinsalz → from -700 m to -1200 m
Depth of the top of Staßfurt-Steinsalz → from -550 m to -1000 m
BGR DBETEC IfG

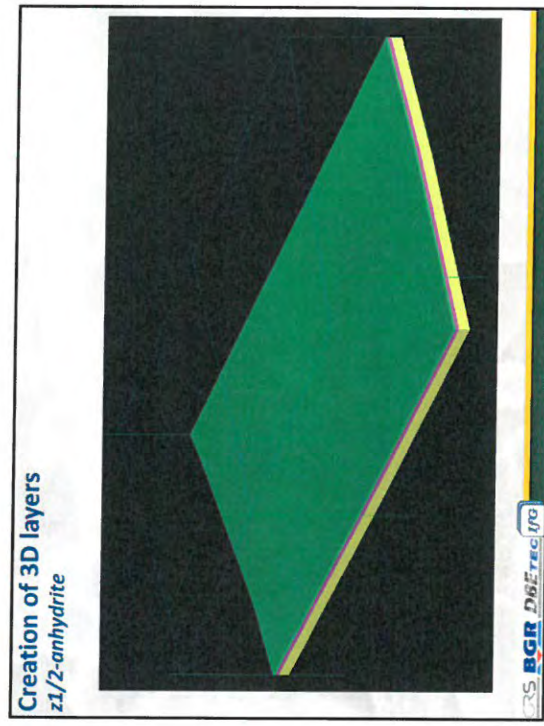

Generic geological profile for the model type „salt pillow"
A
A
m, NN
Farbe
Modelleinheit
Mächtigkeit, m
z2NA 200 600
Depth of the basis of Staßfurt-Steinsalz → from -600 m to -1200 m
Depth of the top of Staßfurt-Steinsalz → from -250 m to -1000 m
BGR DBETEC IfG

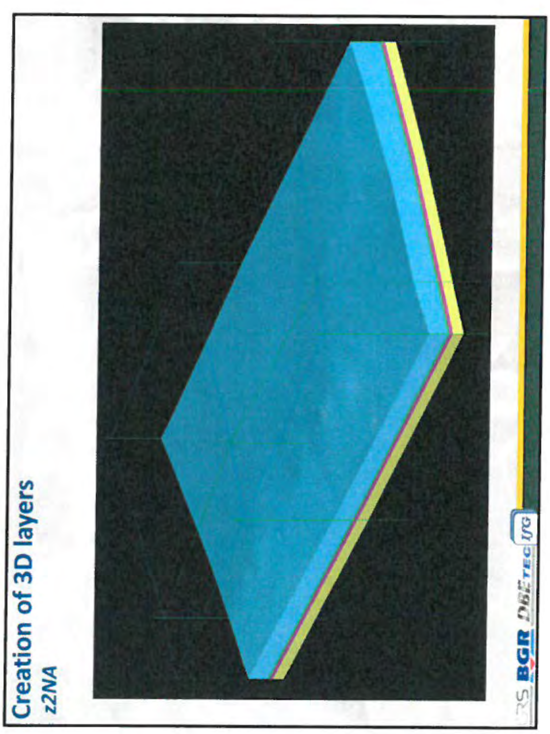

Overview of the modeling area
Type „salt pillow"
Model area: 9,9 km x 12,3 km
Type „flat-bedded salt"
Model area: 2,6 km x 5 km
BGR DBETEC IfG

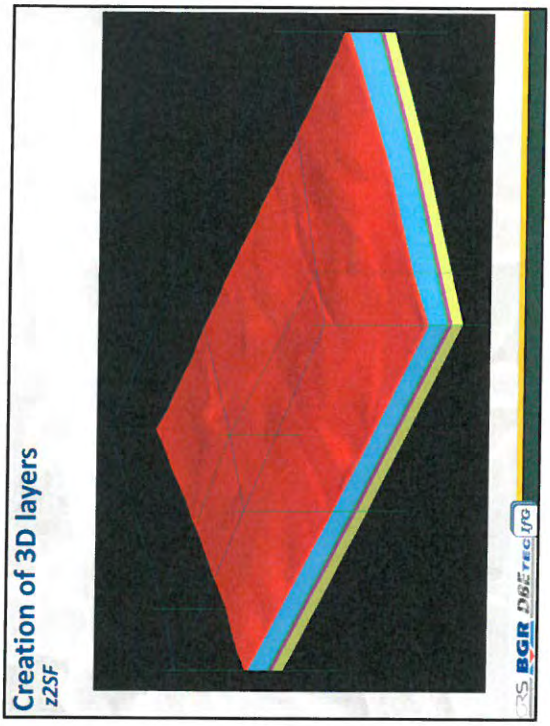

Construction of the 3D model for the type „flat-bedded salt formations"
BGR DBETEC IfG

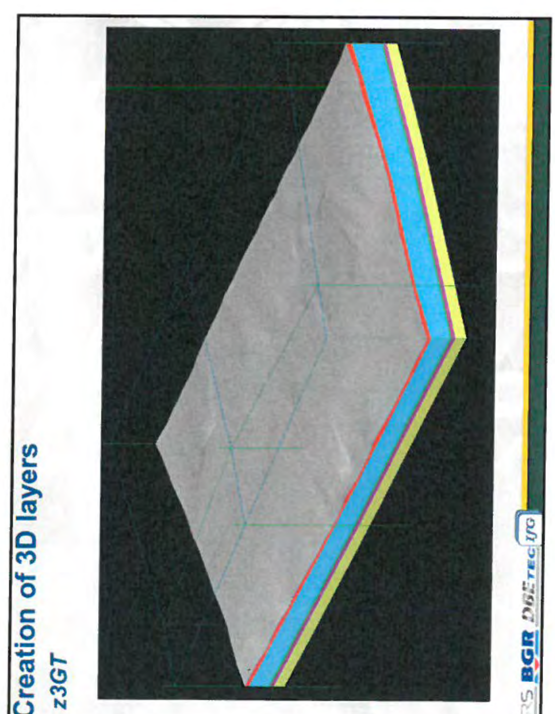

Creation of 3D layers
Sandstone
BGR DBETEC IfG

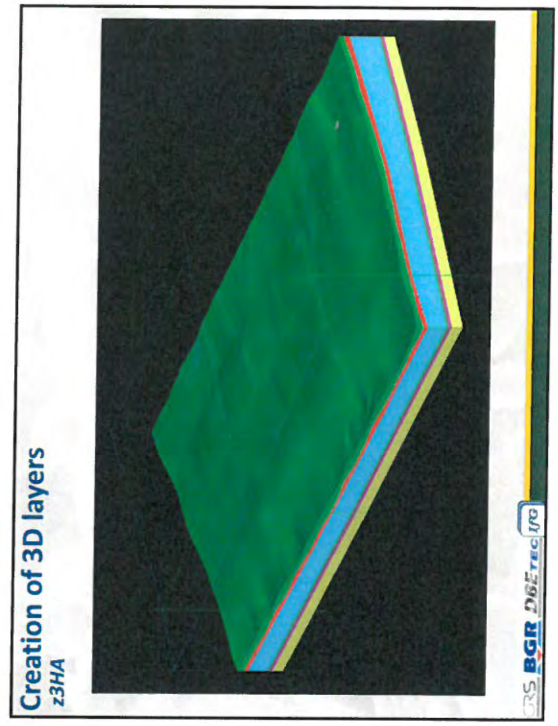

Creation of 3D layers
z1/2-carbonate
BGR DBETEC IfG

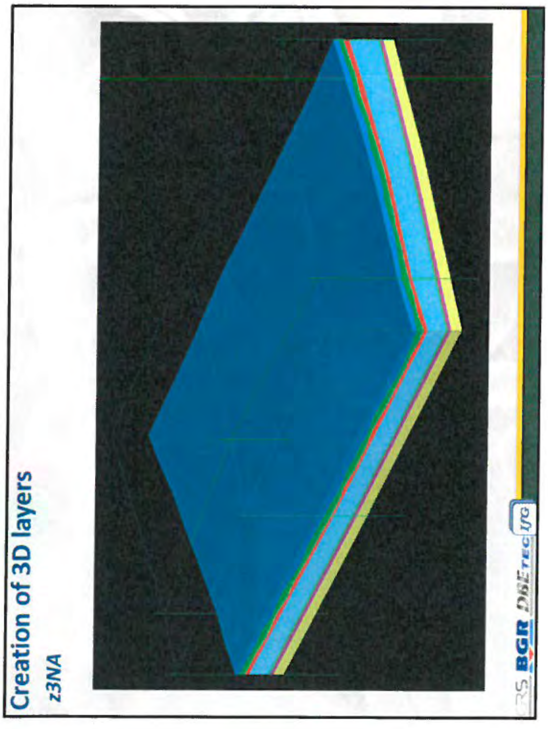

Creation of 3D layers
z1/2-anhydrite
BGR DBETEC IfG

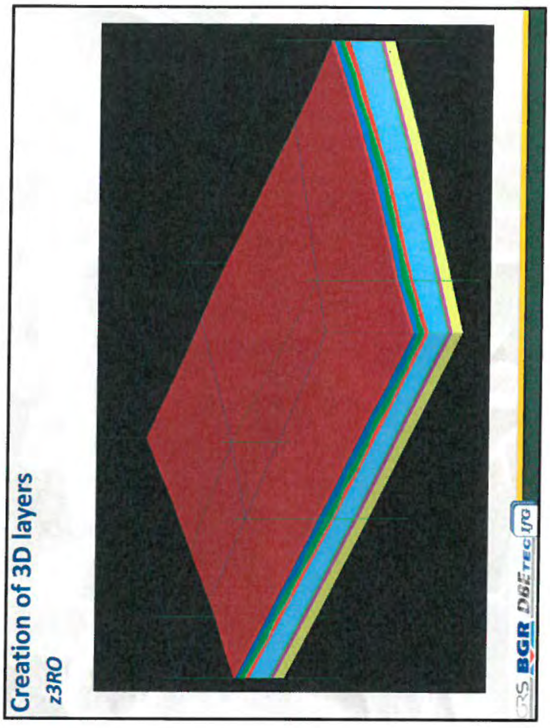

Creation of 3D layers
z2NA

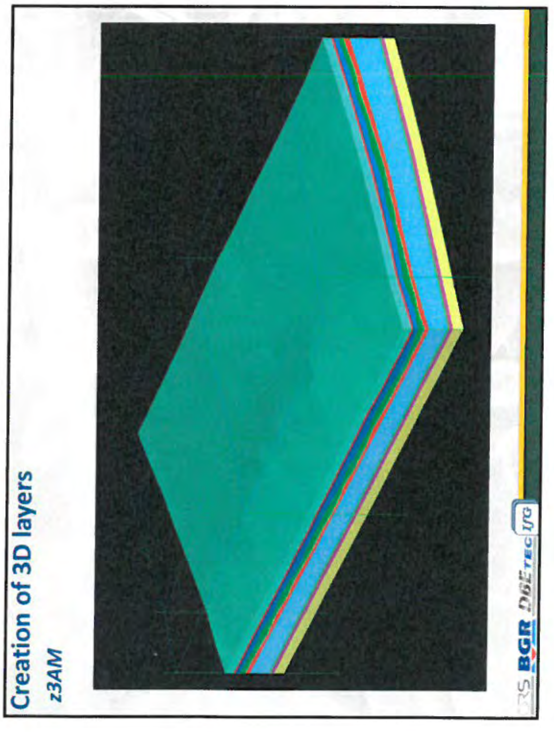

Creation of 3D layers
z2SF

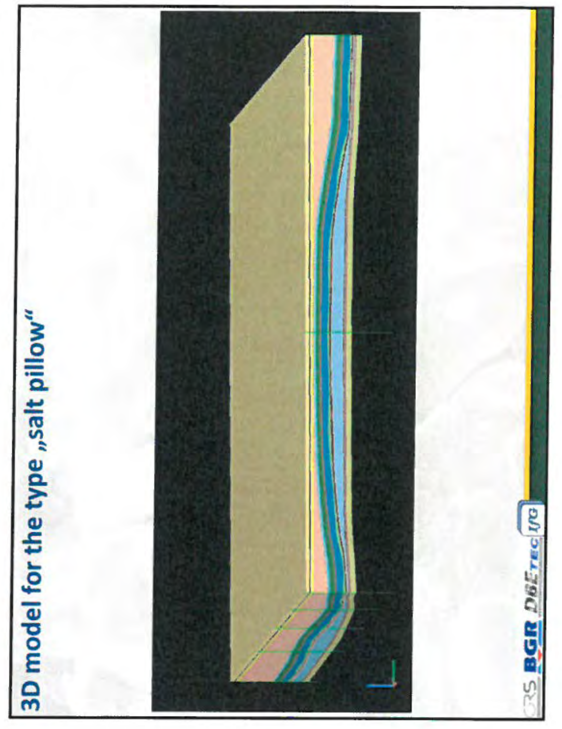

Creation of 3D layers
z3GT


Creation of 3D layers
z3HA


Creation of 3D layers
z3NA


Creation of 3D layers
z3RO


Creation of 3D layers
z3AM


3D model for the type „salt pillow"

Compilation of TM- and THM-material parameters for the numerical modeling

- Density for rock salt
- Density for the host rocks and adjacent rocks
- Thermal parameters
  - Thermal parameters for salt rock
    - Thermal conductivity of salt rock
    - Specific thermal capacity of salt rock
  - Thermal parameters for the host rocks and adjacent rocks
- Mechanical parameters
  - Elastic constants for salt rock
  - Elastic constants for the host rocks and adjacent rock
  - Steady state creep
  - Dilatant behavior
- Hydraulic parameters
  - Permeability of salt rock
  - Porosity of salt rock
  - Density ground water/ saline solutions

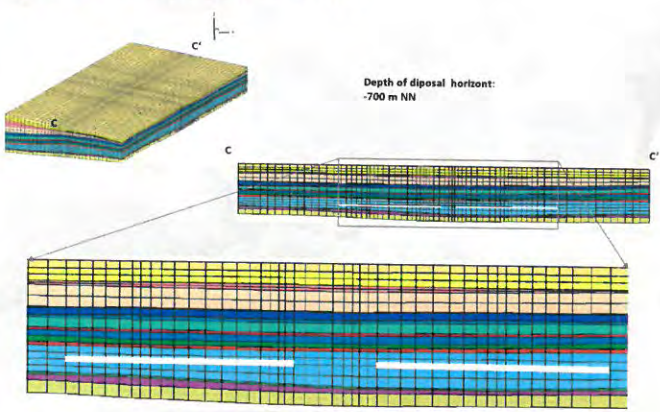
GRS BGR DBETEC IfG

Material parameters (Report from BGR/IfG)

Gesteinsschichten/ Geologische Einheit	Gesteinsschichten Homogenbereich	Symbol	Dichte ρ	Teufendruck-gradient γ	Wärme-leitfähigkeit λ	Spezifische Wärme-kapazität c_p	Wärme-ausdehnungs-koeffizient α_t	Elastizitäts-modul E	Poissonzahl ν
			[kg/m³]	[MN/m³]	[W/(m·K)]	[J/(kg·K)]	[1/K]	[MPa]	[-]
Quartaer	Quartaer	Q	2000	0,022	2,3	950	1,00E-05	100	0,33
Tertiaer	Tertiaer	T	2100	0,022	2,1	905	1,00E-05	500	0,33
mittlerer Bundsandstein unterer Bundsandstein Ohre-Sedimente	Buntsandstein	S	2500	0,022	2,6	760	1,00E-05	15000	0,27
Aller-Steinsalz Roter Salzton_Pegmatitanhydrit	Aller-Steinsalz	NA4	2235	0,022	5,2	860	4,00E-05	25000	0,27
Schwadensalz_Tonmittelsalz Anhydritmittelsalz	Anhydritmittelsalz	AM3	2275	0,022	5,0	860	3,50E-05	30000	0,27
Kalifloez Ronnenberg	Kalifloez Ronnenberg	K3	1850	0,022	1,5	903	2,50E-05	16000	0,26
Leine-Steinsalz	Leine-Steinsalz	NA3	2160	0,022	5,2	860	4,00E-05	25000	0,25
Hauptanhydrit Grauer Salzton	Hauptanhydrit	A3	2700	0,022	4,2	860	1,60E-05	60000	0,25
Kalifloez Stassfurt	Kalifloez Stassfurt	K2	1850	0,022	1,5	903	2,50E-05	17000	0,28
Strassfurt-Steinsalz Strassfurt-Steinsalz_EB	Stassfurt-Steinsalz	NA2	2160	0,022	5,2	860	4,00E-05	33000	0,25
Anhydrit Karbonat	Anhydrit/Karbonat	A2/C2	2700	0,022	4,2	860	1,60E-05	30000	0,27
Sandstein Rotliegendes	Rotliegendes	R	2500	0,022	2,7	760	1,00E-05	17000	0,27

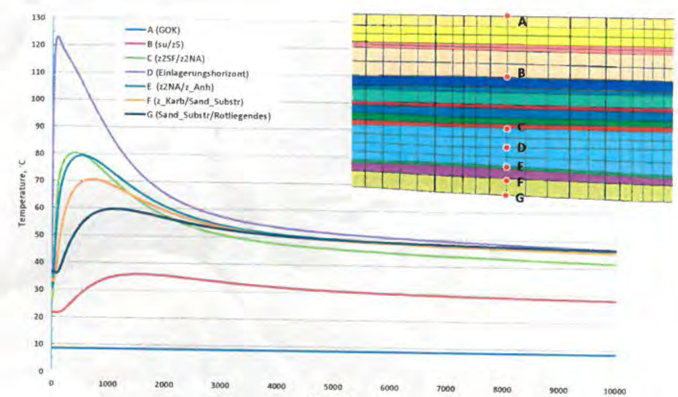
GRS BGR DBETEC IfG

Disposal area within the 3d-model

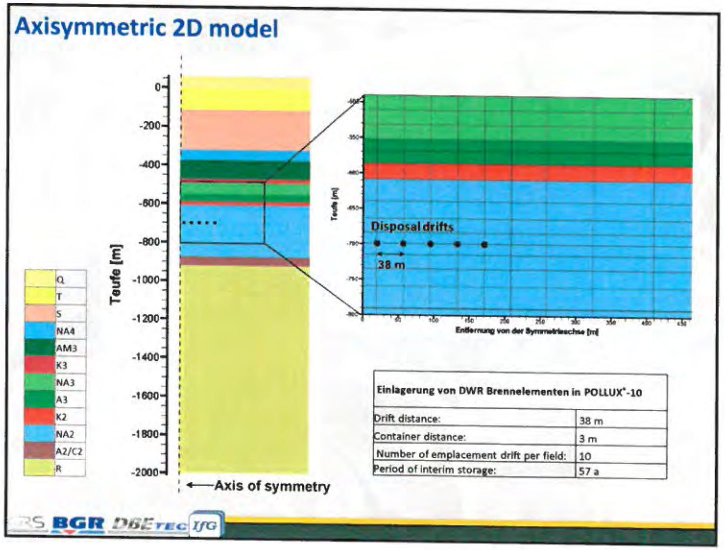


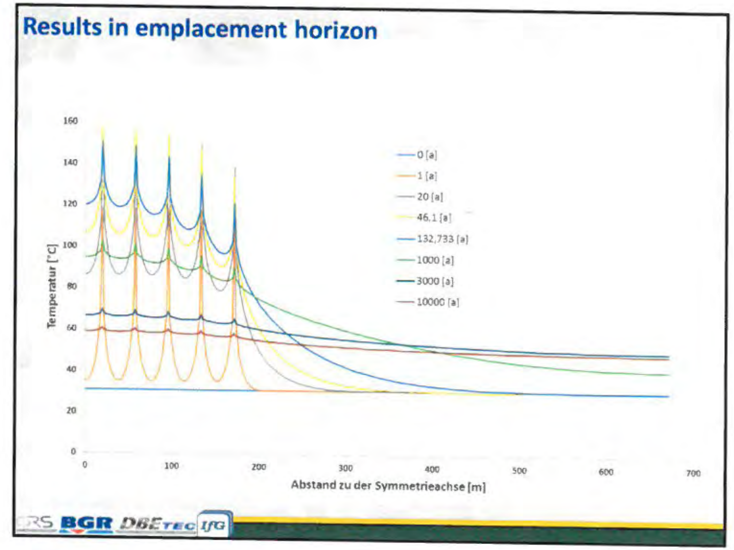
GRS BGR DBETEC IfG

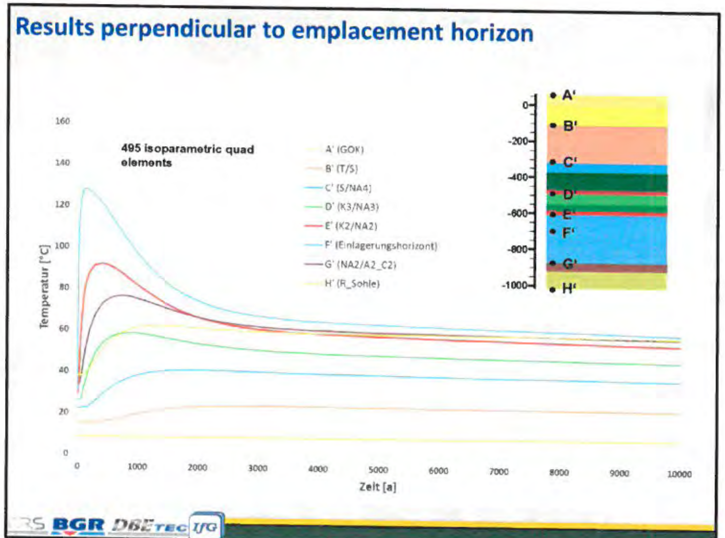
Calculation results

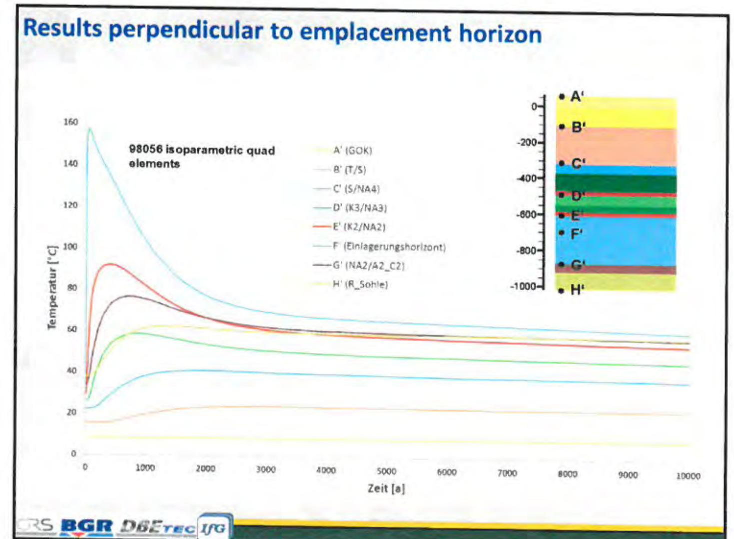


GRS BGR DBETEC IfG

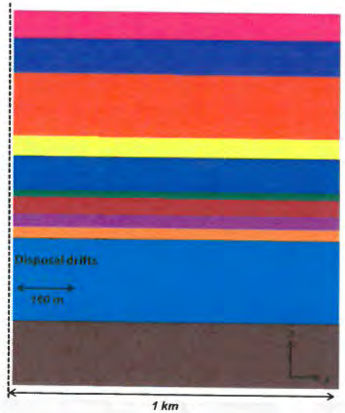

Axisymmetric 2D model
Teufe [m]
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
Q
T
S
NA4
AM3
K3
NA3
A3
K2
NA2
A2/C2
R
Axis of symmetry
Disposal drifts
38 m
Teufe [m]
Entfernung von der Symmetrieachse [m]
Einlagerung von DWR Brennelementen in POLLUX®-10
Drift distance: 38 m
Container distance: 3 m
Number of emplacement drift per field: 10
Period of interim storage: 57 a
BGR
DBETEC
IfG


Results in emplacement horizon
Temperatur [°C]
Abstand zu der Symmetrieachse [m]
0 [a]
1 [a]
20 [a]
46,1 [a]
132,733 [a]
1000 [a]
3000 [a]
10000 [a]
BGR
DBETEC
IfG

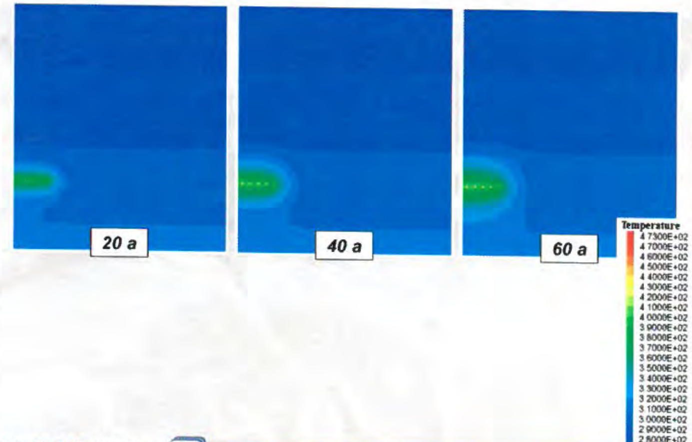

Results perpendicular to emplacement horizon
495 isoparametric quad elements
A' (GOK)
B' (T/S)
C' (S/NA4)
D' (K3/NA3)
E' (K2/NA2)
F' (Einlagerungshorizont)
G' (NA2/A2_C2)
H' (R_Sohle)
Temperatur [°C]
Zeit [a]
BGR
DBETEC
IfG


Results perpendicular to emplacement horizon
98056 isoparametric quad elements
A' (GOK)
B' (T/S)
C' (S/NA4)
D' (K3/NA3)
E' (K2/NA2)
F' (Einlagerungshorizont)
G' (NA2/A2_C2)
H' (R_Sohle)
Temperatur [°C]
Zeit [a]
BGR
DBETEC
IfG

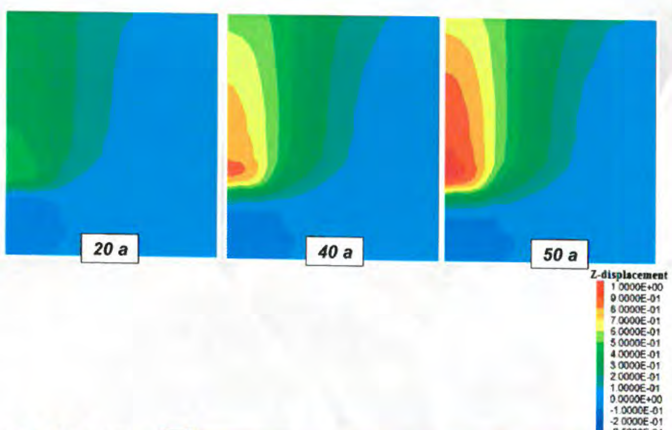
Test model, slice model



Temperature development in the slice model



Uplift in the slice model



Achievements

- ✓ Set of basic design data and requirements accomplished (waste inventory, legal design requirements, description of geological situation for bedded salt, survey of existing safety and demonstration concepts)
- ✓ Generic geologic model developed for both types of bedded salt (type A „flat-bedded salt„ and type B „salt pillow„)
- ✓ Model parameters developed for type "flat-bedded salt"
- ✓ Draft outline of a safety and safety demonstration concept
- ✓ First preliminary numerical calculations
- ✓ Repository concept, thermal design and technical design for the disposal options horizontal borehole disposal and drift disposal in flat-bedded salt developed
- ✓ Interim Report (December 2015) on basic data and repository design requirements, on geologic models as well as on the outline of a safety and safety demonstration concept published

7th US/German Workshop on Salt Repository Research, Design, and Operation

WIPP Recovery and Lessons Learned

Tammy Reynolds – Deputy Project Manager
Nuclear Waste Partnership LLC

Washington, DC
September 7-9, 2016

WIPP Recovery and Lessons Learned

Background

- The Waste Isolation Pilot Plant (WIPP), located in New Mexico began construction in the early 1980's
- Receipt and disposal of Contact Handled (CH) waste began in March 1999
- Receipt and disposal of Remote Handled (RH) waste began in January 2007
- Between March 1999 and February 2014, WIPP safely and compliantly:
  - Received 11, 894 shipments and disposed the waste in the u/g,
    - 90,627 cubic meters of CH TRU waste,
    - 357 cubic meters of RH TRU waste
- In February 2014, WIPP operations were paused when a fire and a radiological event occurred in the underground
- Recovery from the events is in progress and planned to be complete by the end of calendar year 2016. Commencement of waste emplacement activities will begin as soon as it is safe to do so.

WIPP Recovery and Lessons Learned

Fire Event

- February 5, 2014 a fire occurred in the u/g involving a salt haul truck
- 86 workers in the u/g at the time of the fire were safely evacuated
- Investigated by both DOE and NWP
- DOE Accident Investigation Report issued on March 13, 2014

Radiological Event

- February 14, 2014 an exothermic reaction involving the mixture of the organic materials (absorbent and/or neutralizer) and nitrate salts occurred inside a drum.
  - Pressurization of the drum, failure of the drum locking ring, and displacement of the drum lid
  - TRU waste propelled from the drum up into the polypropylene magnesium oxide (MgO) super sacks on top of the containers and onto adjacent waste containers.
    (Note: MgO is an assurance feature to ensure consistent and favorable chemical conditions are maintained in the brines after final facility closure by reacting with any carbon dioxide produced by the decay of organic carbon in the waste and waste emplacement materials.)
  - Radiological Continuous Air Monitor (CAM) alarm received; ventilation interlocked to filtration mode
  - Small amount of leakage bypassed the HEPA filters and released into the atmosphere
  - DOE Accident Investigation Report Phase I (response to the event) – issued on April 22, 2014
  - DOE Accident Investigation Report Phase II (cause of the event) – issued on April 16, 2015

WIPP Recovery and Lessons Learned

Lessons Learned

- **Nuclear Facility vs Mine Culture**
  - Although WIPP is a nuclear facility, there was a mining culture in place vs a nuclear culture
  - Difference in expectations between waste handling and non-waste handling vehicles (combustible buildup, manual vs auto fire detection/suppression)
- **Operability and recognition of impaired critical safety equipment**
  - Fire protection program not adequately implemented at the WIPP facility
  - No controls or programs in place for control of combustible materials or maintaining of fire protection support systems
  - Maintenance program not effectively implemented
    - Combustible buildup on salt haul truck; chaining open ventilation doors; inoperable ventilation fans; inoperable mine phones, obscured evacuation reflectors, disabling of auto fire suppressions system; no overall method to understand status and impact of impaired mine safety related equipment
  - Mindset of production over maintenance based on complex wide priorities to accelerate shipments from generator sites in support of individual site milestones and regulatory agreements

WIPP Recovery and Lessons Learned

Lessons Learned

- Training and drill programs
  - Emergency management/preparedness and response programs not effectively implemented
  - Limited drills, inadequate donning of self-rescuers or SCSRs during training or drills, or hands on training with portable fire extinguishers
  - Inconsistencies between u/g fire response procedures and drills/training (shifting ventilation during evacuation)
- Expectations and capabilities of the Facility Shift Manager to manage all aspects of an emergency or abnormal event
  - CMR response (evaluation and protective actions) was less than adequate
  - Identified problems with communications and alarms during the fire/evacuation delaying egress
- National TRU Program not robust enough to identify incompatible waste
- Communications to the community and regulatory stakeholders was not timely
  - Ensures trust is maintained rather than rebuilding that trust

WIPP Recovery and Lessons Learned

WIPP Recovery Managed as a Project

- Baseline established
- Scope, schedule, cost and risks reflected in the recovery baseline
- Primavera detailed schedule developed
- Progress tracked in Plan of the Day and Plan of the Week meetings
- Critical Path calculated on weekly basis

WIPP Recovery and Lessons Learned

Radiological and Ground Control Recovery

- Radiological release event in February 2014
  - Prevented underground access for several months; required "catch-up" bolting in areas that had not been maintained during that period
  - Created radiologically contaminated areas – complicating all operations including bolting and other ground control
- Ground control catchup efforts in the radiological clean areas is complete. Ground control efforts are now focused in the radiologically contaminated areas
  - 180K sq. ft. has been recovered and are unrestricted
  - 130K sq. ft actively being worked
  - 50K sq. ft. "Restricted"
  - 10K sq. ft. "Prohibited
  - Nominal bolt failure rate 40/week
  - Bolt installation rate 110/week based on 11 shifts of bolting/week

WIPP Recovery and Lessons Learned

Facility/Equipment Improvements

- New Emergency Operating Center (EOC)
- Remodeled training facility
- U/G Ventilation fan reliability improvements
- Hybrid bolters
- Maintenance backlog reduction
- Interim Ventilation System

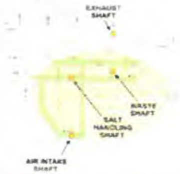
Program Improvements

- Fire Protection Program Plan
- DSA Revision 5 Implemented (STD 3009-2014)
- Increased training for fire response and 10X increase in drills

New Emergency Operations Center

New Equipment

Hybrid Bolting Machine



Combustible Control Zone

WIPP Recovery and Lessons Learned

Enhanced Underground Safety
- New underground notification system
- U/G combustible reduction
- U/G localized fire suppression systems
- Vehicle auto fire suppression systems
- Improved mine stability and ground control

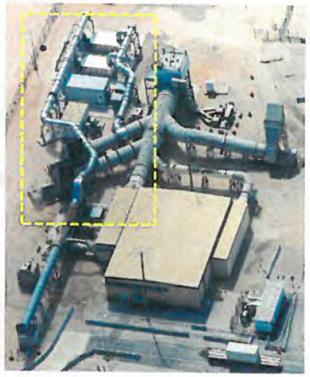
Aggressive Culture Change
- Leadership Academy
- Leaders Forum
- Focus on Values, Expectations, and Standards

Notification System

Vehicle Fire Suppression

WIPP Recovery and Lessons Learned

- **Phase I - Interim Ventilation System**
  - Two HEPA skids and fan units
    - 114,000 cfm of airflow
  - Doubles the existing 60k cfm capacity
  - Ensures adequate air flow at the waste face for resumption of waste emplacement
  - Increase airflow for ground control and maintenance operations
- **Phase II – Supplemental Ventilation**
  - Reconfiguring mine circuits and additional fans
    - 180,000 cfm airflow
- **Phase III – Permanent Ventilation System**
  - Design and construct a new (permanent) ventilation system
    - Capable to provide 420,000 cfm



WIPP Recovery and Lessons Learned

National TRU Program

- DOE released the Enhanced National TRU Program Plan (June 2016)
- DOE placed HOLD on certifying TRU waste for shipment to WIPP until new requirements are met

WIPP Recovery and Lessons Learned

National TRU Program – Moving Forward

- Re-Certification of Generator Sites
- Specific requirements for Previously Certified Waste
  - Chemical Compatibility Evaluation
  - Enhanced Acceptable Knowledge
  - Evaluation of oxidizing chemicals
- Generator Site Technical Reviews

WIPP Recovery and Lessons Learned

Prioritization of Shipments:

- Initial focus of WIPP will be emplacement of waste currently in the Waste Handling Building
- TRU site DOE Field Managers and DOE Headquarters met in August to begin the discussion of TRU waste shipping priorities

WIPP Recovery and Lessons Learned

- Incident Response
- Investigation
- U/G Recovery and Resumption of Ground Control (Bolting)
- Isolation of Panel 6 and Panel 7, Room 7
- Equipment Procurements and Upgrades
- Safety Management Program Improvements
- DSA Revision and Implementation
- Cold Operations
- Management Self Assessment
- Interim Ventilation System
- Contractor Operational Readiness Review
- DOE Operational Readiness Review – Regulator Concurrence
- Authorization to Proceed – Commence Waste Emplacement Operations

7th US/German Workshop on Salt Repository Research, Design, and Operation

Erika A.C. Neeft PhD
Researcher
Central Organization for Radioactive Waste

Washington, DC
September 7-9, 2016

The past Dutch disposal concepts

- Before 1982
- Disposal on Land (OPLA:1982-1992)
- Commission Disposal Radioactive Waste (CORA:1995-2001)
- Research Program into geological disposal of radioactive waste (OPERA: 2011-2016)

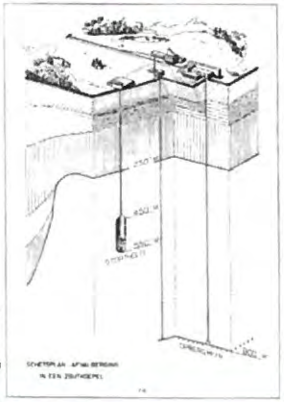
OPERA (2011-2015)

- Hart J, Prij J, Schröder TJ, Vis G-J, Becker D.-A., Wolf J, Noseck U, Buhmann D – Collection and analysis of current knowledge on salt-based repositories, 2015, OPERA-PU-NRG221A
- Hart J, Prij J, Schröder TJ, Vis G-J, Becker D.-A., Wolf J, Noseck U, Buhmann D – Evaluation of current knowledge for building the Safety Case for salt-based repositories, 2015, OPERA-PU-NRG221B

The past Dutch disposal concepts

- Which types of waste were intended to be disposed?
- How is the geological disposal facility envisaged to be constructed?
- How is the waste suggested to be emplaced?
- How is the suggested geological disposal facility suggested to be closed?
- How has the Dutch parliament / government responded to the disposal concepts?

Before 1982

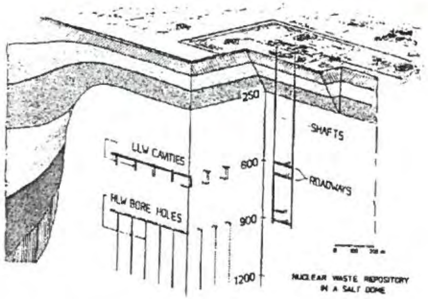


Hamstra, only in Dutch available: Safety analysis for disposal of radioactive waste in a salt dome (Veiligheidsanalyse voor ondergronds in een zoutkoepel opbergen van radioactief afval) RCN-75-040 (1975) 1-75. Available as Appendix of only in Dutch available governmental report: Interdepartementale Commissie voor de Kernenergie (ICK), Radioactieve stoffen in Nederland bij een vermogen aan Kernenergiecentrales van 3500 MWe, 's Gravenhage: Staatsuitgeverij. Verslagen, adviezen rapporten nr. 41 Ministerie van Volksgezondheid en Milieuhygiëne (1975) 1-36

Before 1982

- (Reprocessed) waste from 3500 MWe nuclear power
- Construction (excavation) by dissolution
- Emplacement solid LILW and HLW not indicated
- Closure not indicated
- Government: points of departure used for preliminary post-closure safety assessment became site selection criteria

Before 1982



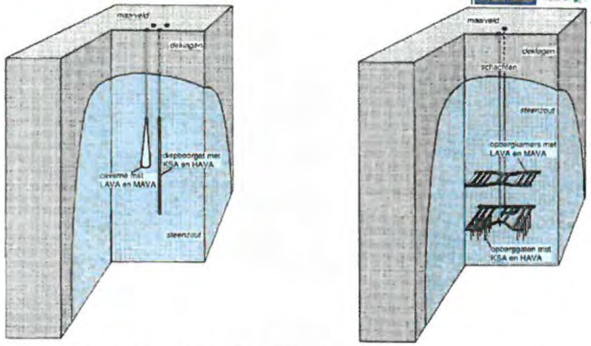
[Hamstra J, Verkerk B, The Dutch geologic radioactive waste disposal project, Commission of the European Communities – Nuclear Science, EUR 7151 (1981) 1-228.

Hamstra J, Janssen LGL, Velzeboer P Th, Further design work on a repository in a salt dome, EUR 9566 EN (1985) 1-51

Before 1982

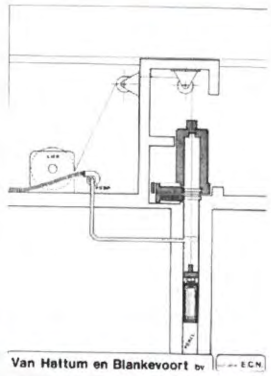
- (Reprocessed) waste from 3500 MWe nuclear power
- Construction (excavation) by dry drilling to limit corrosion of drilling equipment; concreted steel liner for HLW bore holes
- Emplacement solid HLW (vitrified); lowering of flasks
  - Free fall (slowed down by compression of air, reducing impact collision by salt between flasks or deformable head of flask)
  - Wire
- Closure filling boreholes with mixture of slat, clay dust and fly ash being topped by plug of granulate bentonite and sealing by salt-concrete and steel cover plate
- Government: OPLA

OPLA (1982-1992)



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

OPLA (1982-1992)



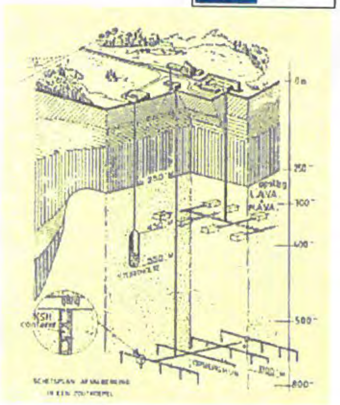
Locatie-onafhankelijke studie inzake de aanleg, bedrijfsvoering en afsluiting van mogelijke faciliteiten voor de definitieve opberging van radioactief afval in steenzoutformaties in Nederland (OPLA 25 in overview report), Koninklijke Volker Stevin (1986) 1-351.

COVRA storage

OPLA (1982-1992)

- Waste from two different nuclear power scenarios
- Construction by 'conventional' mine techniques
- Emplacement of (HLW) waste
  - in brine filled borehole by a wire in overpack (boreholes)
  - Road-like vehicles (mine)
- Closure
  - Salt creep (boreholes)
- Response government (1987) / parliament (1993)

OPLA (1982-1992)



Ministry of Housing, Physical Planning and Environment, Basisnotitie ten behoeve van de ontwikkeling van een toetsingscriterium voor de ondergrondse berging van radioactief afval (TOR) September 1987

OPLA (1982-1992)

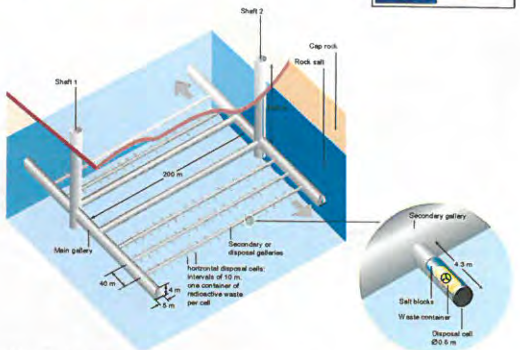
- Nuclear power waste
- Construction
  - Disposal caverns solid LILW either drilling or dissolution
  - Small disposal boreholes
- Emplacement
  - Solid LILW dumping / road like vehicles
  - Solid (vitrified HLW) making a stacking
- Closure
  - Every empty void volume filled with suitable material

OPLA (1982-1993)

- Parliament (1993)
  - 1) Isolate, control and monitor (ICM) principle; the disposal facility should be organized in such a way that a maximum in safety can be achieved under normal and exceptional or unexpected circumstances. Therefore, isolation (of the waste) and control (of the safety) by possible human intervention should be optimal. Retrievability was considered necessary for the control of safety.
  - 2) Integrated chain management; the waste should remain available for reuse should possibilities emerge to reintroduce the waste in the chain in an environmentally sound manner. Retrievability was considered necessary for potential reuse of the waste.

Dutch parliament paper: Opbergen van afval in de diepe ondergrond, Kamerstukken II, 1992-1993, 23163, nr. 1, 1-9.

CORA (1995-2001)



Was only available in Dutch now in English
Hart J, Prij J, Schröder TJ, Vis G-J, Becker D.-A., Wolf J, Noseck U, Buhmann D – Collection and analysis of current knowledge on salt-based repositories, 2015, OPERA-PU-NRG221A

CORA (1995-2001)

Was only available in Dutch now in English
Hart J, Prij J, Schröder TJ, Vis G-J, Becker D.-A., Wolf J, Noseck U, Buhmann D – Collection and analysis of current knowledge on salt-based repositories, 2015, OPERA-PU-NRG221A

CORA (1995-2001)

- Vitrified HLW
- Construction 'conventional' mine techniques
- Emplacement by road-like vehicles
- Closure by a suitable material
- Response Dutch parliament (2002)
  - Retrievability of waste is feasible

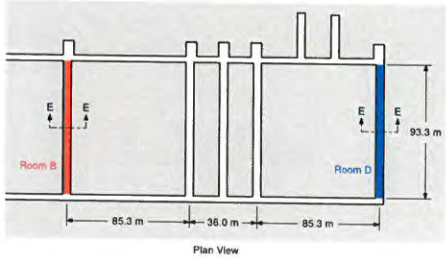
Reinvestigation into Closure Predictions of Room D at the Waste Isolation Pilot Plant

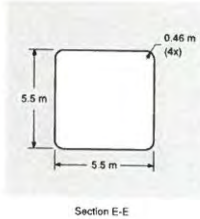
Benjamin Reedlunn
Sandia National Laboratories

Washington, DC
September 7-9, 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Room B and D Dimensions





2

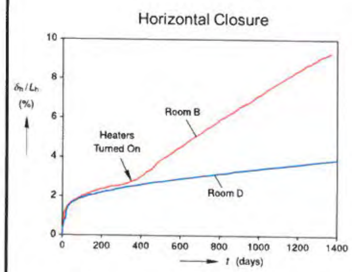
Photos of Room B and D

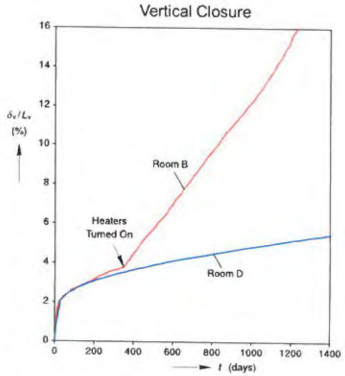
Room B

Room D

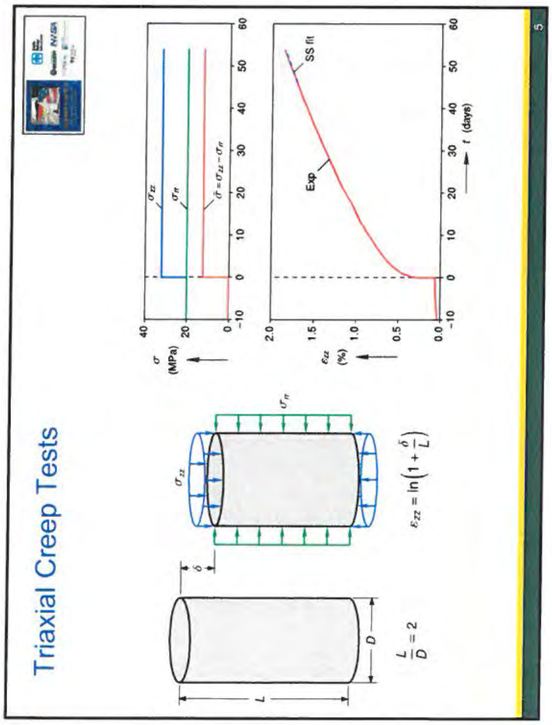
3

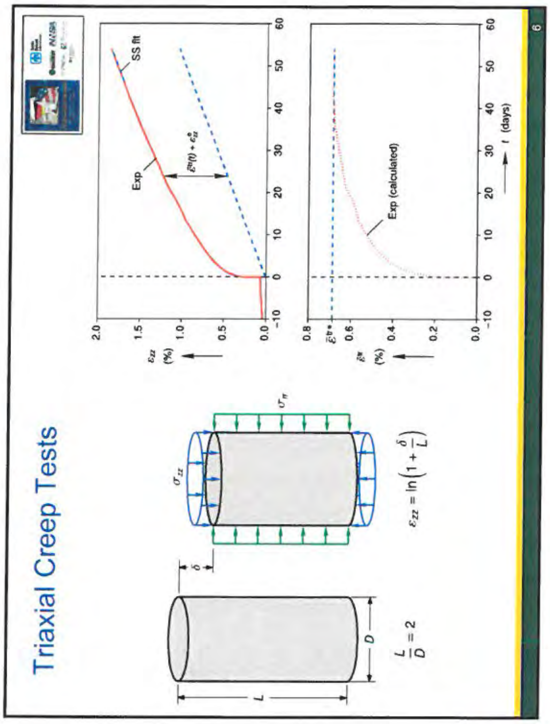
In-Situ Closure Measurements

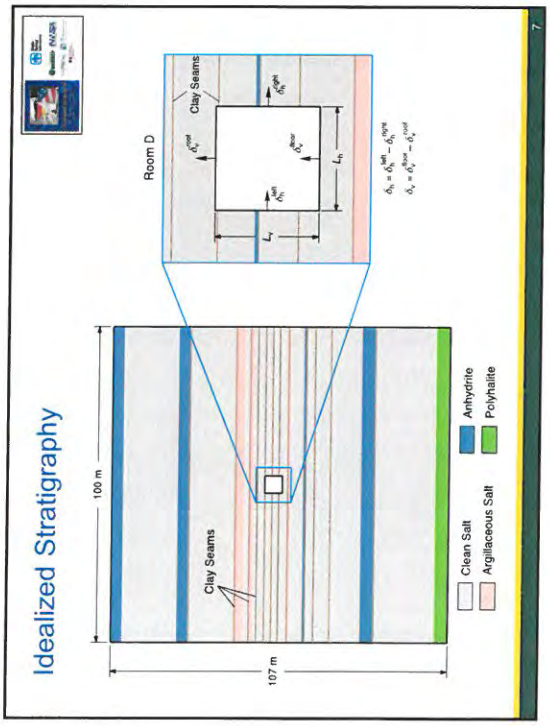


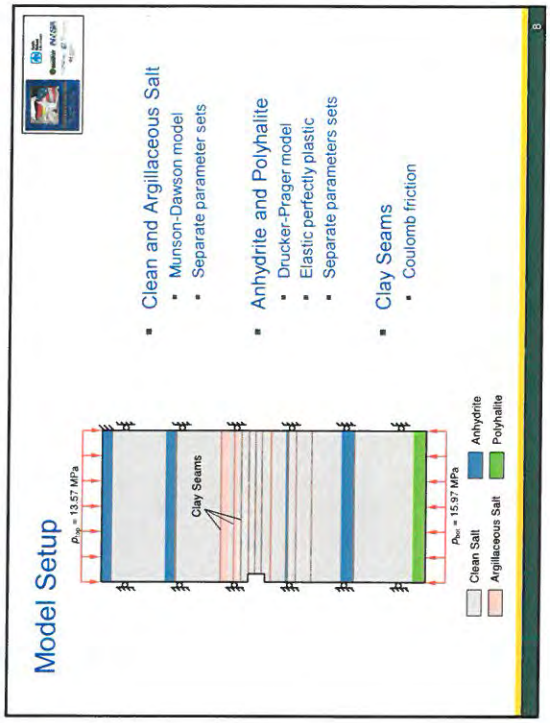


4


Triaxial Creep Tests
L/D = 2
ε_zz = ln(1 + δ/L)
σ_zz
σ_rr
σ (MPa)
ε_zz (%)
Exp
SS fit
t (days)
5


Triaxial Creep Tests
L/D = 2
ε_zz = ln(1 + δ/L)
σ_zz
σ_rr
ε_zz (%)
Exp
SS fit
Exp (calculated)
t (days)
6


Idealized Stratigraphy
107 m
100 m
Clay Seams
Room D
Clean Salt
Argillaceous Salt
Anhydrite
Polyhalite
7


Model Setup
p_top = 13.57 MPa
p_bot = 15.97 MPa
Clay Seams
Clean Salt
Argillaceous Salt
Anhydrite
Polyhalite
Clean and Argillaceous Salt
Munson-Dawson model
Separate parameter sets
Anhydrite and Polyhalite
Drucker-Prager model
Elastic perfectly plastic
Separate parameters sets
Clay Seams
Coulomb friction
8

Legacy Simulations

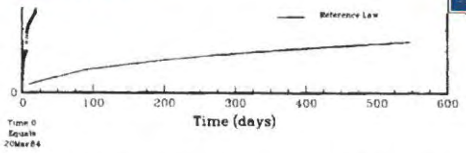


Figure 8. Manual and Remote Vertical Closure Data for Room D (and Reference Law Calculation)

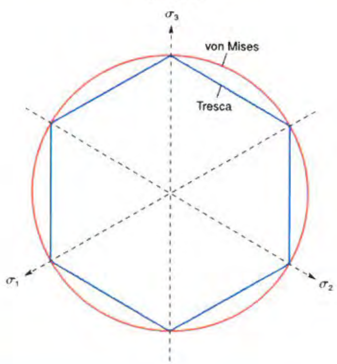
instrument hole drilling. By preplanning the locations of the gages, manual and remote, it was reasonable to combine the plots, and maintain a continuous record of room closure. The zero station mining sequence measurements just described were located within 0.6 m of the remote measurements for room closure. In Figure 8 these two data sets are combined. It is important to emphasize that the data acquisition systems for the manually read mining sequence closure and the remotely read closure measurements were each made independently. Although a match between the two

Munson, DE, Torres, TM, & Blankenship, DA. 1986. Early results from the thermal/structural in situ test series at the WIPP. In: The 27th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.

9

Changed the Equivalent Stress

π-Plane



Steady State Creep Rate

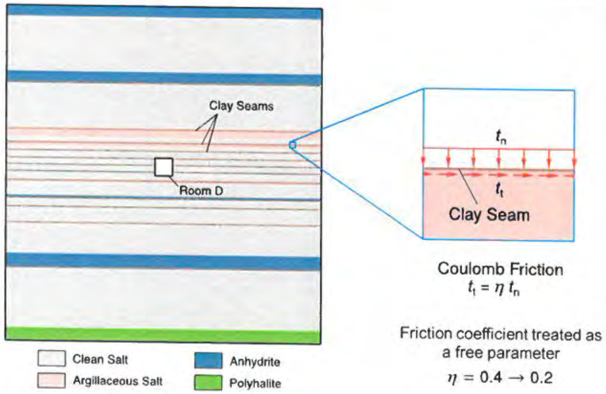
$$\dot{\varepsilon}^{ss} \propto \left(\frac{\bar{\sigma}}{\mu}\right)^n$$

Transient Creep Strain Limit

$$\bar{\varepsilon}^{tr*} \propto \left(\frac{\bar{\sigma}}{\mu}\right)^m$$

10

Changed the Friction Coefficient



Coulomb Friction

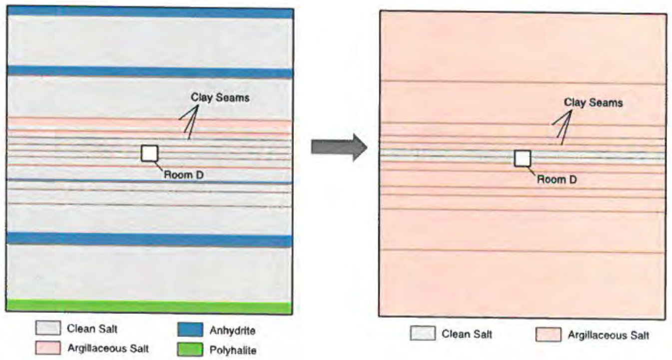
$t_t = \eta\, t_n$

Friction coefficient treated as a free parameter

$\eta = 0.4 \rightarrow 0.2$

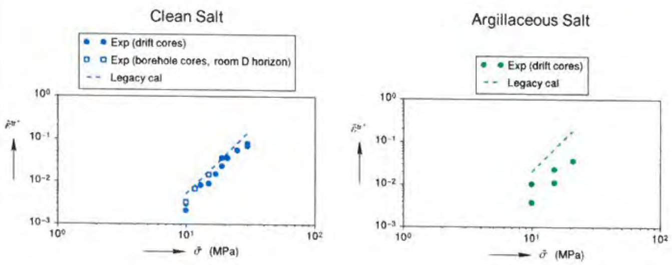
11

Changed the Stratigraphy



12

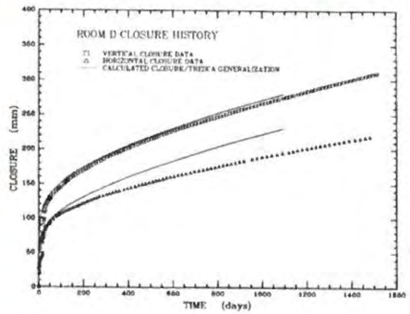
Changed the Material Parameters



Argillaceous transient strain limit treated as a "free parameter".

Legacy Predictions

- Changed from von Mises to Tresca equivalent stress
- Changed the clay seam friction coefficient from 0.4 to 0.2
- Changed from mostly clean salt to mostly argillaceous salt
- Changed the material model calibrations
  - Argillaceous strain limit treated as a free parameter



Munson, D., Fossum, A. Senseny, P., Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures, SAND88-2948, 1988

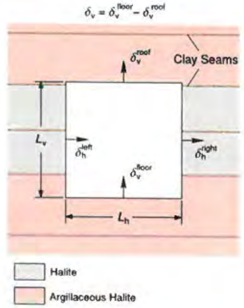
Legacy Predictions

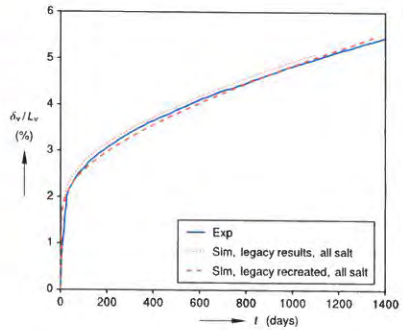
- Tuning of model parameters is common industry practice
  - Tune against one *in-situ* measurement
  - Compare against other *in-situ* measurements
- Our goal is to predict **solely** from laboratory test data
  - Requires a stronger scientific basis
  - Enables predictions at a **new** repository

Recreation of Legacy Simulations

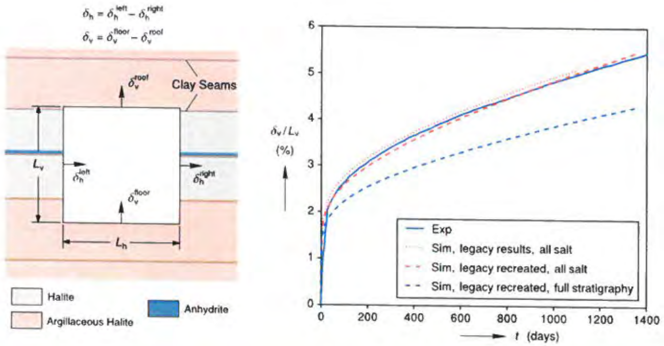
$\delta_h = \delta_h^{left} - \delta_h^{right}$

$\delta_v = \delta_v^{floor} - \delta_v^{roof}$





Recreation of Legacy Simulations



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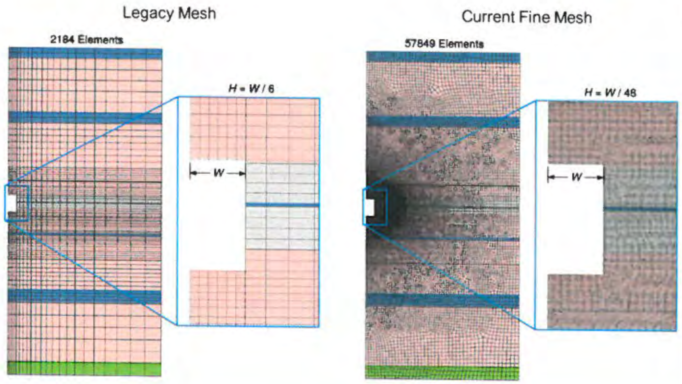
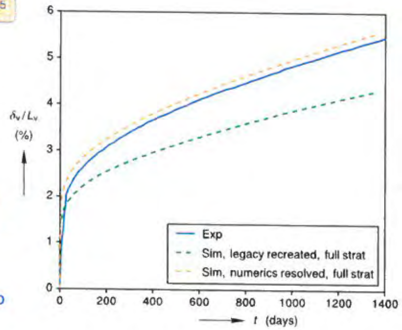
Changed the Mesh



18

Resolving the Numerics

- Change the Mesh
- Changed $R_{tol} = 10^{-3}$ to $R_{tol} = 10^{-5}$
- Switched to a higher quality element type
- Changed the contact enforcement algorithm
- Switched from non-associated flow rule to an associated flow rule for the anhydrite
- Added a pressure ramp down to ease into the instantaneous excavation



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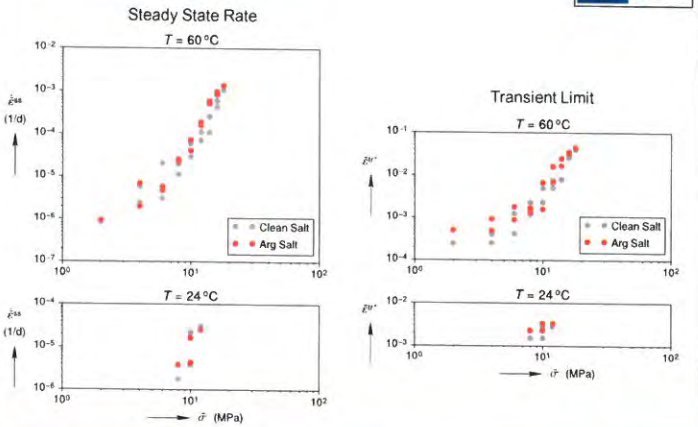
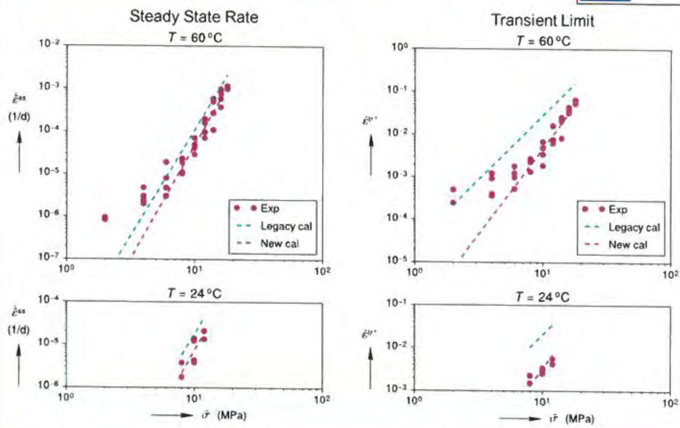
New Cores Extracted in 2013

20

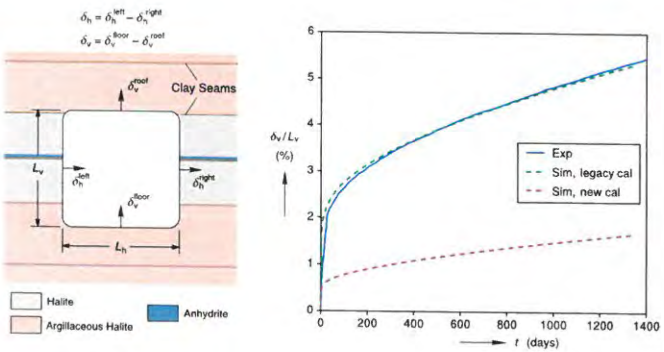
Clean vs. Argillaceous



New Munson-Dawson Calibration



Closure Prediction with New Calibration



List of Open Questions

- Creep at low equivalent stresses
- Extent of simulation boundary
- Lost transient strains
- Creep of argillaceous vs. clean salt
- Sliding at clay seams
- Anhydrite material model
- Salt moisture content
- Reconstruction of closure measurements

Summary

- In 1987, the simulations under-predicted the room closure by roughly 4X. In 1989, Darrell Munson adjusted the model to match the experiments.
- After including the anhydrite and resolving the numerics, the predictions match the experiments.
- New, laboratory based, salt calibration under-predicts the room closure by roughly 3X.
- Open questions remain
  - Creep at low equivalent stresses
  - Extent of simulation boundary
  - Lost transient strains
  - Creep of argillaceous vs. clean salt
  - Sliding at clay seams
  - Anhydrite material model
  - Salt moisture content
  - Reconstruction of closure measurements

7th US/German Workshop on Salt Repository Research, Design, and Operation

Presenter: Sandra Fahland
BGR, Hannover, Germany

Washington, DC
September 7-9, 2016

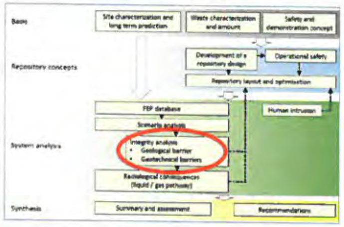
Further Important Topics in Rock Salt Geomechanics – State 2016

Repositories in salt formations - present and future work related to integrity analyses

- Geomechanical integrity analysis of the repository is a main topic of performance assessment
- 3 main salt related topics have been identified (5th US-German Workshop 2014)

(1) how salt deforms in the long term
(2) integrity analysis of rock salt barrier
(3) consolidation of crushed salt

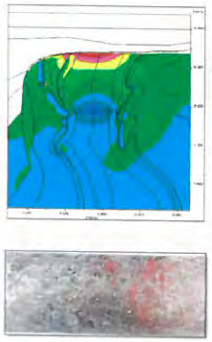
Andreas Hampel	AH Dr. Andreas Hampel
Sandra Fahland, Jörg Hammer	BGR
Nina Müller-Hoeppe	DBE TEC
Klaus Wieczorek	GRS
Till Popp, Wolfgang Minkley	IfG
Frank Hansen	Sandia National Laboratories
Joachim Stahlmann	TU Braunschweig
Karl-Heinz Lux	TU Clausthal



- Progress in 2015/16
- Reminder on issues still pending
- New topics

Salt – barrier properties

Intact rock salt



EDZ

Crushed salt backfill

The challenge ... how does salt behave in the long term?

Boundary conditions:	
Forecast period:	10^3 < time (years) < 10^6
Deformations:	$0.1 < \varepsilon < 1$
Deformation rates:	$1 \cdot 10^{-17} < \dot{\varepsilon}\,(1/s) < 3 \cdot 10^{-11}$
Temperatures:	20°C - 200°C

Modelling the salt barrier behavior (THMC)

- BMWi Joint Project „*Comparison of current constitutive models for rock salt*" (2004 – 03/2016)
- BMWi Joint Project WEIMOS „*Further development and qualification of the rock mechanical modelling for the HLW disposal in rock salt*" (WEIMOS), started April 2016 - Partners: AH, IfG, IUB, TU-BS, TUC, SNL
  - Creep at small deviatoric stresses
  - Tensile stress
  - Healing of damage: influence pT
  - Influence of inhomogeneities (e.g. interfaces)

Presentation A. Hampel

Experimental database

- Creep experiments at small deviatoric stresses
  - Berest (SMRI): uniaxial creep test
  - BGR: running (>1 y now)
  - IfG: long tests are started / a high resolution creep test rigg is under construction
- EU Project DOPAS – LASA EDZ: Experimental data related to salt/concrete interfaces (GRS)

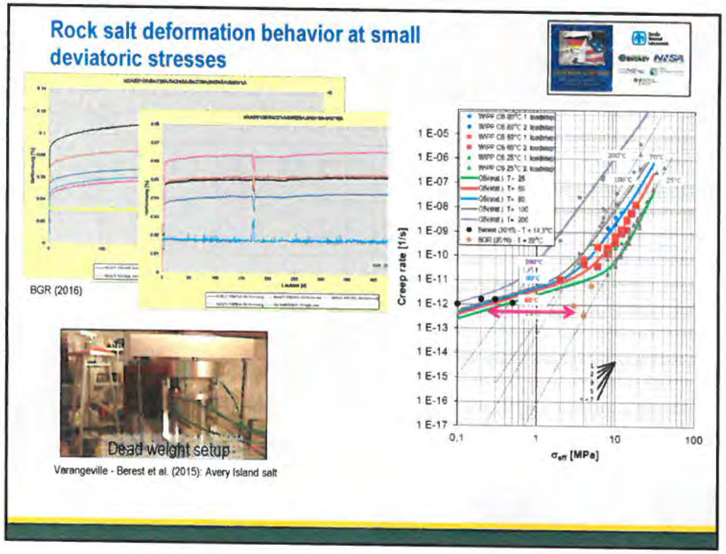
Presentation K. Wieczorek

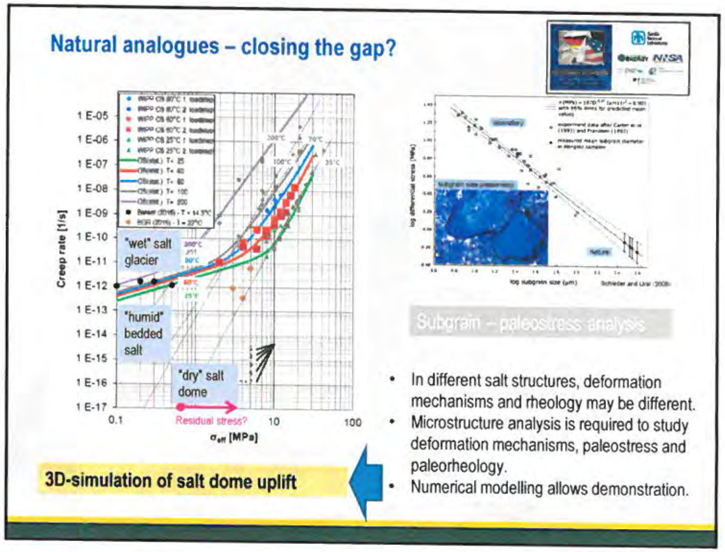
Currently pending

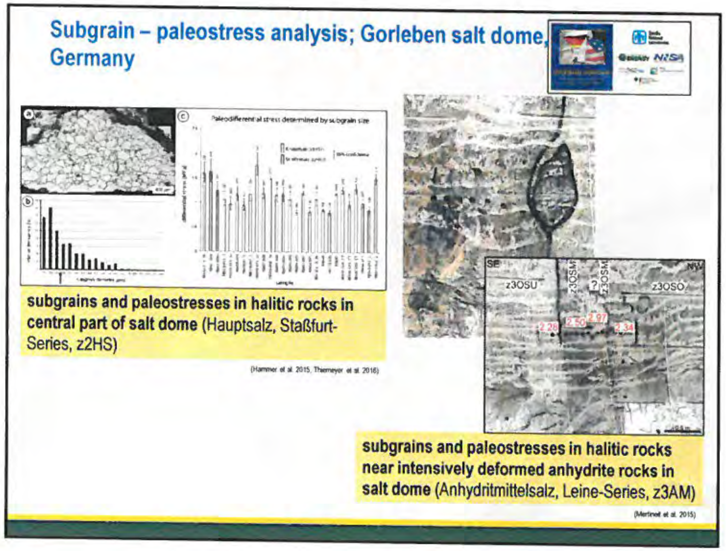
- Assessing the suitability of the constitutive laws by recalculating failure events (⇒ KOSINA)

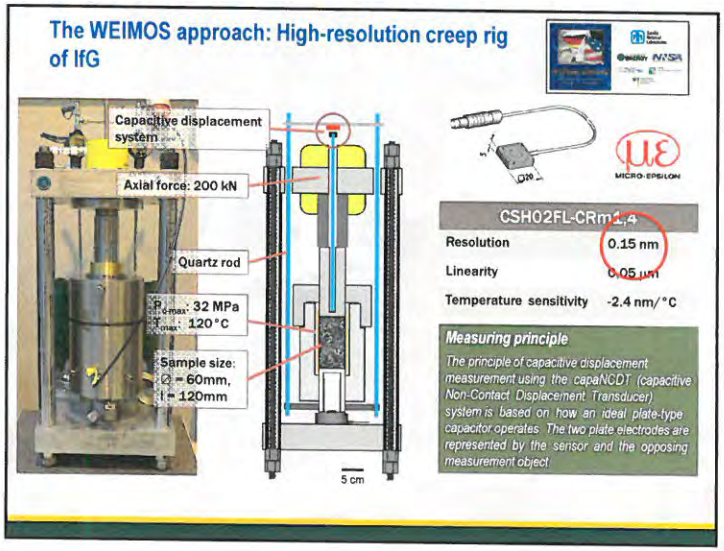
Forthcoming topics

- "Relaxation"
- Pressure solution creep


Rock salt deformation behavior at small deviatoric stresses
BGR (2016)
Dead weight setup
Varangeville - Berest et al. (2015): Avery Island salt
Creep rate [1/s]
1 E-05
1 E-06
1 E-07
1 E-08
1 E-09
1 E-10
1 E-11
1 E-12
1 E-13
1 E-14
1 E-15
1 E-16
1 E-17
0,1
1
10
100
σeff [MPa]


Natural analogues – closing the gap?
Creep rate [1/s]
"wet" salt glacier
"humid" bedded salt
"dry" salt dome
Residual stress?
σeff [MPa]
3D-simulation of salt dome uplift
Subgrain – paleostress analysis
In different salt structures, deformation mechanisms and rheology may be different.
Microstructure analysis is required to study deformation mechanisms, paleostress and paleorheology.
Numerical modelling allows demonstration.


Subgrain – paleostress analysis; Gorleben salt dome, Germany
subgrains and paleostresses in halitic rocks in central part of salt dome (Hauptsalz, Staßfurt-Series, z2HS)
(Hammer et al. 2015, Thiemeyer et al. 2016)
z3OSU
z3OSM
z3OSO
subgrains and paleostresses in halitic rocks near intensively deformed anhydrite rocks in salt dome (Anhydritmittelsalz, Leine-Series, z3AM)
(Mertineit et al. 2015)

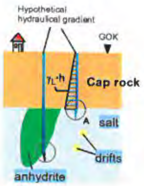

The WEIMOS approach: High-resolution creep rig of IfG
Capacitive displacement system
Axial force: 200 kN
Quartz rod
σmax: 32 MPa
Tmax: 120 °C
Sample size: Ø = 60mm, l = 120mm
5 cm
MICRO-EPSILON
CSH02FL-CRm1,4
Resolution 0.15 nm
Linearity 0.05 µm
Temperature sensitivity -2.4 nm/°C
Measuring principle
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

Integrity of the salt barrier

Criteria to assess integrity are decisive to prove effectiveness of salt barrier's safety function

Present status

- dilatancy criterion (isotropic)
- minimum stress/fluid pressure criterion (isotropic)



Under consideration

- load-dependent dilatancy criterion (BGR)
- anisotropic fluid pressure criterion, directional infiltration (THM process) - TUC/IfG/BGR/DBETEC
- The dihedral angle – An additional percolation threshold? Science paper *„Deformation-assisted fluid percolation in rock salt"* by S. Ghanbarzadeh et al.

→ DAEF – statement April 2016
→ Break-out-session US/German Workshop 2016
→ KOSINA: Percolation tests at high pT cond. (-100 MPa/120°C)

First steps/pending

- discontinuum approaches ⇒ DBETEC, IfG
- Fully coupled thermo-hydro-mechanical simulations ⇒ TUC, IfG

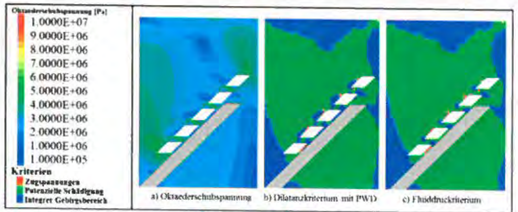
Forthcoming topics

- additional (hypothetical) failure modes TUBS, DBETEC
- influence of residual stresses

Additional (hypothetical) failure modes

Isotropic fluid pressure criterion
$\sigma_{min} > p_{fl}$
using effective stresses (Terzaghi)
$\sigma'_{min} = \sigma_{min} - p_{fl} > 0$
$\sigma_{min} = \sigma_3$ least principal stress
p_{fl} = hypothetical hydraulic pressure
$\sigma'_{min} = \sigma'_3$ effective least principal stress

Isotropic dilatancy criterion (Christescu/Hunsche)
$\tau_{zul}/\sigma^* = a \cdot (\sigma_m/\sigma^*)^2 + b \cdot (\sigma_m/\sigma^*)$
using effective stresses (Terzaghi)
$\tau'_{zul}/\sigma^* = a \cdot (\sigma'_m/\sigma^*)^2 + b \cdot (\sigma'_m/\sigma^*)$
τ octahedral shear stress
σ_m mean stress
σ^* scaling factor
τ' effective octahedral shear stress
$\sigma'_m = (\sigma_1 + \sigma_2 + \sigma_3 - 3p_{fl})/3$ effective mean stress



properties of a viscous solid ⟷ vs ⟷ properties similar to a suspension

Crushed salt consolidation

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

Experimental investigations

REPOPERM II long-term tests (4 y) finished (GRS, final report in preparation)

Long-term compaction tests (up to 10 y), BGR develops a new experimental setup

Crushed salt backfill in-situ consolidation state re-investigated after 15 y in the framework of the Asse site investigations (IfG)

State of constitutive models

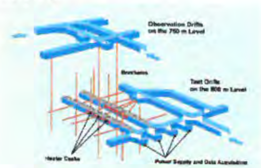
DAEF initiative on crushed salt behavior is established

First results

2-phase-flow (to appear, GRS)

Pending

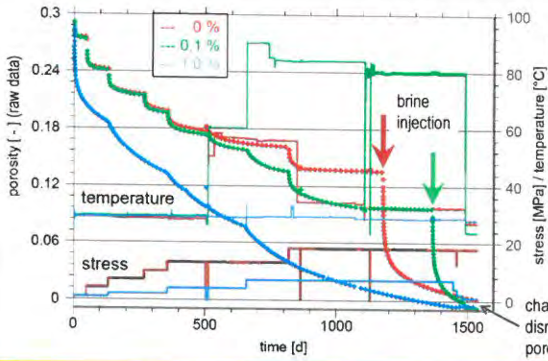
Natural analogues



Salt consolidation lab experiments in the REPOPERM project

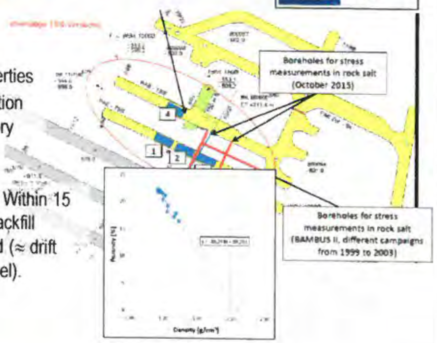
REPOPERM II

Multistep load tests, different initial solution contents, varying temperature, later flooding



Revisitation of the BAMBUS site – part of Asse site investigations

Aim of investigations
- ➢ Evaluation of the backfill properties
- ➢ Better assessment of stabilization measures in the Asse repository



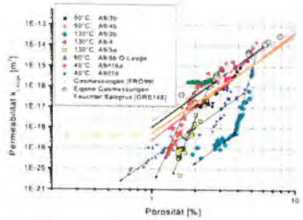
- Backfill compaction proceeds: Within 15 years, a further reduction of backfill porosity by 3 – 5% is observed (≈ drift convergence at the 800-m-level).
- The backfill is very dry.

- Texture and lab investigations were performed by Sandia (Hansen, 2016)

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

DAEF initiative on crushed salt consolidation

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



Work topics
- Classification of the available experimental data sets:
  - reliability in the low porosity range
  - suitability for model calibration
- Recommendations for completing the data base
- Comparison of available constitutive models
- Development of a strategy for calibration, bench marking and improvement of models

Partners:
- GRS, BGR, DBETEC, IfG, TUC

- Participation of the US-colleagues is highly desirable

Work schedule
- ➢ Presentation at the DAEF-Workshop 2016
- ➢ Summary (NEA) report until 10/2016
- ➢ Preparation of an US/GERMAN joint project proposal until the end of the year

Summary

Repositories in salt formations - present and future work related to integrity analyses

- ➢ Geomechanical integrity analysis of the repository is a main topic of PA
- ➢ 3 main salt related topics have been identified (5th US-German Workshop 2014)

(1) how salt deforms in the long term
(2) integrity analysis of rock salt barrier
(3) consolidation of crushed salt

- ➢ Progress in 2015/16 and remaining open issues

Ongoing key activities

- BMWI - Joint Project (WEIMOS), started April 2016
  Several experiments are already running or planned
- Percolation – experimental proof at repository conditions
- DAEF initiative on crushed salt behavior established - US/German collaboration discussed

Acknowledgements

Many thanks...

...to all colleagues and participating organizations

Andreas Hampel	Dr. Andreas Hampel
Sandra Fahland, Jörg Hammer	BGR
Nina Müller-Hoeppe	DBETEC DBE TECHNOLOGY GmbH
Klaus Wieczorek	GRS
Till Popp, Wolfgang Minkley	IfG Institut für Gebirgsmechanik GmbH Leipzig
Frank Hansen	Sandia National Laboratories
Joachim Stahlmann	Technische Universität Braunschweig
Karl-Heinz Lux	TU Clausthal

for their contributions

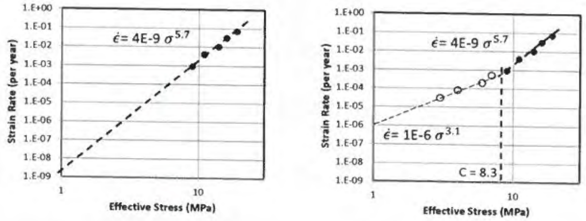
and BMUB and BMWi and their related organizations for their financial support.

7th US/German Workshop on Salt Repository Research, Design, and Operation

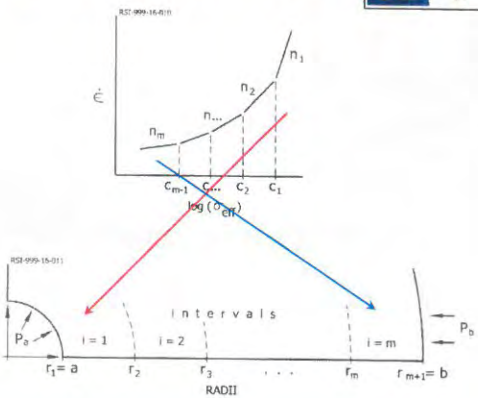
Leo L. Van Sambeek
RESPEC

Washington, DC
September 7-9, 2016

Conventional Salt Creep



Multi-Segmented Creep Law



Radial Stress Boundary Conditions $(b \rightarrow \infty)$

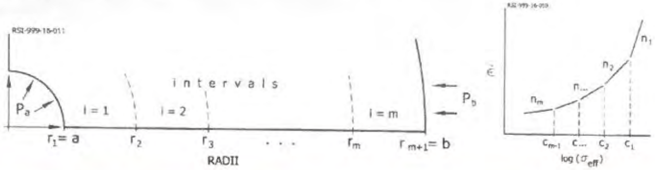
$\sigma_r(r_1) = -P_a$ $\qquad r_1 = a$

$\sigma_r(r_2) = \sigma_r(r_3) + [c_1 - c_2] n_2/\sqrt{3}$ $\qquad r_2 = a\left[\sqrt{3}/n_1 c_1 \{-\sigma_r(r_2) - P_a\} + 1\right]^{n_1/2}$

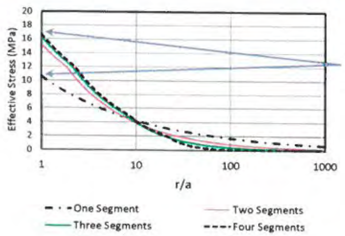
$\sigma_r(\mathrm{K}) = [\sigma_r(r_{i+1})] + [c_{i-1} - c_1] n_i/\sqrt{3}$ $\qquad r_i = r_{i-1}[c_{i-2}/c_{i-1}]^{(n_{i-1})/2}$

$\sigma_r(r_m) = -P_b + c_{m-1} n_m/\sqrt{3}$ $\qquad r_m = r_{m-1}[c_{m-2}/c_{m-1}]^{(n_{m-1})/2}$

$\sigma_r(r_{m+1} \rightarrow \infty) = -P_b$ $\qquad r_{m+1} = b$



Example (P_a = 0 and P_b=15 MPa)



Compare Effective Stress at Cavern Wall For High-Stress and Multi-Segmented Creep Laws

Multi-Segmented Creep Law Can Make 10 Times More Cavern Closure

Number of Creep-Law Segments	Parameters Involved	Steady-State Volumetric Closure Rate per Year
1	n_1 and A_1	0.010
2	n_1, n_2 and A_1, A_2	0.061
3	n_1, n_2, n_3 and A_1, A_2, A_3	0.085
4	n_1, n_2, n_3, n_4 and A_1, A_2, A_3, A_4	0.095




Comparison of salt cavern and repository modeling

7th US/German Workshop on Salt Repository Research, Design, and Operation

Steven R. Sobolik
Sandia National Laboratories
Albuquerque, New Mexico, USA

Washington, DC
September 7-9, 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2016-7826C

Introduction

- US-German Workshops have focused effort on developing thorough understanding of salt repository design, analysis, operation, and long-term prediction.
- Necessary component of these efforts is predictive modeling of the mechanical behavior of the repository during the operational period and long-term.
  - Validation (Benchmark comparison of WIPP Rooms B & D)
  - Salt mechanical models & properties such as creep, strength, and dilatancy envelopes are based on laboratory tests
- Inevitably discrepancies exist between model results and observed behavior.

Characteristics of Repository Modeling

- Prediction of future repository behavior for operational concerns and long-term performance
- License application – demonstrate repository behavior compliance to specific set of regulatory standards
- Prediction of room closure rates for disposal, worker safety, and seal performance
- Capability to predict salt response to short-term stress changes (other than post-mining transient creep) not currently required

Cavern Modeling

Requirements have evolved over time

- Models originally required to provide prediction of surface subsidence, rate of cavern closure for capacity planning; used single creep model, set of properties based on limited lab tests
- Early predictions were for long-term (20-50 years) future behavior; models eventually required validation with past behavior
- As storage sites age, new issues include highly variable cavern closure rates, cavern integrity, well casing integrity, accessibility to oil due to cavern geometry features (sagging roofs, salt fall damage to hanging strings)
- These issues require **confident** analysis of transient creep response of salt to short-term, large pressure changes

Progression of Complexity of Salt Cavern Geomechanical Models

Earliest Models	Progression of Model Complexity	Reason for Model Advancement
Primary Purpose: Long-term projection of surface subsidence, cavern volume closure	Primary Purpose: Analysis of individual cavern behavior, use as diagnostic tool, aid for developing strategies for well & cavern integrity management and remediation	As the sites age after 35+ years of use, creep-induced and other problems occur, requiring modeling tools with better resolution, validation, and problem-solving utility
Simplified dome geometries (30-degree wedge to simulate 19-cavern field; half-dome with symmetry axis)	Full dome included in model; initially as extruded "cylinder" of footprint, now as genuine rendering of shape based on seismic data	Need to know geomechanical behavior of specific caverns based on geometry, location, proximity to side of dome (post-Bayou Corne)
Caverns shaped as simple cylinders or frustums	Caverns shapes based on axisymmetric (and now, true) renderings of sonar-measured geometries	Need to know GM behavior resulting from cavern geometry – effect on dilatant/tensile stresses, casing integrity
Power law creep model (single steady-state mechanism)	M-D creep model (Multiple steady-state creep mechanisms with transient; Munson, 1998)	Need to evaluate cavern response to transient large ΔP events such as workovers

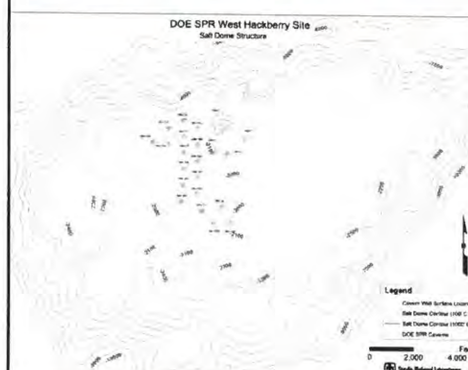
Progression of Complexity of Salt Cavern Geomechanical Models

Earliest Models	Progression of Complexity	Reason for Advancement
Single set of salt creep properties based on lab tests of up to 6 samples (Munson, 1998)	Cavern-specific creep properties (K_0 transient multiplier, A_2 steady-state coeff.) calibrated to try to match measured cavern volume closures	Volume closure rates for caverns of similar geometry, depth vary across a site: West Hackberry by factor of 3, Bryan Mound by factor of 10
Model predictions compared to historical cavern volume closure, surface subsidence, one single A_2 multiplier for entire site (power law creep)	Same data used for model calibration, with partial success; for West Hackberry, K_0 from Munson multiplied by 18.2, A_2 by 0.89-3.2	Better match of individual cavern closure performance hopefully leads to more confident predictions of future cavern behavior
Prescribed constant wellhead pressure with workovers at 5-year intervals	Historical wellhead pressures through current times, then future prescribed pressures	More accurate past history; sympathetic pressure behavior of caverns adjacent to those under workover
Simplified renderings of salt dome, caprock, surrounding rock as single-unit, homogeneous (no faults or shear zones), perfectly bonded	Inclusion of regions with significantly different creep properties; inclusion of low E/low strength interface zones between salt & caprock, salt and surrounding rock	Site-specific observations: casing damage at salt-caprock interface at Big Hill; interface zone, inward-slope at salt dome wall for Bayou Choctaw; different salt zones at Bryan Mound

Two SPR model examples

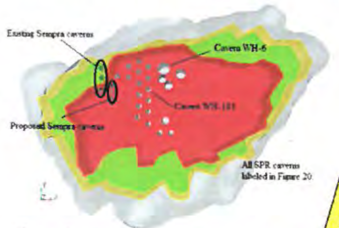
- West Hackberry – well-constrained salt dome
  - Homogeneous salt
  - Axisymmetric caverns
  - No obvious fault or shear zone features
  - Competent caprock
- Bryan Mound – highly variable salt dome
  - Highly heterogeneous salt
  - Bizarre cavern shapes, caused by anhydrite/clay seams and impurities, faults, and shear zones
  - Gas intrusion from outside the formation into several caverns
  - Caprock steam-mined for sulfur in 1920s
  - Abandoned large-diameter cavern in middle of site, ongoing concern for potential cavern collapse

West Hackberry SPR Site

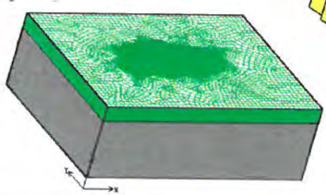


- U.S. SPR site in SW Louisiana
- ~228 MMB of oil storage in 22 caverns (WH-6 retired)
- 5 unusually-shaped, reasonably axisymmetric storage caverns (#6, 7, 8, 9, 11) built in 1940s-1950s.
- 17 cylindrical-shaped storage caverns (#101-117) built in early 1980s.
- Approximately 480 m sandstone overburden, 120 m anhydrite/carbonate caprock over salt dome.
- **WH salt is reasonably homogeneous, isotropic, relatively high creep**

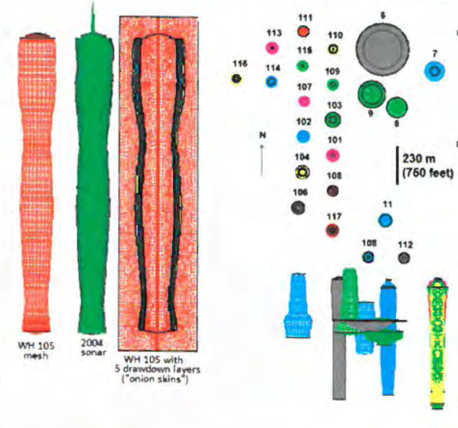
Full Dome Model for WH



- Contains entire WH salt dome, all 22 WH storage caverns, 3 Sempra caverns west of WH site
- Full mesh contains 5.95 million elements

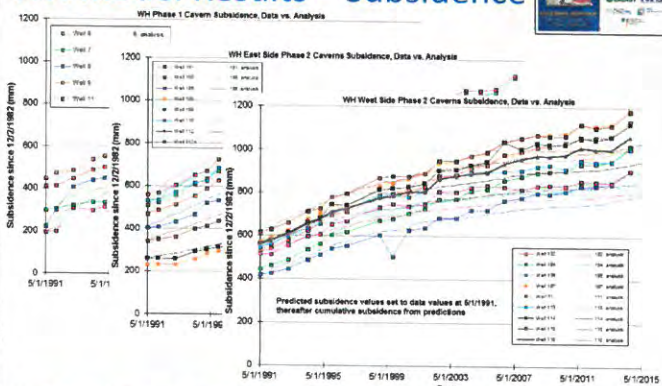


Full Dome Model for WH p. 2



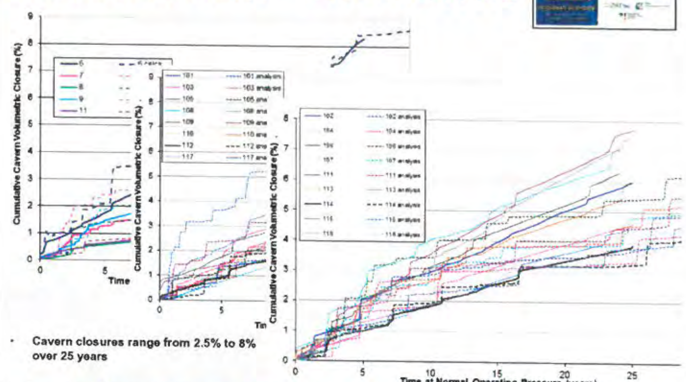
- All caverns meshed to sonar-based geometries – axisymmetric, based on area-averaged radius at each sonar depth
- 5 leach layers ("onion layers") included for nearly all WH caverns (4 layers for WH-8, 3 layers for WH-9, for ease of mesh construction)

WH Model Results – Subsidence



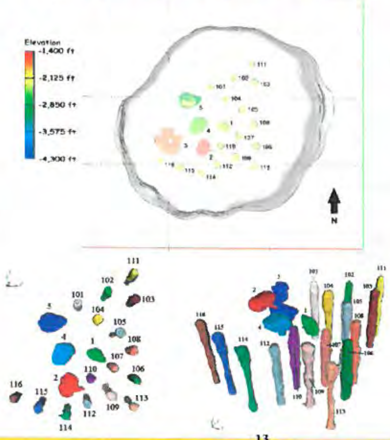
- Surface subsidence is integrative effect of closure of all caverns – easier data set to predict
- WH model predicts surface subsidence over WH very well (~1.2 m)
- Slight underprediction of subsidence on west side – off-site cavern influence?

WH Model Results – Cavern Closure



- Cavern closures range from 2.5% to 8% over 25 years
- Cavern-specific creep parameters used here differ somewhat (but not significantly) from laboratory properties (Munson, 1998)
- WH model predicts overall cavern closure fairly well; discrepancy on normal operating closure between wellhead pressure values, GM model

Bryan Mound SPR Site



Bryan Mound site includes:

- ~226 MMB of oil storage.
- 4 unusually-shaped storage caverns (#1, 2, 4, 5) built in 1940s-1950s.
- 16 cylindrical-shaped storage caverns (#101-116) built in early 1980s.
- Approximately 230 m sandstone overburden, 85 m anhydrite/ carbonate caprock over salt dome.
- <u>Highly heterogeneous salt</u> with anhydrite/clay seams, faults, shear zones
- Caprock mined for sulfur in 1920s – large vugs, thermal signature remain

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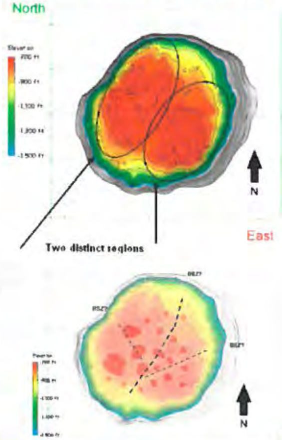
Heterogeneity of Salt



- Salt dome is bisected by several boundary shear zones consisting of faults, salt spines, anhydrite/clay seams, and other anomalies (from seismic, sonar, borehole data).
- Due to these features, the salt creep rates are highly heterogeneous across the site.

Cavern	Closure, BBL/yr	Cavern	Closure, BBL/yr
BM101	5,365	BM109	8,543
BM102	4,944	BM110	3,150
BM103	11,680	BM111	7,813
BM104	2,948	BM112	6,858
BM105	3,683	BM113	10,223
BM106	10,460	BM114	21,304
BM107	4,061	BM115	21,034
BM108	2,702	BM116	6,135

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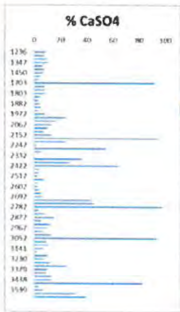
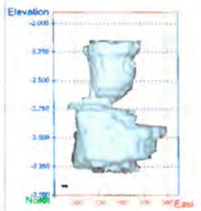
Bryan Mound Cavern 5

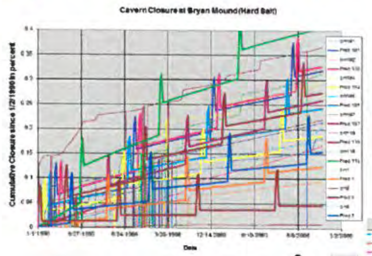
- 36 MMB volume (largest SPR cavern)
- Accessibility to oil in lower lobe
- Salt falls from neck region damaging string
- Emulsion issues when water is pumped in for oil removal
- Gas intrusion issues (anhydrite providing possible flow path)
- Casing failures due to large roof diameter
- Effect on stability of nearby caverns
- Difficulty in modeling creep due to heterogeneous impurity content



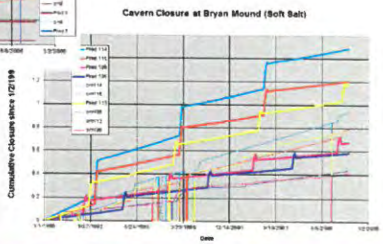
Example: Anhydrite % from well BM5 core samples taken in 1957



Bryan Mound – Cavern Closure



- 2011 predictions using regional (hard, soft) creep properties
- Cavern closures range from 0.1% to 1.0% over 20 years
- New Bryan Mound site model currently in development



Summary

- Geomechanical modeling is not exact, often not close.
- Pre-repository prediction of behavior will ultimately not match measured behavior due to the application of homogeneous properties to a heterogeneous domain.
- Requirements of a site model will change/evolve during the lifetime of the site (pre-construction, early operations, later operations), and models will need to evolve accordingly.
- Laboratory tests will present a limited picture of the properties of salt in a repository domain.
- Knowledge of the nonconformities of a bedded or domal salt (faults, interfaces, clay or anhydrite seams, etc.) will introduce issues that may need to be addressed in upgraded mechanical models.

THANK YOU FOR YOUR ATTENTION!

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Fluid dynamic processes within a closed repository with or without long-term monitoring

7th US/German Workshop on Salt Repository Research, Design, and Operation

R. Wolters, K.-H. Lux, U. Düsterloh

Chair in Waste Disposal and Geomechanics
Clausthal University of Technology

September 7-9, 2016
Washington, DC

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Clausthal University of Technology

Outline

- Long-Term Monitoring Options
- Fluid Dynamic Processes within a Closed Repository
- TH2M-Coupled Simulation Tool *FTK*
- Numerical Simulation Results
- Conclusions

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Fluid dynamic processes within a closed repository with or without long-term monitoring

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Long-Term Monitoring Options

Motivation

In Germany, according to its final report, the „Endlagerkommission" prefers the disposal of high-level waste within a repository built in deep geological formations.

But:

Reversibility of decisions as well as retrievability of the waste canisters should be possible for future generations because there might be a significant improvement of scientific knowledge and technology concerning the handling of high-level waste or there might occur an unexpected development of the repository system.

For this reason, a long-term monitoring option should be implemented into the repository concept to provide data about the time-dependent physical as well as chemical situation within the repository system.

How could a long-term monitoring option be realized?

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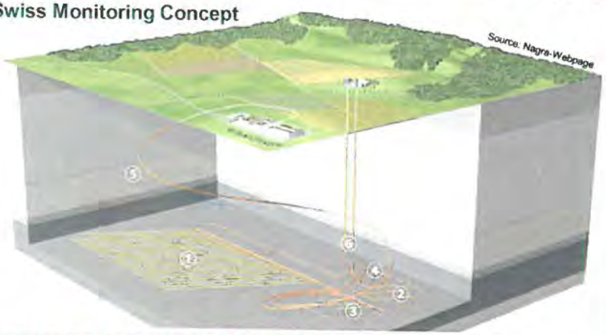
Long-Term Monitoring Options

Swiss Monitoring Concept



How can the measured data be transferred from the pilot facility to the main facility?
How to be sure that the main facility works correctly if the pilot facility works correctly?

1 Main facility SF/HLW
2 ILW repository
3 Pilot facility
4 Test zones
5 Access tunnel
6 Ventilation shaft and construction shaft

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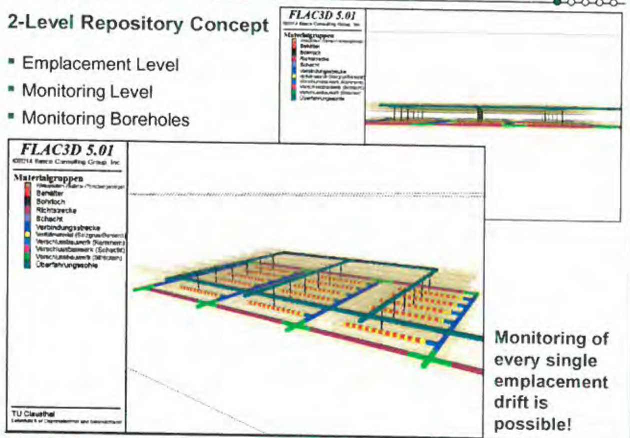
Long-Term Monitoring Options

2-Level Repository Concept

- Emplacement Level
- Monitoring Level
- Monitoring Boreholes



Monitoring of every single emplacement drift is possible!

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Long-Term Monitoring Options

2-Level Repository Concept

- Emplacement Level
  - backfilled and sealed like in repository concept without monitoring option
- Monitoring Level
  - access to monitoring boreholes
  - kept open during monitoring phase
  - backfilled and sealed after monitoring phase (including shaft closure)
- Monitoring Boreholes
  - drilled to emplacement drifts and instrumented before waste emplacement
  - provide access to measurement equipment for repair, energy supply, and data transfer
  - kept internally open during monitoring phase, but covered by some kind of sealing construction at the upper end of the boreholes
  - lined to prevent borehole convergence during monitoring phase
  - unlined, backfilled, and sealed after monitoring phase

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Fluid Dynamic Processes within a Closed Repository

Mechanical Processes

- Salt rock mass:
  - Creep behaviour
  - Thermomechanically induced damage leading to an increase of secondary porosity as well as of secondary permeability
  - Sealing/healing of microfissures
  - Stress redistribution
- Crushed salt:
  - Compaction leading to a reduction of porosity and permeability as well as to increasing compaction stresses

Hydraulic Processes

- Flow of liquids an gases (2-phase flow)
- Hydraulically induced damage in salt rock mass
- Increase of gas pressure due to temperature increase, gas compression, and gas generation

Thermal Processes

- Heat conduction considering non-constant thermal properties

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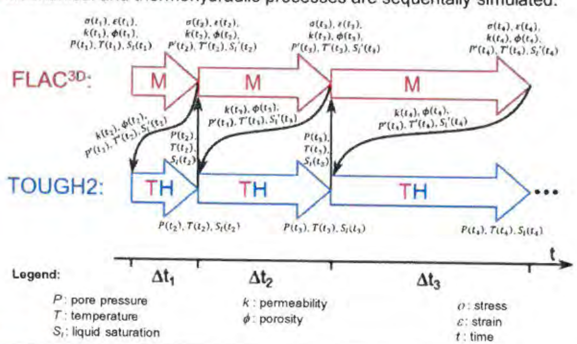
TH2M-Coupled Simulation Tool *FTK*

- The TH2M-coupled simulation tool *FTK* is based on the two numerical codes *FLAC^{3D}* and *TOUGH2*.
- Mechanical and thermohydraulic processes are sequentially simulated.



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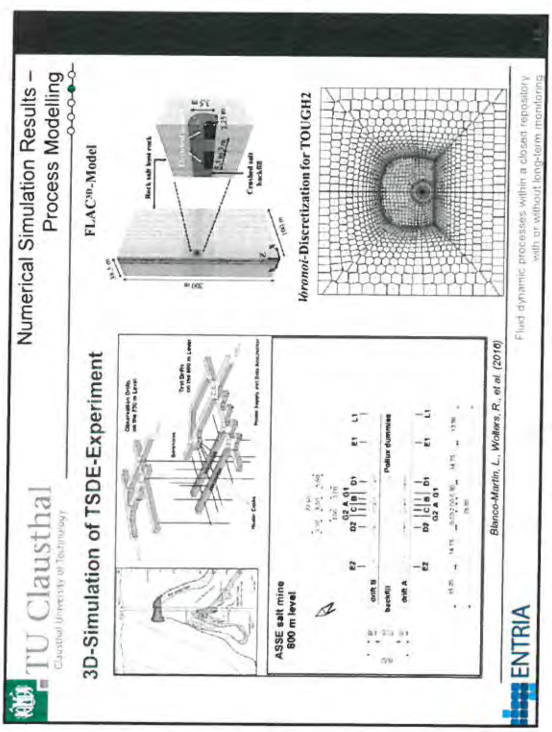
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Numerical Simulation Results – Process Modelling
3D-Simulation of TSDE-Experiment
ASSE salt mine 800 m level
FLAC3D-Model
Voronoi-Discretization for TOUGH2
Blanco-Martin, L., Wolters, R., et al. (2016)
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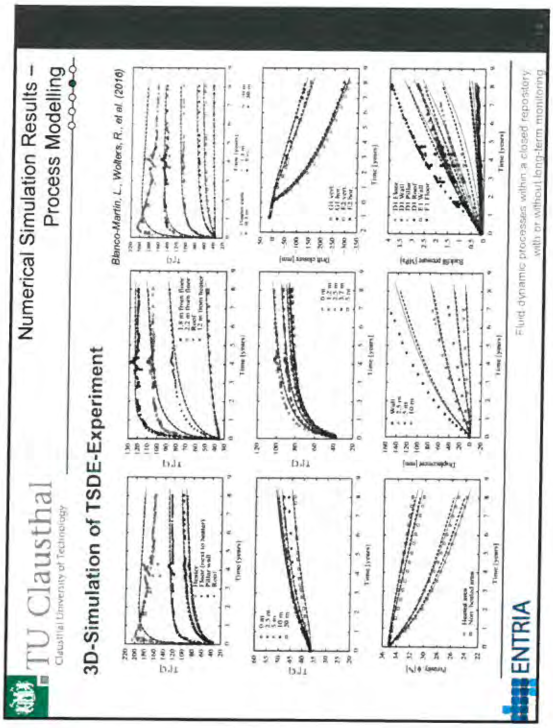
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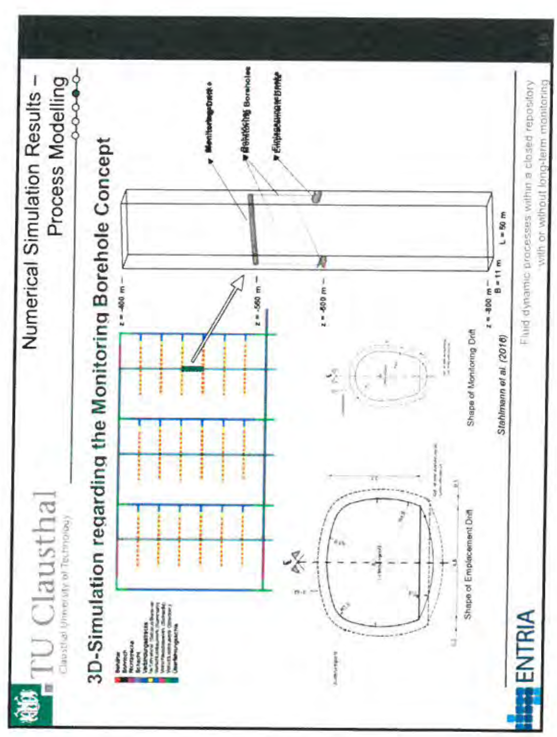
TU Clausthal
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Numerical Simulation Results – Process Modelling
3D-Simulation regarding the Monitoring Borehole Concept
Shape of Emplacement Drift
Shape of Monitoring Drift
Stahlmann et al. (2016)
Fluid dynamic processes within a closed repository with or without long-term monitoring
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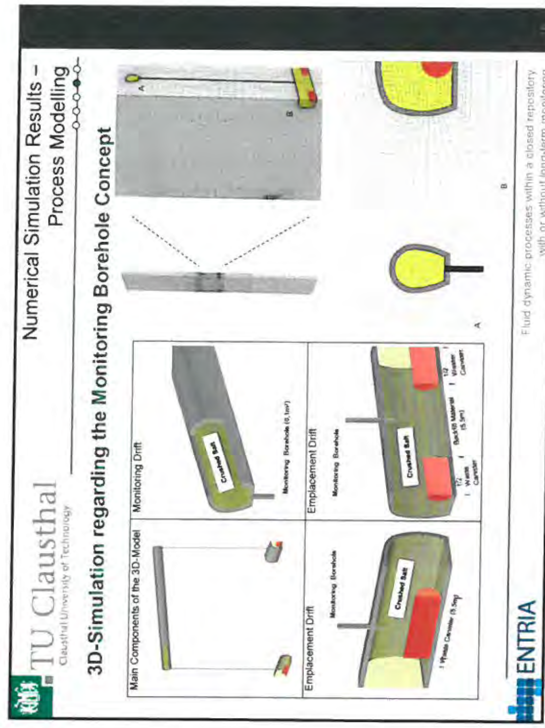
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Numerical Simulation Results – Process Modelling
3D-Simulation regarding the Monitoring Borehole Concept
Main Components of the 3D-Model
Monitoring Drift
Emplacement Drift
Monitoring Borehole
Crushed Salt
Fluid dynamic processes within a closed repository with or without long-term monitoring
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- Long-Term Monitoring Options
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- TH2M-Coupled Simulation Tool *FTK*
- **Numerical Simulation Results**
  - Process Modelling
  - **System Modelling**
- Conclusions

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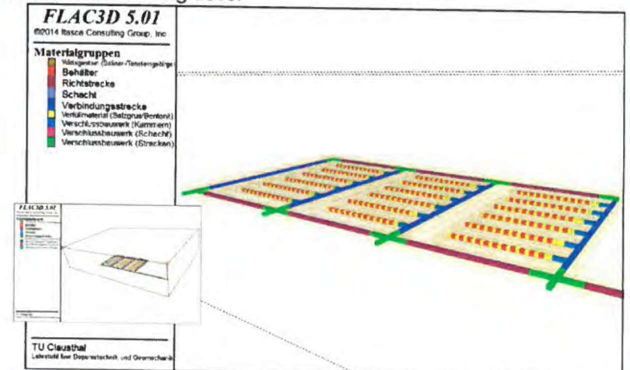
Numerical Simulation Results – System Modelling

3D-Simulation of a Repository System in Rock Salt Mass without Monitoring Level



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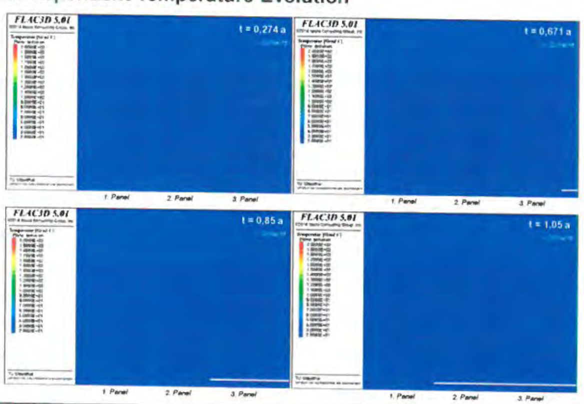
Numerical Simulation Results – System Modelling

Time-dependent Temperature Evolution



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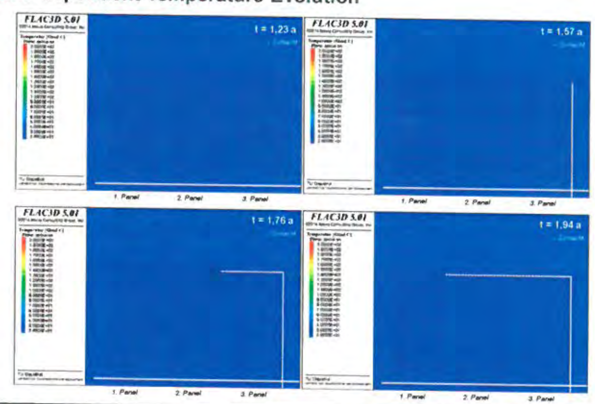
Time-dependent Temperature Evolution



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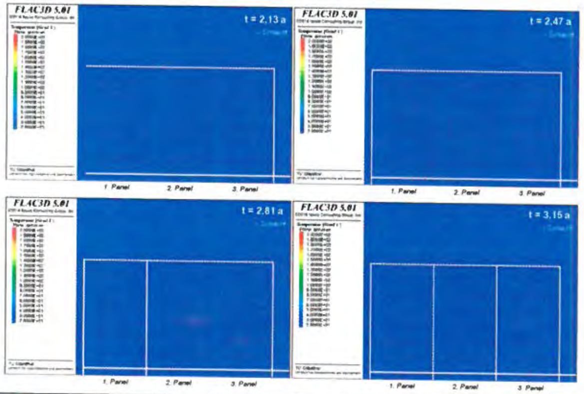
Time-dependent Temperature Evolution



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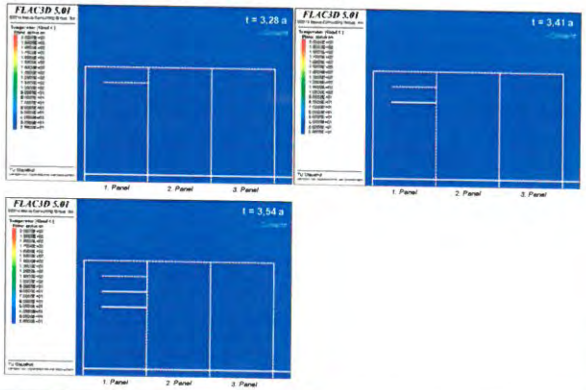
Time-dependent Temperature Evolution



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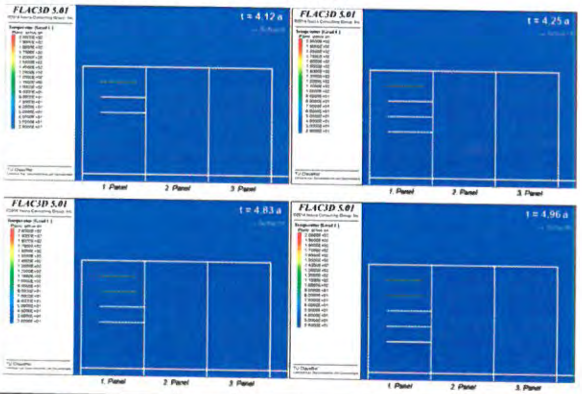
Time-dependent Temperature Evolution



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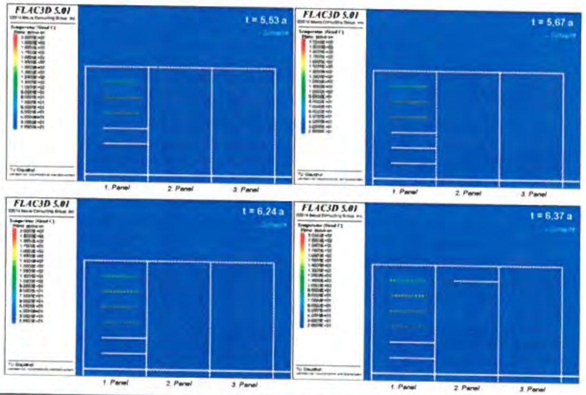
Time-dependent Temperature Evolution



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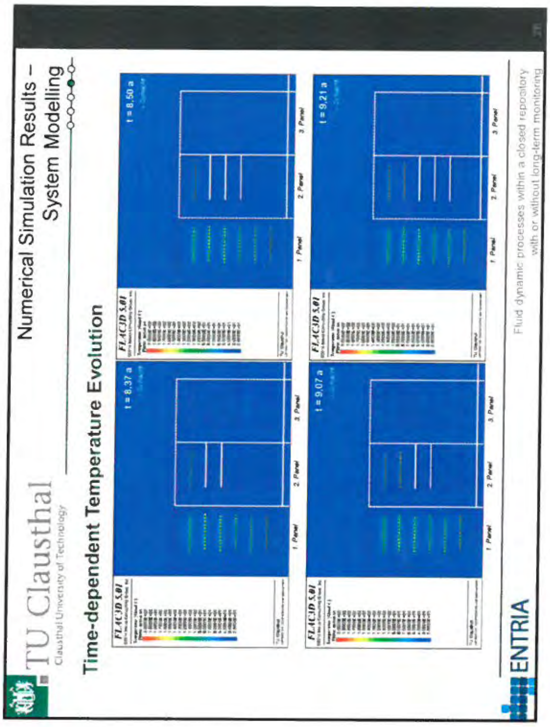
Fluid dynamic processes within a closed repository with or without long-term monitoring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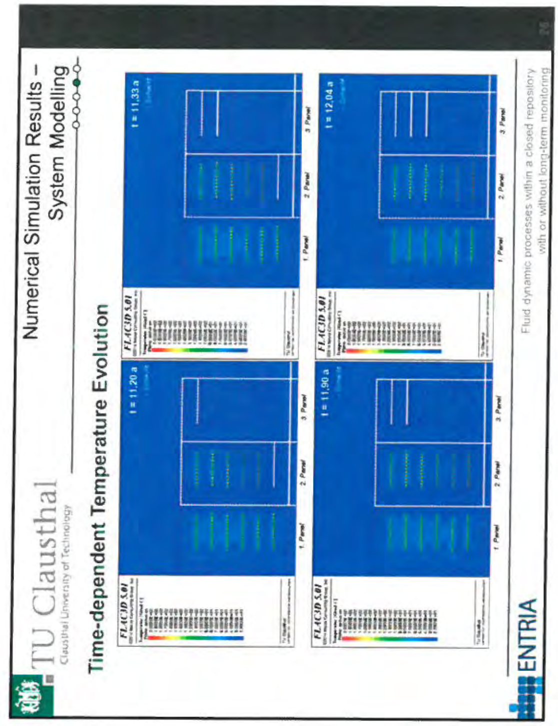
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 8,37 a
t = 8,50 a
t = 9,07 a
t = 9,21 a
Fluid dynamic processes within a closed repository with or without long-term monitoring
ENTRIA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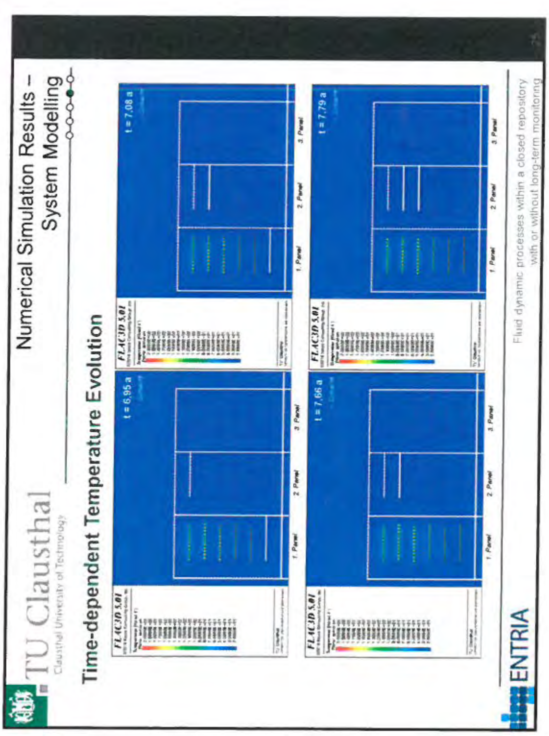
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 11,20 a
t = 11,33 a
t = 11,90 a
t = 12,04 a
Fluid dynamic processes within a closed repository with or without long-term monitoring
ENTRIA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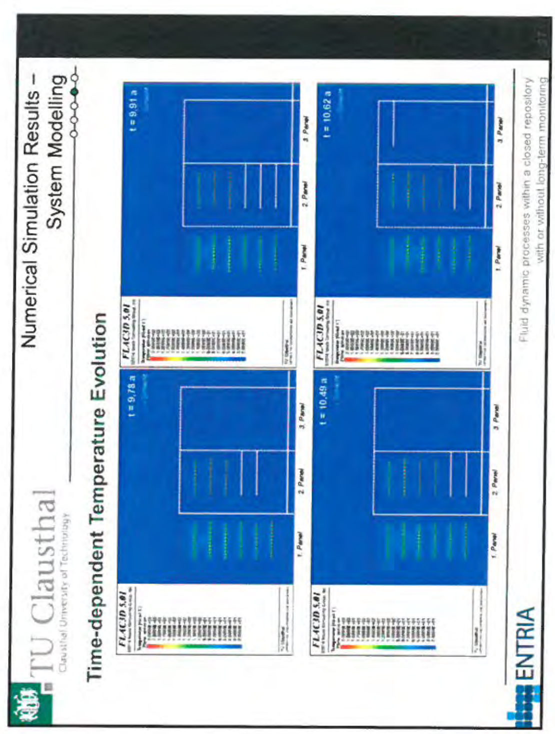
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 6,95 a
t = 7,08 a
t = 7,66 a
t = 7,79 a
Fluid dynamic processes within a closed repository with or without long-term monitoring
ENTRIA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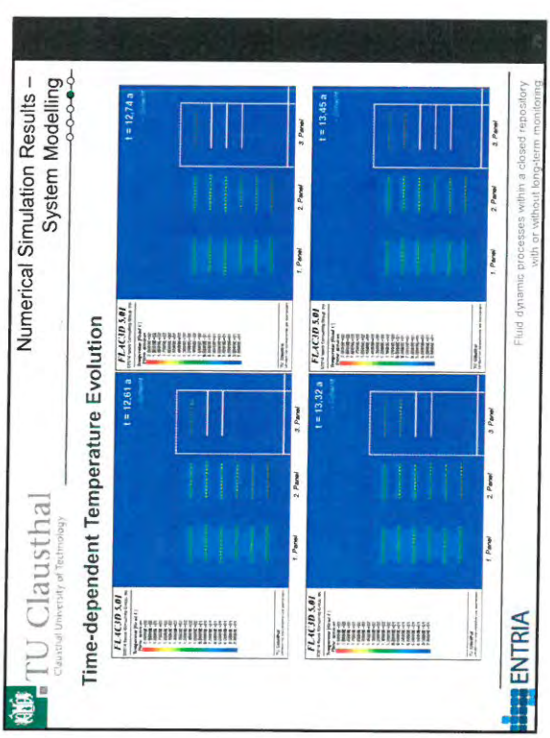
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 9,78 a
t = 9,91 a
t = 10,49 a
t = 10,62 a
Fluid dynamic processes within a closed repository with or without long-term monitoring
ENTRIA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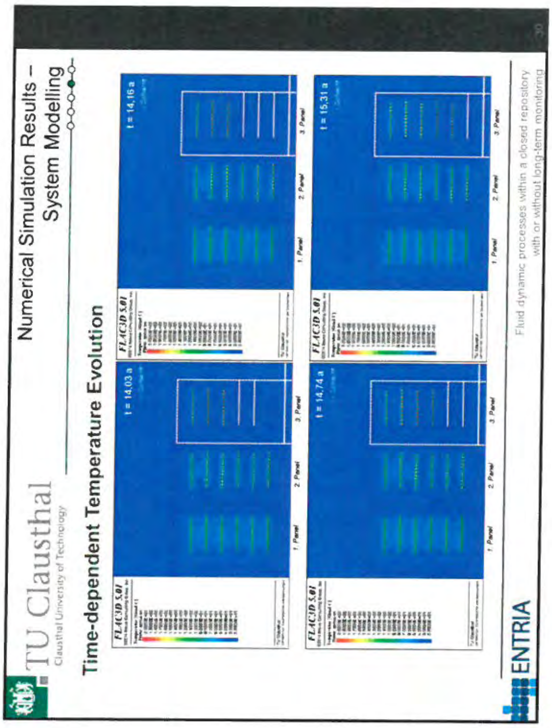
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
FLAC3D 5.01
t = 12,61 a
t = 12,74 a
t = 13,32 a
t = 13,45 a
1. Panel
2. Panel
3. Panel
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring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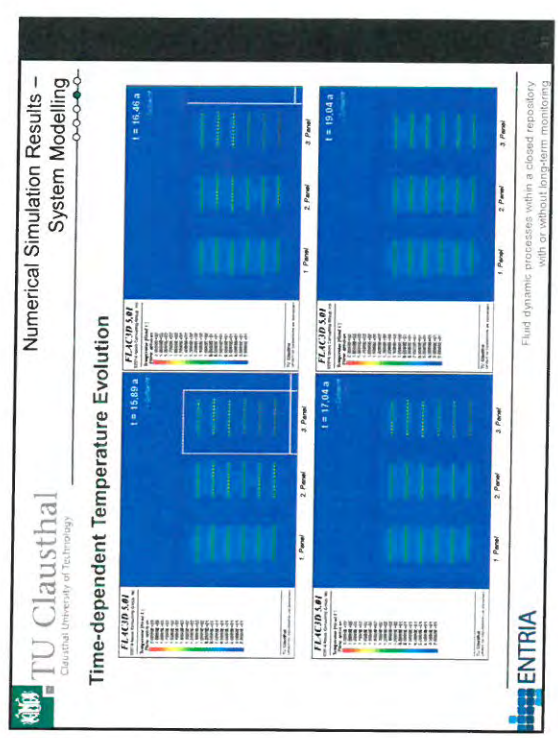
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
FLAC3D 5.01
t = 14,03 a
t = 14,16 a
t = 14,74 a
t = 15,31 a
1. Panel
2. Panel
3. Panel
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring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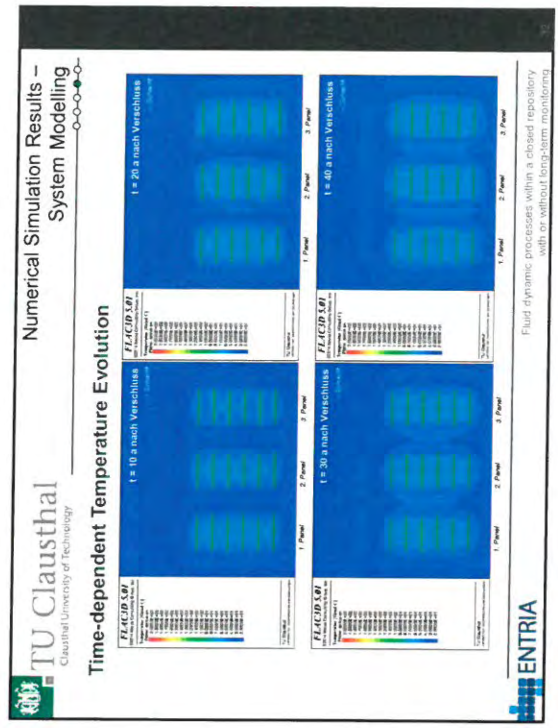
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
FLAC3D 5.01
t = 15,89 a
t = 16,46 a
t = 17,04 a
t = 19,04 a
1. Panel
2. Panel
3. Panel
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring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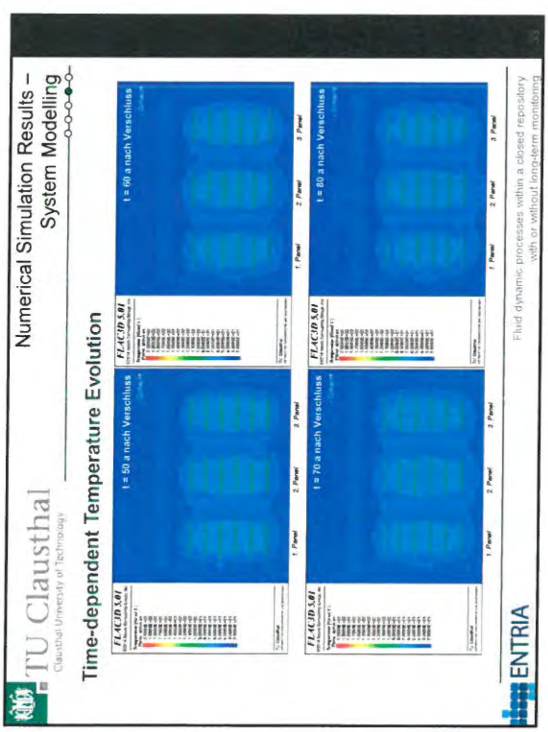
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
FLAC3D 5.01
t = 10 a nach Verschluss
t = 20 a nach Verschluss
t = 30 a nach Verschluss
t = 40 a nach Verschluss
1. Panel
2. Panel
3. Panel
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring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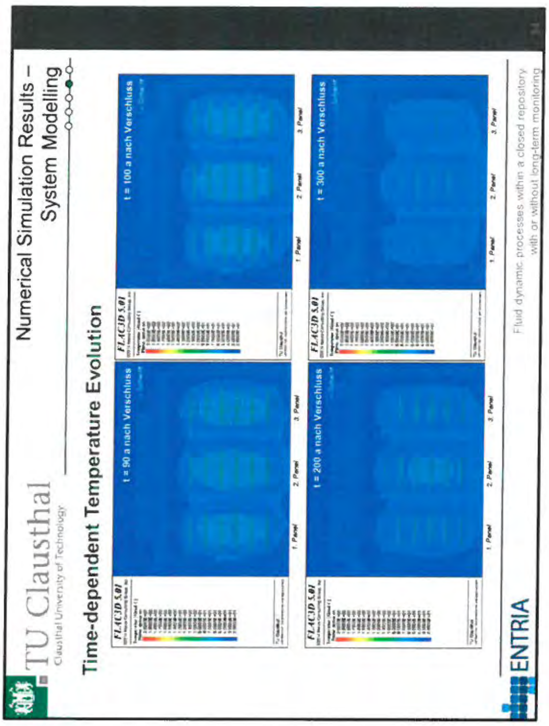
Clausthal University of Technology
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 50 a nach Verschluss
t = 60 a nach Verschluss
t = 70 a nach Verschluss
t = 80 a nach Verschluss
1 Panel
2 Panel
3 Panel
FLAC3D 5.01
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring
33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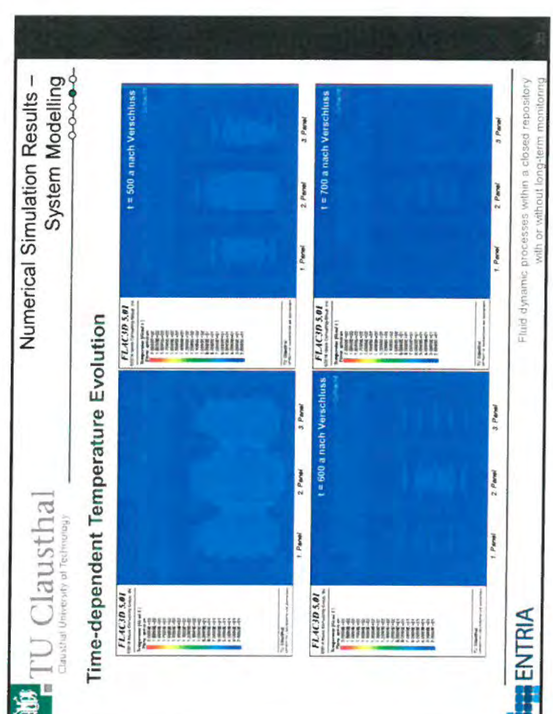
Clausthal University of Technology
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 90 a nach Verschluss
t = 100 a nach Verschluss
t = 200 a nach Verschluss
t = 300 a nach Verschluss
1 Panel
2 Panel
3 Panel
FLAC3D 5.01
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring
34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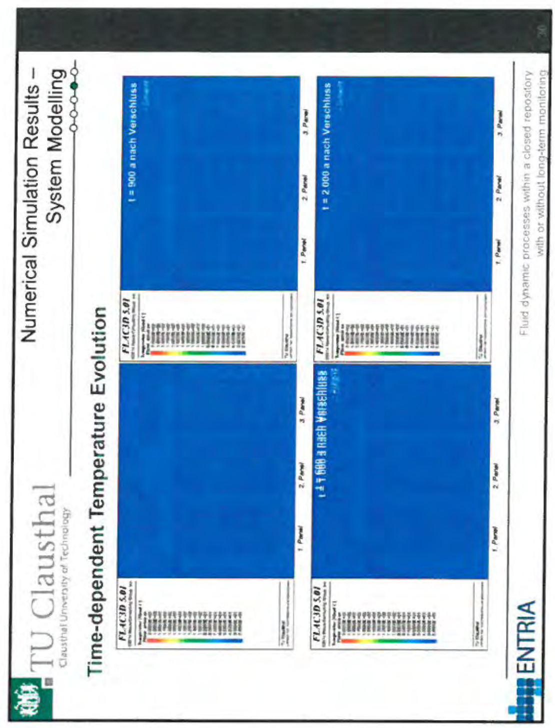
Numerical Simulation Results – System Modelling
Time-dependent Temperature Evolution
t = 500 a nach Verschluss
t = 600 a nach Verschluss
t = 700 a nach Verschluss
1 Panel
2 Panel
3 Panel
FLAC3D 5.01
ENTRIA
Fluid dynamic processes within a closed repository with or without long-term monitoring


TU Clausthal
Clausthal University of Technology
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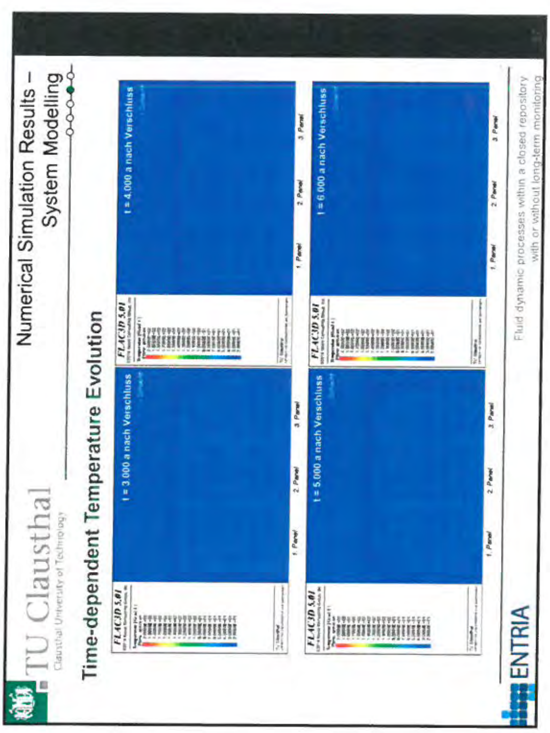
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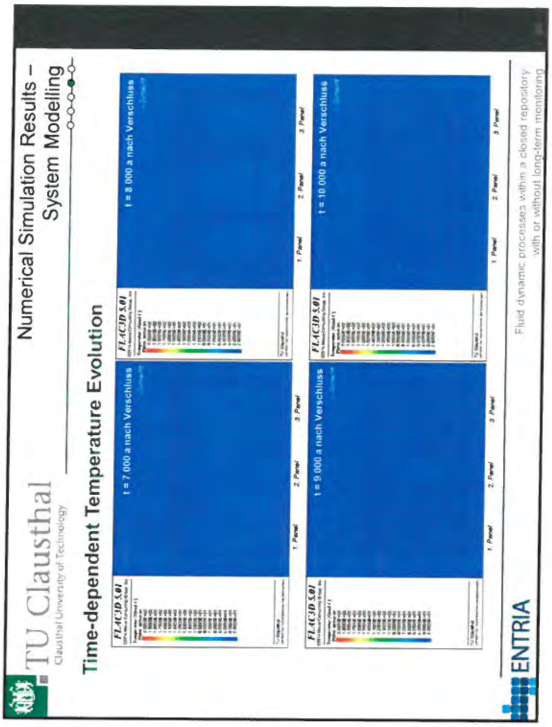
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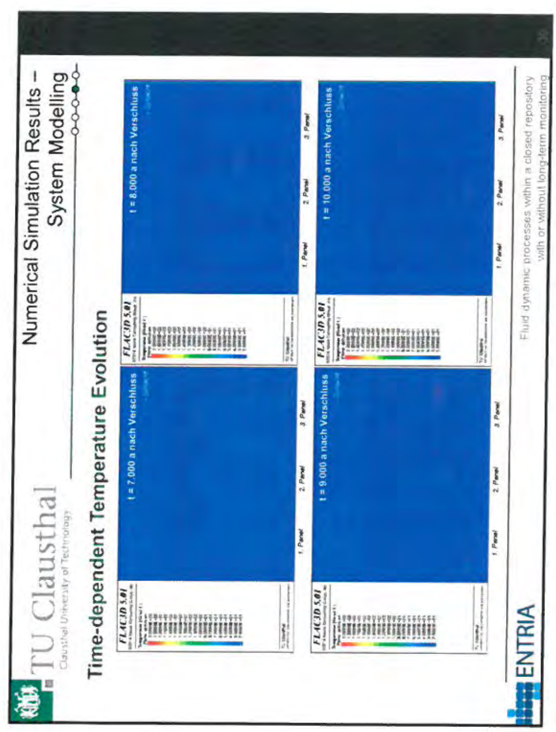
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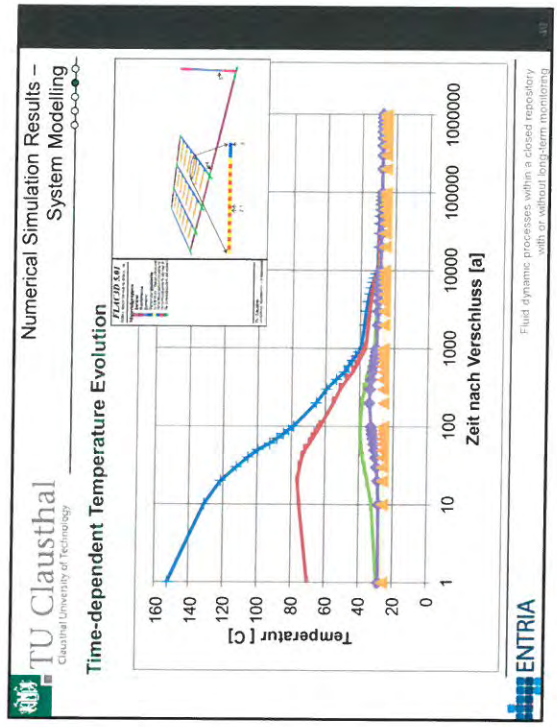
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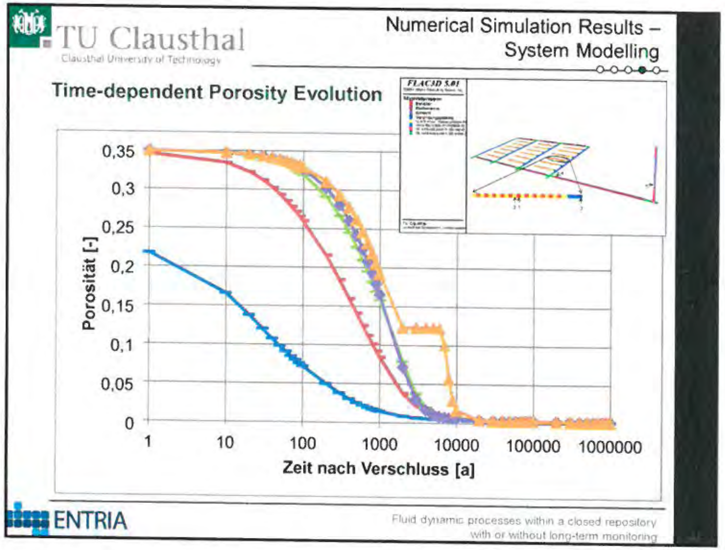
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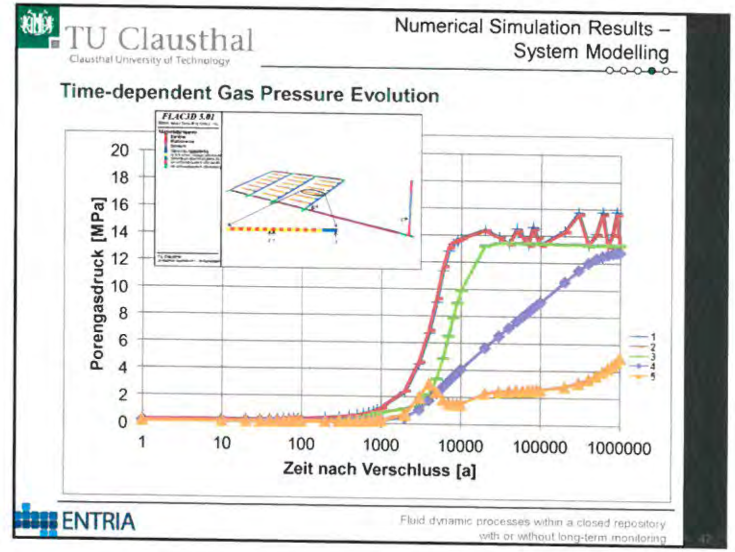
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Clausthal University of Technology
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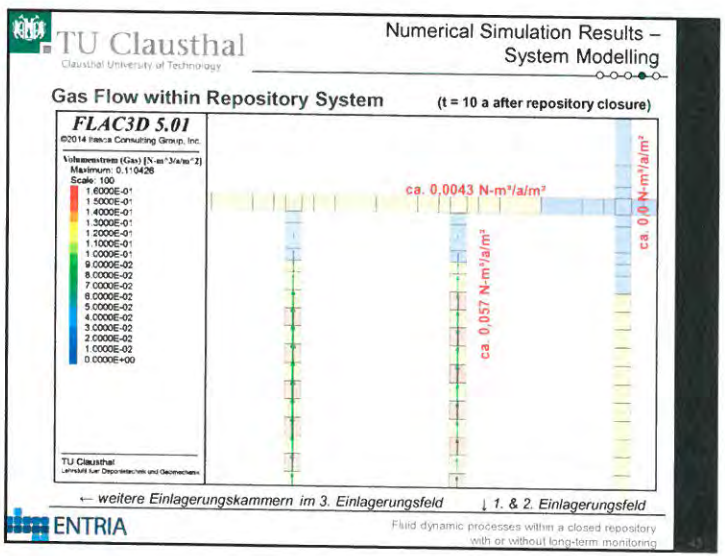
with or without long-term monitoring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TU Clausthal
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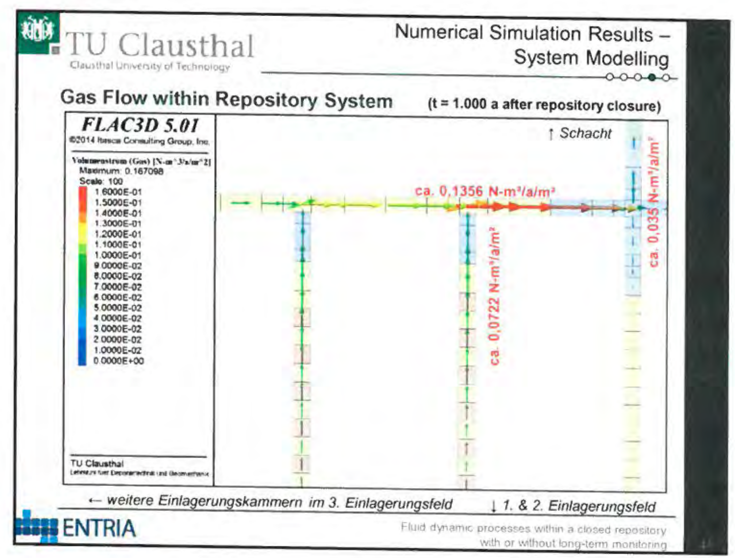
↓ 1. & 2. Einlagerungsfeld
ENTRIA
Fluid dynamic processes within a closed repository
with or without long-term monitoring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System Modelling
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TU Clausthal
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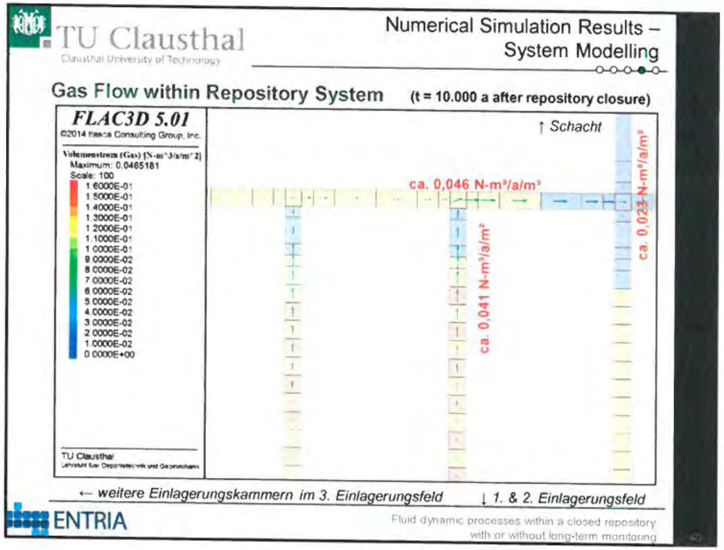
Fluid dynamic processes within a closed repository
with or without long-term monitoring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Numerical Simulation Results –
System Modelling
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TU Clausthal
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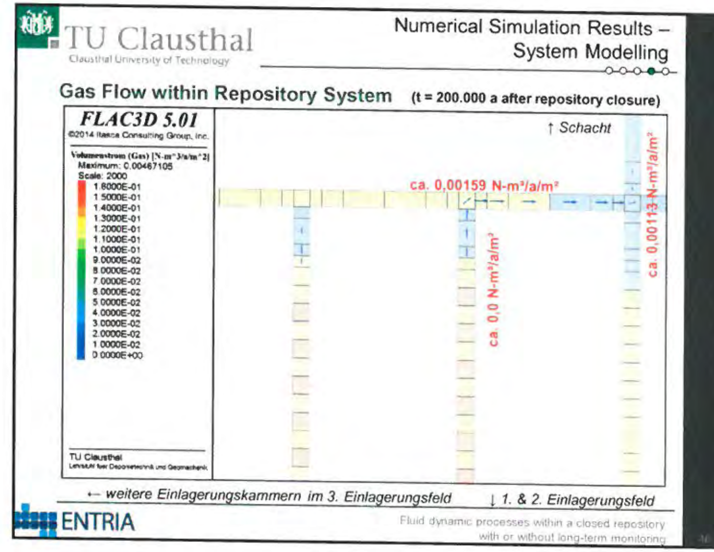
ENTRIA
Fluid dynamic processes within a closed repository
with or without long-term monitoring


TU Clausthal
Clausthal University of Technology
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TU Clausthal
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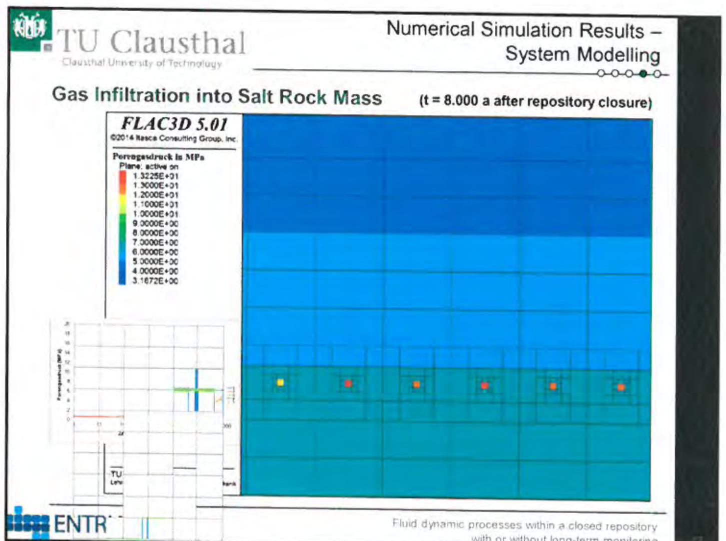
↓ 1. & 2. Einlagerungsfeld
ENTRIA
Fluid dynamic processes within a closed repository
with or without long-term monitoring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Clausthal University of Technology
Numerical Simulation Results –
System Modelling
Gas Infiltration into Salt Rock Mass
(t = 8.000 a after repository closure)
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Porengasdruck in MPa
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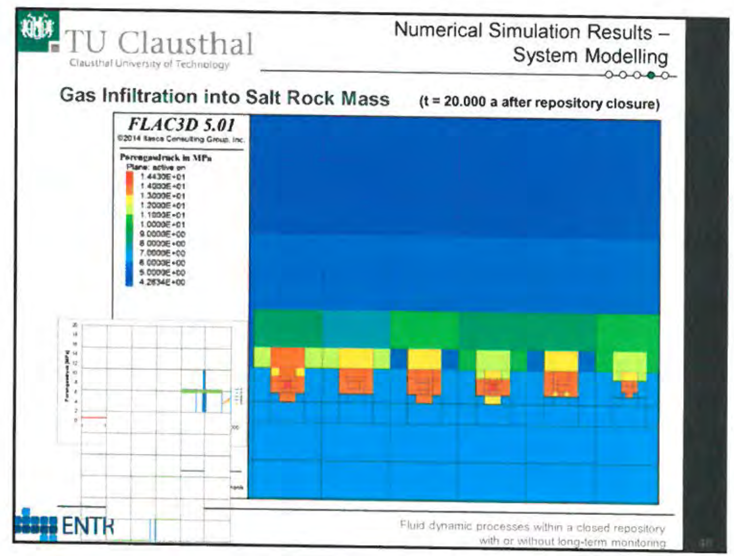
Fluid dynamic processes within a closed repository
with or without long-term monitoring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System Modelling
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Porengasdruck in MPa
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Fluid dynamic processes within a closed repository
with or without long-term monitoring

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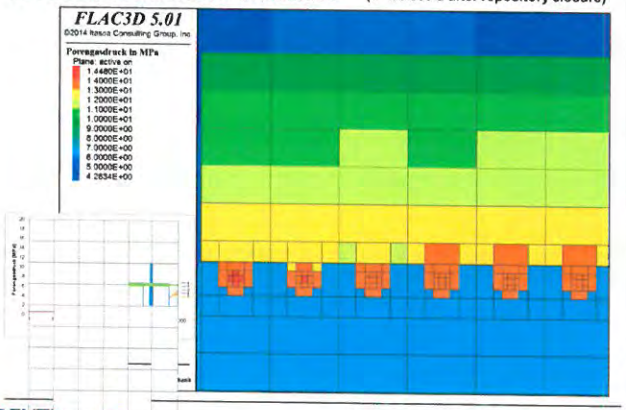
Numerical Simulation Results – System Modelling

Gas Infiltration into Salt Rock Mass (t = 80.000 a after repository closure)



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Fluid dynamic processes within a closed repository with or without long-term monitoring

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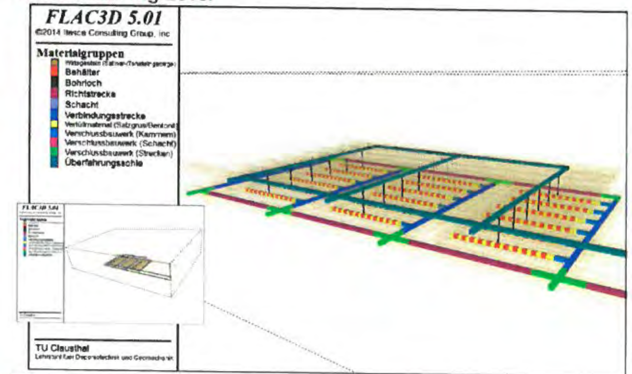
Numerical Simulation Results – System Modelling

3D-Simulation of a Repository System in Claystone Rock Mass with Monitoring Level



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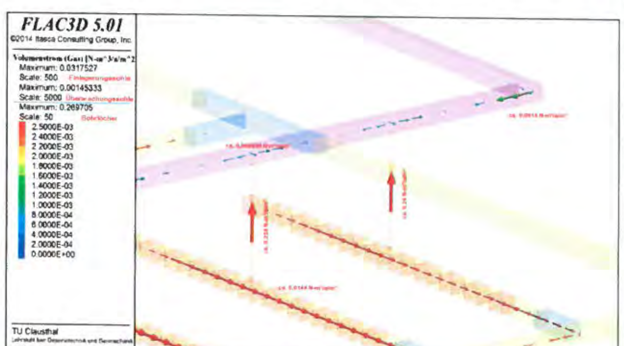
Numerical Simulation Results – System Modelling

Gas Infiltration into Claystone Rock Mass (t = 900 a after repository closure)



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Fluid dynamic processes within a closed repository with or without long-term monitoring

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Outline

- Long-Term Monitoring Options
- Fluid Dynamic Processes within a Closed Repository
- TH2M-Coupled Simulation Tool *FTK*
- Numerical Simulation Results
- **Conclusions**

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Fluid dynamic processes within a closed repository with or without long-term monitoring

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Conclusions

- Capabilities of the simulation tool *FTK* to evaluate the barriers integrity over time including TH2M-coupled processes like rock mass convergence, backfill compaction, heat production, gas production, 2-phase flow, and pressure-driven infiltration have already been demonstrated in former works, e.g. at SaltMech 8 or at 5th US/German Workshop on Salt Repository Research, Design, and Operation.
- The simulation tool *FTK* can be used to analyze the long-term TH2M-coupled behaviour of a repository system in salt rock mass.
- (...)

DOPAS: Full-scale demonstration of the feasibility and performance of plugs and seals

DOPAS

German contribution:
CH/HM coupled behaviour of shaft sealing materials

Oliver Czaikowski, Kyra Jantschik, Helge C. Moog, Klaus Wieczorek & Chun-Liang Zhang
GRS , Germany

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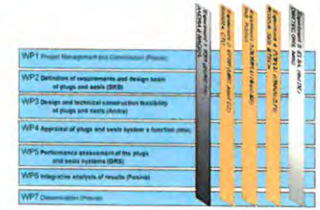
The DOPAS Project

- Five experiment being designed, implemented and assessed across seven work packages
- Supported by materials development
- Three experiments in crystalline rocks:
  - DOMPLU (Äspö)
  - POPLU (ONKALO)
  - EPSP (Josef)
- One experiment related to clay:
  - FSS (St Dizier)
- A set of experiments and performance assessment studies related to salt:
  - ELSA (generic German concept)



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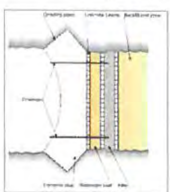
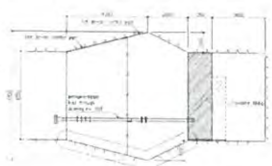
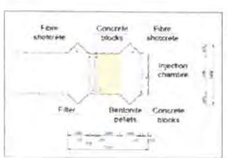
Experiments in crystalline and clay rock



DOMPLU (SKB) and **POPLU** (POSIVA):
- confine the backfill in the tunnel, support backfill saturation and to provide a barrier against water flow / bentonite erosion
- Main components: concrete plug and watertight seal





EPSP (SURAO/CTU):
- Composite structure of concrete domes and bentonite pellets

FSS (ANDRA):
- Limit water flow and reduce groundwater velocity
- Swelling clay core and low-pH concrete containment

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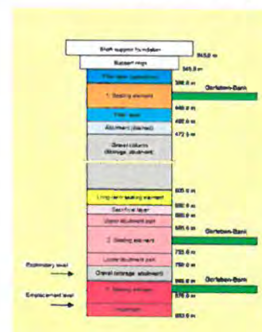
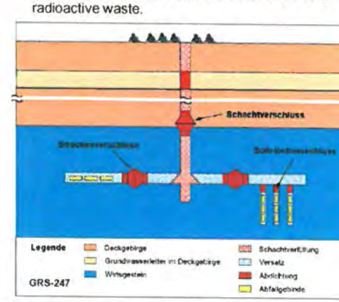
German shaft sealing concepts



Reference conceptual design for the German shaft seal. The Gorleben-Bank is a folded anhydrite layer in the rock salt (Müller-Hoeppe *et al.* 2012a).

German disposal concept
- Multiple barrier system consists of technical (disposal container), geotechnical (sealing elements) and geological (host rock) barriers.
- Barriers shall prohibit intrusion of saline brines to the radioactive waste.



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Issues addressed by GRS within DOPAS

- **Investigation of chemical-hydraulic behaviour of cement based sealing materials in rock salt (LAVA)**
  - Batch experiments with crushed concrete suited to investigation of water-rock interactions.
  - In-diffusion experiments with concrete and brine in order to determine the rate of alteration of the porous matrix.
  - Experiments with concrete brine at the contact with the EDZ in order to determine the rate of alteration of the sealing material owing to advective flow at the boundary to the rock formation.
  - Accompanied by numerical modelling activities.

    Deliverable D3.29
- **Investigation of hydro-mechanical behaviour of cement based sealing materials in rock salt (LASA)**
  - Multistep creep tests on samples of concrete for the determination of creep parameters.
  - Triaxial compression tests on samples of concrete with axial flow of gas for determination of time-dependent compaction and damage evolution.
  - Experimental long-term simulations of the systems rock salt / concrete using large hollow salt cylinders filled with concrete under varying isostatic load and constant brine pressure.
  - Accompanied by numerical modelling activities.

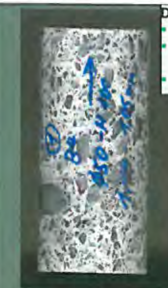
    Deliverable D3.31
- **Hydro-mechanical behaviour of claystone-bentonite-mixture as seal material (THM-Ton)**
  - Investigations on the long-term behaviour of the clay rock (Ucc, TCc, gas flow, swelling properties).
  - Experiments to characterize the geotechnical properties of compacted claystone-bentonite-mixtures as sealing material (water retention curves, water re-saturation, water permeability and gas migration, swelling capacities).
  - Accompanied by numerical modelling activities.

    Deliverable D3.32

Available material for lab tests (in situ / lab)

Drift sealing element
- Depth 945 m, finished in 1992
- Salt concrete
  (72% crushed salt, 18% cement, 10% NaCl-brine)
- 8 m in length, 5.5 m in width, 3.4 m in height

Rock salt
from the Excavation Damaged Zone (EDZ)

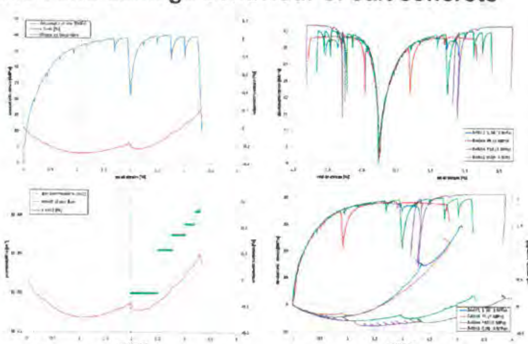


Salt concrete
crushed salt, blast-furnace cement, NaCl-brine

Sorel concrete
crushed salt, magnesium oxide, $MgCl_2$-brine

Crushed claystone/ bentonite mixtures
with grains d < 10 mm

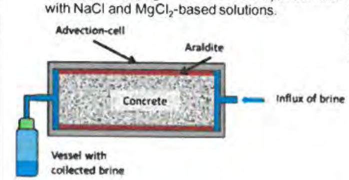
Deformation and damage behaviour of salt concrete



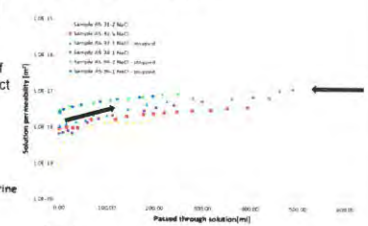
Stress-strain-permeability behaviour of salt concrete samples

Permeability evolution of sorel concrete (corrosion processes)

Advection experiments with sorel concrete
- Investigation of development of permeability of sorel concrete (MgO-based concrete) in contact with NaCl and $MgCl_2$-based solutions.



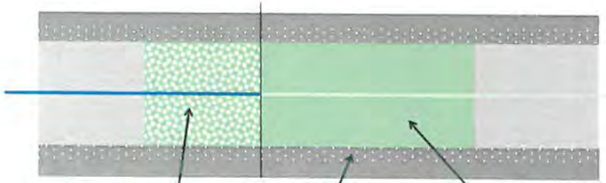
Functional principle
- Concrete is placed in advection cell, cast in araldite
- Inflow: Solution pressure 20 bar.
- Outflow: Solution is collected and permeability calculated.



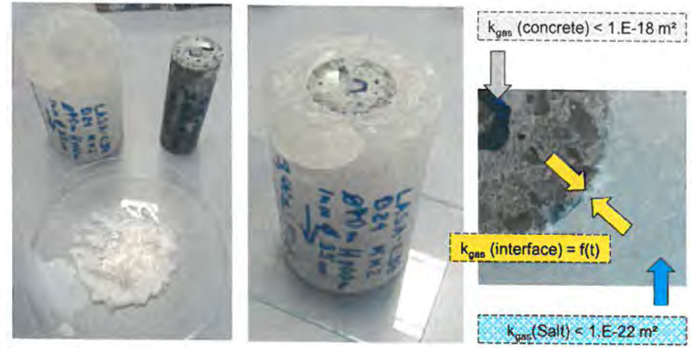
Results

Sorel concrete / NaCl-based solution
- Permeability measureable after 7 to 60 days.
- Clear increase of permeability in all samples up to a level of 10^{-17} m^2/s.
- *Assumption:* no further increase of permeability because solution passes sample faster than it needs for corrosion if a value around 10^{-17} m^2/s is reached.

Sealing in integrated PA: Closer to reality



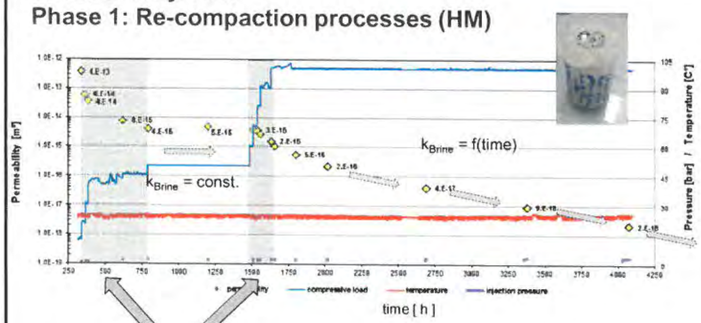
Hydraulic sealing capacity of combined samples



Hollow salt cylinder, salt concrete core and salt slurry

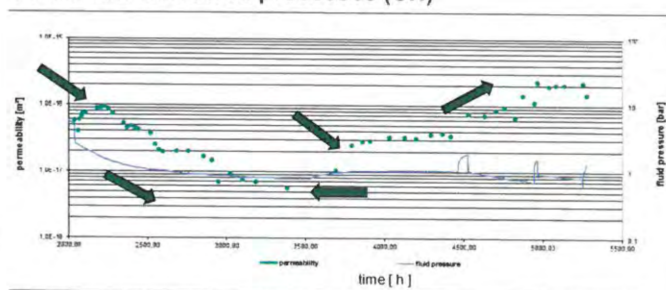
Complete combined sample

Combined system
Phase 1: Re-compaction processes (HM)



Phase 1: Compaction of the sample – confining pressure 5 and 10 MPa, sample stays in contact with NaCl-based solution ⇒ Permeability to NaCl-based solution is around 10^{-18} m²/s.

Combined system
Phase 2/3: Corrosion processes (CH)



Phase 2: Permeability increases immediately in contact with $MgCl_2$-based solution, probably as result of higher injection pressure. Afterwards, permeability decreases because Brucit ($Mg(OH)_2$) is built and plugs the pores. Additionally, pH decreases to 8-9.

Phase 3: The smaller pH-value results in decomposition of portlandite ($Ca(OH)_2$) and CSH-phases (Calcium-silicate-hydrates). ⇒ Permeability increases.

Conclusions and further R&D work

Coupled behaviour of sealing materials in contact with surrounding rock

- GRS is investigating combined systems of salt concrete seal elements and surrounding rock salt at the laboratory scale in order to get the temporal evolution of the overall permeability.

Currently, the following results have been obtained:

- At dry conditions and at a moderate confining stress up to 5 MPa, reconsolidation is slow. A potentially existing highly permeable contact seam between the seal element and the rock will not be closed, at least not in the short term.
- With an intact seal element, a confining stress of 5 MPa is, however, sufficient to prevent brine flow along the seal. In the presence of brine, contact seam and EDZ are quickly closed, resulting in overall permeability below 10^{-20} m^2.
- A pre-damaged seal element (e.g., damaged by shrinkage fracturing during construction) will not be reconsolidated at a confining stress of 5 MPa, even if brine is present.
- At a stress level of 10 MPa reconsolidation of the pre-damaged seal element is effective and permeability decreases.
- Chemical alteration processes can be observed when a corrosive brine is present.

The next steps in the experimental investigations will be:

- to dismantle the re-consolidated sample and use microscopic methods to investigate pathway reduction and
- to perform further experiments to investigate variability of results and derive generally valid material behaviour.

Available physical models of rock salt and salt concrete have been applied already but simulation/improvement cycles should be performed to advance model qualification.

Acknowledgements

DOPAS

J. Dittrich
U. Hertes
T. Hörbrand
J. Müller

Questions ...

The research leading to these results has received funding from the European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013, under Grant Agreement No. 323273 for the DOPAS project and the Federal Ministry for Economics and Energy (BMWi), represented by the Project Management Agency Karlsruhe (PTKA-WTE), contract no. 02E11122 / 02E11132 / 02E10377.

Shaft seals for HLW repositories (ELSA project)

Philipp Herold[1], Michael Jobmann[1], Wolfram Kudla[2], Matthias Gruner[2]

[1]DBE TECHNOLOGY GmbH
[2]TU Bergakademie Freiberg

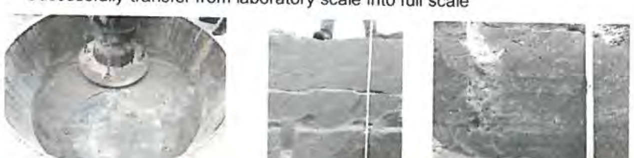
Washington, DC
September 7-9, 2016

Contents

Compaction of crushed salt–clay–mixtures

Results from 6th US/German Workshop in Dresden:

- Vibrating pre-compaction satisfied our expectations
- All mixtures performed well
- Handling of the mixture with a maximum grain size of 4 mm ("mOBSM") has almost no segregation effects
- Due to impulse compaction, the mixture "OBSM" (max. grain size 10 mm, water content 3.4 m%) reached total porosities around 9.6 % (mOBSM ~11.9 %, with water content of 4.4 m%)
- Calc. air voids are in a range between 1.8 and 3.5 %
- Due to surface bulking, final compaction affected only at the bottom
- Successfully transfer from laboratory scale into full scale



Compaction of crushed salt–clay–mixtures

Next steps:

- Development and test of a "shaft-impact-compactor"
- Based on existing dynamic compaction equipment and optimized for underground conditions:
  - Falling weight: 1000 … 5000 kg
  - Falling height: 0.3 … 2.0 m
  - Compaction foot with diameter 0.8 m (pre test) and 2.0 m (shaft)
  - "Weight-saving" and smaller construction for higher flexibility in shaft working

→ Repeat in-situ test with the new compactor and with only one reference mixture

Compaction of crushed salt–clay–mixtures

Alternative option: Binary mixture

Component 1: Rock salt roller press compacts
Component 2: Crushed salt–clay–mixture (< 4 mm)


Layer of Rock Salt Compacts

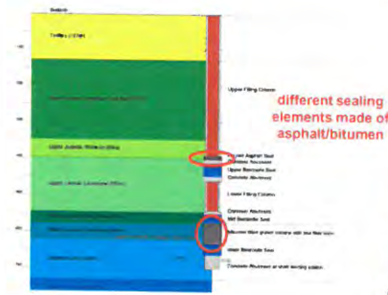

Binary Mixture after Oedometer Test at 5 MPa

- \+ Well-known technology (bentonite binary mixture for shaft sealing)
- \+ Low water content (no added water)
- \- Additional roller compaction process
- \- High permeability: $3 \cdot 10^{-14}$ m² (due to low density of component 2)

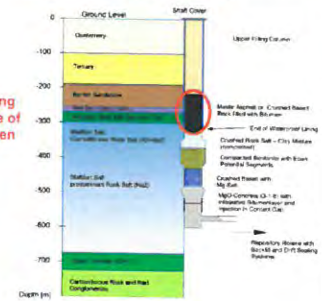
Shaft sealing concepts

ELSA project includes development of shaft sealing elements and corresponding shaft sealing concepts for salt and clay formations

Sealing concept for Jurassic clay formations as expected in southern Germany:



Sealing concept for bedded rock salt as known in northern Germany:



Bitumen and asphalt

System	Bitumen Sandwich	Bitumen filled gravel column	Asphalt with rounded gravel
Function	Sealing	Sealing and Abutment	Sealing and Abutment
Design			
Materials	Bitumen with different viscosity	Crushed Basalt 32 / 63 mm Bitumen, standard or with filler	Rounded Basalt 20 / 40 mm Bitumen, standard or with filler
Related to	Konrad project	ERAM project	ELSA project
Status	•Conceptual design •**In-situ test planned within ELSA-Project**	•Pilot tests at TU Bergakademie Freiberg (presentation at 5th Workshop in Santa Fe) •Full-scale field test (BISETO Project, supported by BfS) •**In-situ test within ELSA Project**	•design and development •**In-situ test within ELSA Project**

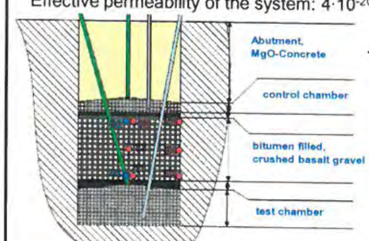
Bitumen and asphalt

Crushed Basalt Gravel – filled with Bitumen

In-situ test during ELSA project:

- Borehole D = 0.5 m, H = 1.0 m
- Crushed Basalt 32 / 63 mm (1.708 g/cm³)
- Filled with straight-run Bitumen (at 170 °C)

Initial permeability of the rock salt: $2 \cdot 10^{-22}$ m² (gas)
Effective permeability of the system: $4 \cdot 10^{-20}$ m² (gas)



Bitumen and asphalt

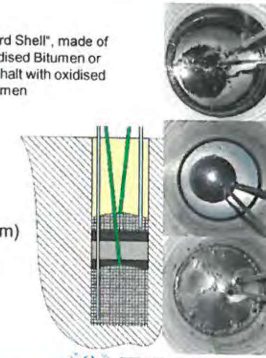
Asphalt with special aggregates

Laboratory and in-situ tests during ELSA project:

- First lab tests to identify compaction properties of the rounded gravel and suitable bitumen/gravel mixture
- Same dimensions as Type 1 test (Borehole D = 0.5 m, L =1.0 m)
- Mixture of rounded Basalt (20/40 mm) with straight-run Bitumen at 140 °C

Bitumen and asphalt

Concept "Soft Core + Hard Shell"



In-situ test during ELSA project:

- Two in-situ tests in rock salt (boreholes D = 0.3 m)
- Initial permeability of the rock salt:
  $6 \cdot 10^{-22}$ m² (gas) and $5 \cdot 10^{-22}$ m² (gas)
- Effective permeability of the system:
  $2 \cdot 10^{-20}$ m² (gas) and $6 \cdot 10^{-20}$ m² (gas)
  $1 \cdot 10^{-20}$ m² (NaCl solution)

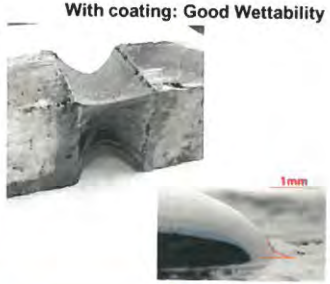
Bitumen and asphalt

Bitumen Priming Coat - Improvement of Wettability to Rock Salt

- Bitumen Priming Coat - Improvement of wettability to rock salt
- Licensed by mining authority
- Patent DE 102008050211

No Coating: Bad Wettability

With coating: Good Wettability

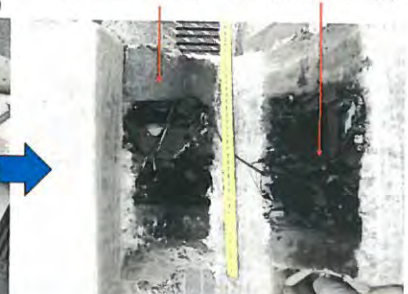


Bitumen and asphalt

Concept "Soft Core + Hard Shell"

Removal of the bitumen seal

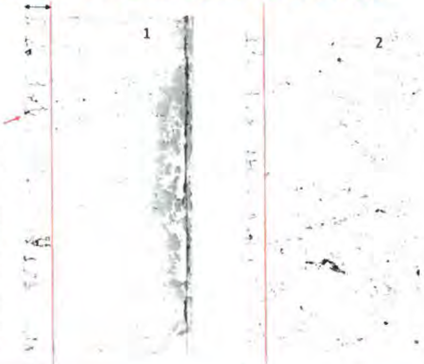
Over-drilled sample (D = 0.5 m)



Bitumen and asphalt

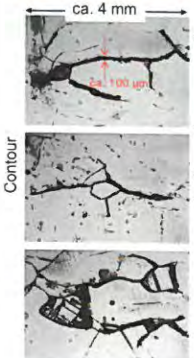
Concept "Soft Core + Hard Shell"
Sealing Performance of Bitumen in the Contact Zone and in the EDZ

Bitumen penetrates cracks (max. 0.5 cm)

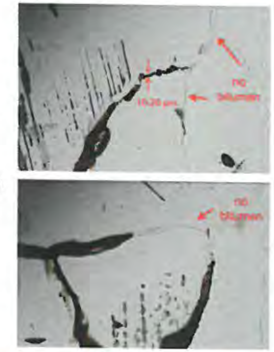


Bitumen and asphalt

Concept "Soft Core + Hard Shell"
Sealing Performance of Bitumen in the Contact Zone and in the EDZ



- Steady pressure (1.1 MPa) over long time (several weeks) allows inflow
- All micro-cracks next to contour filled
- Air filled endings
- Corresponds to expected rheological behavior (viscosity at 20°C 1E7 Pa*s, see also Working package 5 – Numerical Calculations)



MgO-Concrete

Label C3 with long-term stable phase (3-1-8)

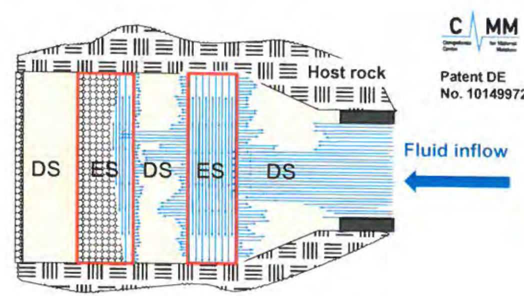
- In-situ test in rock salt (D = 1 m, L = 2 m)
- Start: June 2014
- Finish: January 2016
- Removal and sampling during the last months
- Ongoing analysis
- Composition:

MgO (active)	6.75 %
$MgCl_2$-Solution	15.83 %
Aggregate (incl. Quartz Flour)	77.42 %

+ Thermodynamically stable phase up to 80 °C and if concentration of Mg^{2+} in salt solution > 0.5 mol / kg H_2O
+ Low dT_{Max} (at adiabatic conditions: 54.7 K, during in-situ test 40 K)
+ Contact pressure at the rock salt contour > 2 MPa (measurement limit) at 2.5 mm/m expansion

– Stress Relaxation

Sandwich system for bentonite seal

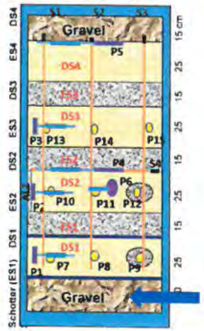


Multi-layer sealing system of bentonite (DS) and equipotential layers (ES)
→ Homogeneous wetting and swelling
→ Functionality independent of host rock

Sandwich system for bentonite seal

Semi-technical scale experiments

HTV-1 and HTV-4: shaft sealing



HTV-2 and HTV-3: drift sealing

Sandwich system for bentonite seal

- **Next Step:** Scheduling separate project for the in-situ test of a sandwich sealing system at the Mont Terri Test Site in Switzerland
- Target time: start in 2017 … 2018
- Proposer/Coordination: KIT-CMM, BGR, GRS

- Further partners:
  Swisstopo, ENSI, Nagra (Switzerland)
  TU Bergakademie Freiberg
  IBeWa, Freiberg
  Thomas Schmidt KG, Dornburg-Langendernbach

Summary

- Development of "shaft-impact-compactor" after successful large-scale test of compaction of crushed salt-clay-mixtures initiated
- Development of alternative Binary Mixture based on pellets and powder

- In-situ test for all types of bitumen/asphalt seals realized
- Measured system permeability is close to initial host rock permeability
- Bitumen penetrates EDZ and fills cracks

- First in-situ test of new MgO-concrete label C3

- Semi-technical scale experiments of bimodal bentonite sealing for a planned separate in-situ test at Mont Terri Site

Acknowledgements

Many thanks…

…to all colleagues and participating organizations:

…to the Federal Ministry for Economic Affairs and Energy (BMWi) and the Project Management Agency Karlsruhe (PTKA) of the Karlsruhe Institute of Technology (KIT) for funding the R&D project


DBE TEC
Thank you
for your attention.
P. Herold - 08/2016
US/D Workshop
Washington, USA, Sept. 7-9, 2016
21
DBE TEC

Asse II Mine – Retrieval of the Waste Taking into Account the Best Possible Emergency Preparedness

Matthias Mohlfeld
Federal Office for Radiation Protection (BfS), Germany

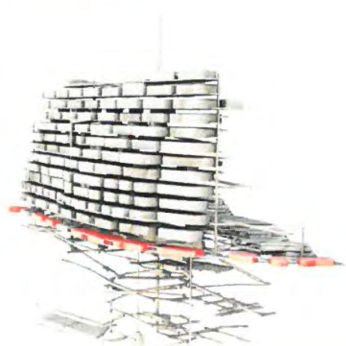
Washington, DC
September 7-9, 2016

Key Data

Asse II mine

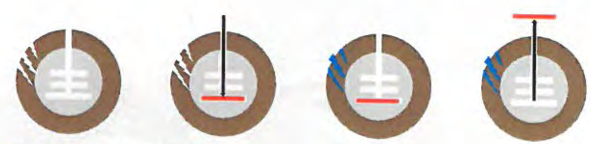
- Waste emplacement: 1967-78
- Low and intermediate level waste
- Brine inflow from the overburden rock since 1988
- Intended option for decommissioning: Retrieval

The Mine



A "research mine" that should never have been used for the disposal of radioactive waste.

Four Steps - One Problem.



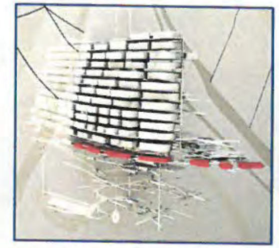
The Asse II mine. The fault. The problem. The task.

Asse II – The Mine

The Asse II mine. The fault. The problem. The task.

Mining vs. Disposal

Purpose of mines



Maximal extraction of raw materials

Purpose of repositories

Safe enclosure of radioactive waste

The Asse - A Salt-Mining Region

Asse II – The Fault

The Asse II mine. The fault. The problem. The task.

Emplacement

Period

1967 – 1978

Volume

125,787 waste packages / ca. 47,000 cubic meters

Type of waste

Low- and medium-level radioactive waste

9

Asse II – The Problem

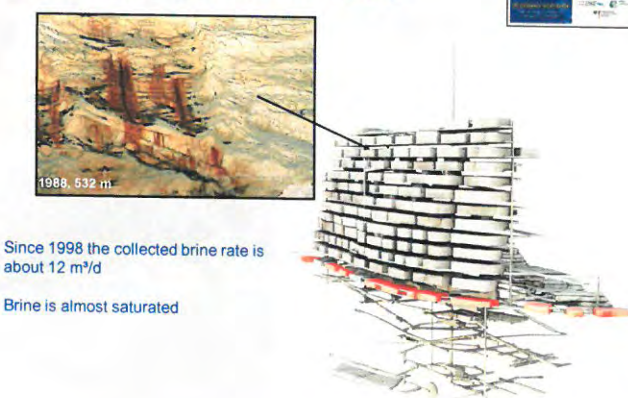
The Asse II mine. The fault. The problem. The task.

10

The Mountain Is Moving

11

Inflow of Brines since 1988



Since 1998 the collected brine rate is about 12 m^3/d

Brine is almost saturated

12

Asse II – The Task

The Asse II mine. The fault. The problem. The task.

13

Decommissioning According to the Atomic Energy Act (AtG)

2009

§ 57b AtG

„The Asse II mine shall be decommissioned immediately."

2009 - 2010

Retrieval **Relocation** **Backfilling**

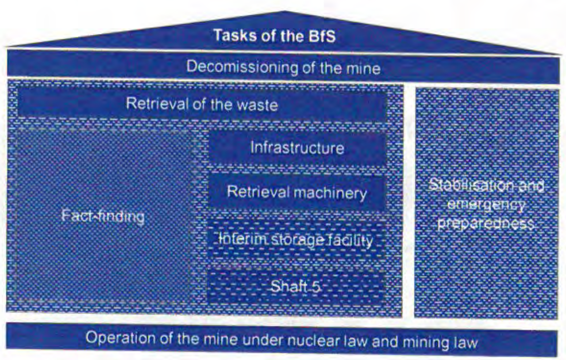
2013

§ 57b AtG

„The Asse II mine shall be decommissioned immediately. […]
The Asse II mine shall be decommissioned after the retrieval of the radioactive waste."

14

Tasks of the BfS



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Stabilisation and Emergency Preparedness -

Measures to stabilise the mine openings and to protect the emplacement chambers:

- *to continue safe operation*
- *to maintain the integrity as best as possible*
- *to achieve the best possible emergency preparedness in the event of an increase in brine inflow*
- *to keep the basis for the retrieval of the waste*

Prepatory measures for fast reaction in the event of an emergency:

- *for fullfilling the waste chambers*
- *for flooding the mine with saturated brine*
- *for stabilizing the mine with compressed air*
- *for the shaft closures*

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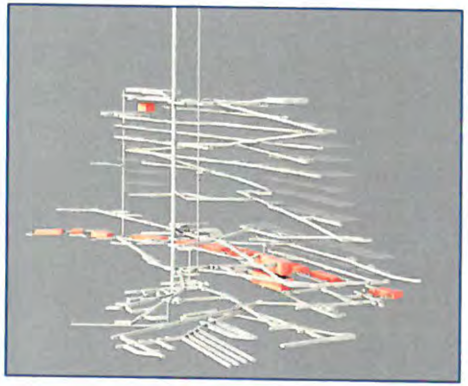
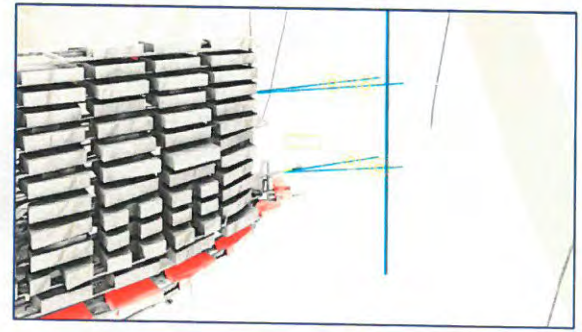
The Mine Today



Exploration Shaft 5



Interim Storage Facility

Demands and Contradictions

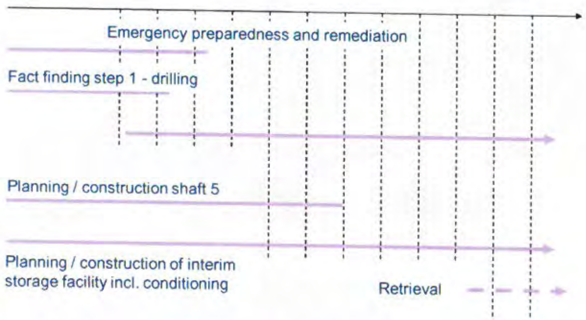
Retrieval? - Immediately!

Disposal at Konrad Repository? - No!

Interim storage facility? - Nimby!

Retrieval? - Mission impossible!

Asse Decommissioning Project – Time Schedule



"Lex-Asse": Retrieval legally laid down as decommissioning option to be pursued.
Enables parallel action (to invest before the results of the fact finding are available)

21

Thank you!

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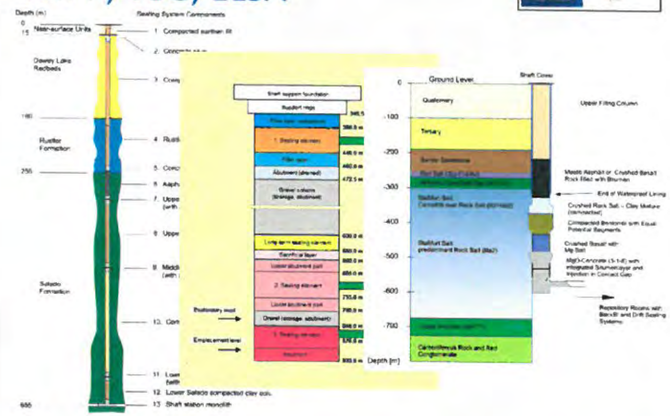
7th US/German Workshop on Salt Repository Research, Design, and Operation

Discussion on key technical issues regarding plugging and sealing

Nina Müller-Hoeppe, Klaus Wieczorek
DBE TEC / GRS, Germany

Washington, DC
September 7-9, 2016

Shaft sealing concepts: WIPP, VSG, ELSA



Common sealing materials

- Various types of concrete (salt conc., sorel conc., ...)
- Clay (bentonite)
- Asphalt/bitumen
- Crushed salt, possibly with added brine or clay

- Concrete materials are also envisaged for drift seals (German repository concept)

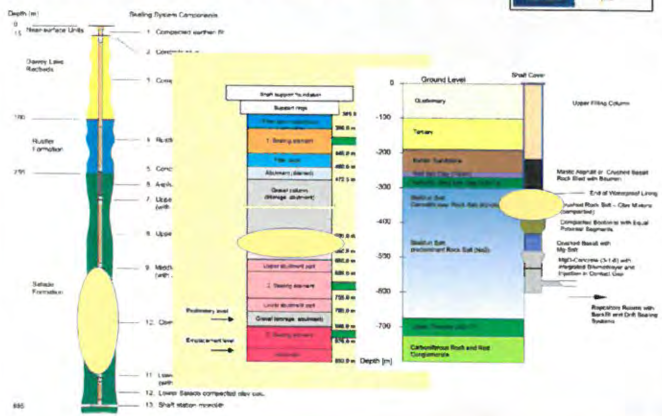
- Crushed salt is also backfill material and takes an important safety functions in the operational phase as well as long-term (sealing function in the German concept)

Important questions regarding technical barriers

- Shaft and drift seals
  - Construction of concrete components
  - Long-term stability / corrosion
  - Resaturation of clay components
  - Reconsolidation (crushed salt)
  - Evolution of disturbed rock zone
  - Evolution of contact zone

- Backfill
  - Reconsolidation – time frame and prediction
  - Hydraulic properties at low porosity, two-phase flow

Crushed salt in shaft seals



Crushed salt in recent perception

- New German safety requirements for HLW (2010)
  → crushed salt backfill takes important barrier function
- REPOPERM projects (2009, 2016)
- Preliminary safety analysis Gorleben (2012)
  → Process understanding/modelling capability of
  - reconsolidation of crushed salt backfill
  - transport properties at low porosities
  - Two-phase flow behaviour in consolidating crushed salt
- Salt reconsolidation – principles and applications (2014)
- DAEF initiative on crushed salt reconsolidation (now!)

DAEF initiative

- Objective
  - Develop strategy for reliable prediction and assessment of crushed salt reconsolidation and hydraulic impact
- Approach
  - Inventory and evaluation of existing experimental data and material models
  - Identification of shortcomings
  - Recommendations for database completion and model development/ validation
- Partners
  - BGR, DBE TEC, GRS, IfG, TUC
- Paper in preparation („Draft 0" available)

Results in a nutshell

- Existing experimental database is not sufficient for the task of model validation
  - Main problems: test conduction, precise kowledge of actual stress state (in oedometer tests), accuracy of porosity measurement at high reconsolidation, sample pre-treatment
  - Many tests in the medium porosity range, not in the low-p. range

  → Need appropriately designed tests for model validation/calibration
- Many material models available, but...
  - Zhang, Sjaardema/Krieg, Hein, Olivella/Gens, Heemann, ...
  - Most of the models are currently implemented, they are at best partially validated, not all required phenomena are implemented

Comments of the German Association for Repository Research (DAEF)

Till Popp, Wolfgang Minkley
Institute for Geomechanics GmbH (IfG)

Washington, DC
September 7-9, 2016

2

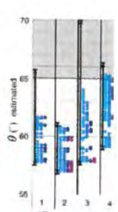
Ghanbarzadeh et al., 2016 - What is the explosive?

IfG

✓ **The study confirms already existing observations of Lewis & Hollnes (1996), but ...**

❖ *The low permeability of static rock salt is due to a percolation threshold.* ✓

- *However, deformation may be able to overcome this threshold and allow fluid flow.*
- *The observed hydrocarbon distributions in rock salt require that percolation occurred at porosities considerably below the static threshold due to deformation-assisted percolation.*
- *Therefore, the design of nuclear waste repositories in salt **should guard against deformation-driven fluid percolation**. In general, static percolation thresholds **may not always limit fluid flow in deforming environments.***



➢ Sophisticated analysis is needed to proof if the **integrity of the geological barrier salt is really violated according to this thesis**

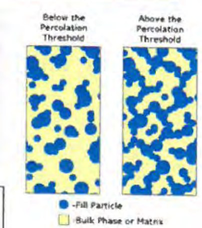
➢ **Why are Hydrocarbons inside salt?**

3

Percolation threshold – Evaluation of salt barrier Integrity

IfG

Percolation threshold is a mathematical concept related to percolation theory, which is the formation of long-range connectivity in random systems. Below the threshold a giant connected component does not exist; while above it, there exists a giant component of the order of system size.
https://en.wikipedia.org/wiki/Percolation_threshold



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

➢ This corresponds:

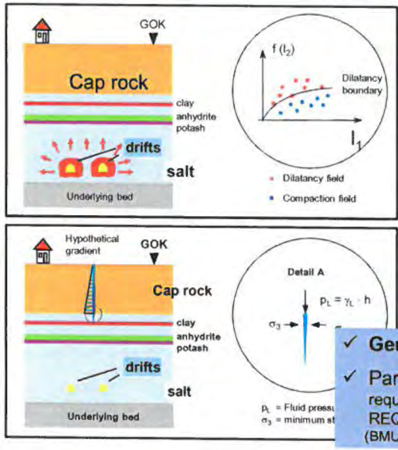
(1) at deviatoric conditions with the **dilatancy boundary** and

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

4

Geomechanical proof of the salt barrier integrity

IfG



Dilatancy criterion

Minimum stress criterion

- ✓ **Generally accepted!**
- ✓ Part of the integrity analysis, as requested by the GERMAN SAFETY REQUIREMENTS (BMU, 2010)

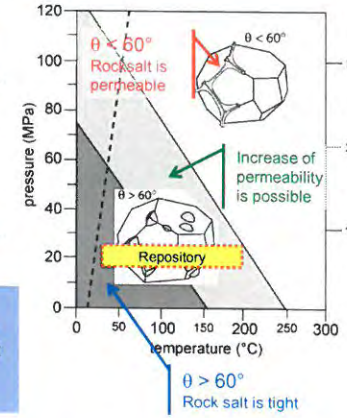
A 3rd threshold ? The dihedral angle θ for the salt-brine system

IfG

PT-dependent change of the wetting properties between brine and salt :

- Change of the wetting angle – development of connected pore channels along triple junctions (Lewis & Holness, 1996).
- Increase of the permeability up to 10^{-16} m² (Schleder et al., 2007).

✓ **Well known theory, but neglected because the pT-conditions are not relevant for a salt repository (e.g. VSG)**



6

The material tested vs. natural salt

IfG

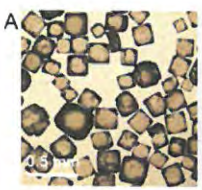


Table salt: Grain sizes: 200 – 400 µm

Composition: analytical grade halite (99.9% pure)

For each experiment, about **150 mg** of halite and **7-15 mg** of distilled water used

⇒ Water will dissolve salt

⇒ **4,5 – 9 wt.-%** correspond to **7 – 16 Vol.-%** = brine filled porosity of the condensed material

Natural rock salt (e.g. bedded salt Harlingen)

Grain sizes: < 1 mm ... 10 mm ... 1dm

Composition: > 90% Halite, anhydrite, clay, accessoric minerals

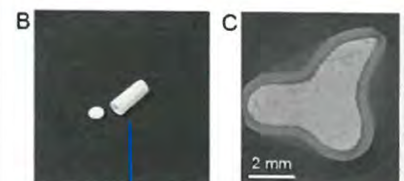
⇒ Water content, usually **0,1 – 1 wt.-%**

✓ **The grain scale distributions and the water content are not realistic!**

7

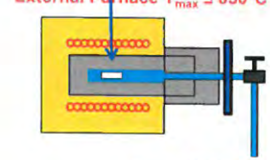
The experimental approach – Undrained Hydrostatic Experiment

IfG



Teflon capsule and covered with a Teflon lid

External Furnace $T_{max} \leq 850°C$



p_{max} = 400 MPa

- The teflon capsule is positioned inside a platinum tube (5 mm outer diameter) in a
- Pressure vessel: 20 to 100 MPa; 100 to 275°C
- **Quenched to room conditions** within 1 minute, i.e. putting the autoclave in water

✓ **Grain boundary opening due to unloading effects respectively thermal shrinking**

Hydro-thermal autoclaves with ovens

8

The texture investigation method - Pore-Scale Imaging

Equilibrated salt-brine structure, reconstructed from X-ray micro-tomographic images of synthetic salt sample scanned by 1.1µm resolution. Each side of the cube corresponds to 660µm. left: Salt grain separation using watershed algorithm. right: medial-axis or skeleton of pore space. (source: https://sites.google.com/a/utexas.edu/ghsoheil/research)

University of Texas High-Resolution X-ray Computed Tomography Facility

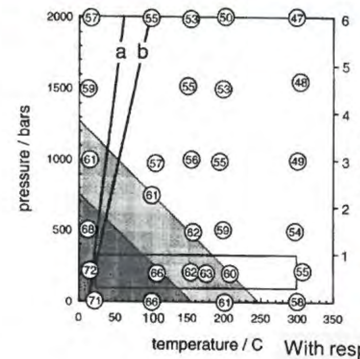
Zeiss (formerly Xradia) microXCT 400 scanner:

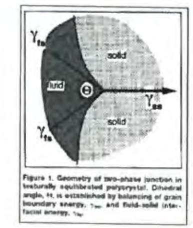
- 3D resolution to ca. 1.1 µm pixel
- Image analysis:
  - Reduction of noise level
  - Converting grayscale image data into segmented images
  - Filtering the segmented data
  - Quantification and post processing
- **Pore space topology and connectivity**
- **Estimate of the Dihedral Angle**

✓ **It's an indirect method which quality depends on the data evaluation ...**

9

The original data sets from Lewis and Hollnes (1996)





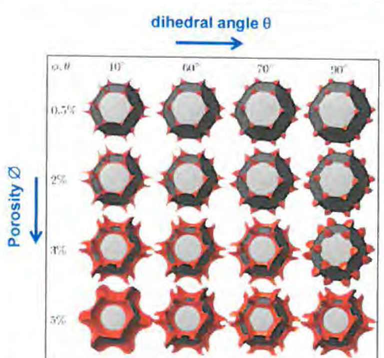
✓ **The pore property changes described by the dihedral angle are small !!**

With respect to experimental artefacts due to grain boundary opening ..

- **What is the reliability of the estimate of the Dihedral Angle?**

10

The static pore-scale theory - influence of porosity /water content?



Modeling of Textural Equilibrium using synthetical 3D-networks indicates that independently from the dihedral angle connectivity of pores depends on porosity (respectively the amount of brine)

✓ Under consideration of natural salt properties the observed phenomena are probably not realistic, **mainly due to the unusual high water content realized in the experiments**

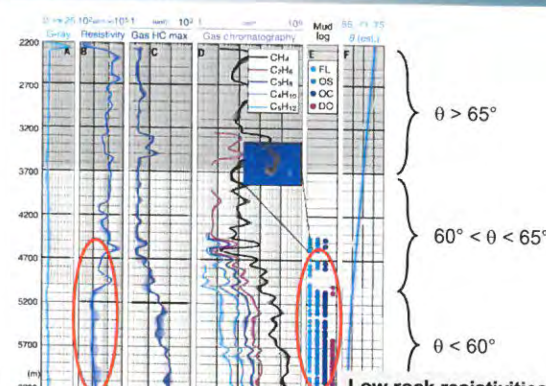
Soheil Ghanbarzadeh

WHAT STARTS HERE CHANGES THE WORLD

(source: https://sites.google.com/a/utexas.edu/ghsoheil/research)

11

Experiment vs. Nature: salt from drill holes

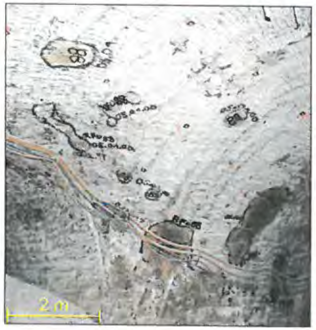


Petrophysical observations in wells - Occurence of HC in salt

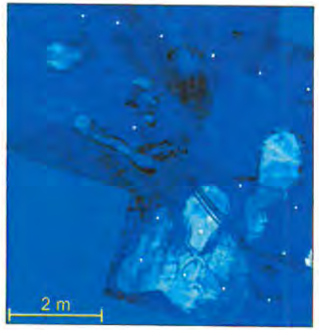
Low rock resistivities and occurence of HC may give hints for fluid-connected pore space due to percolation

Occurence of hydrocarbons in the salt dome Gorleben (1)

Artifical light

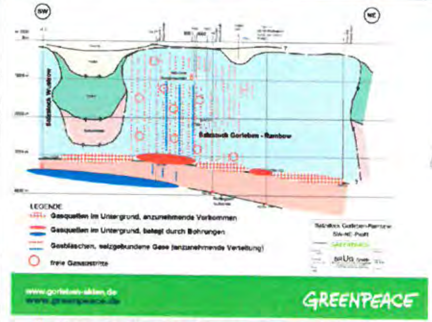


UV-Light



13

Occurence of hydrocarbons in the salt dome Gorleben (2)

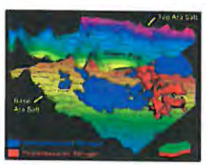


- **Conclusion in Greenpeace (2010) –** Hydrocarbons below a salt deposit contradict against a repository because the fluids will migrate through the salt ⇒ **no long-term safety**

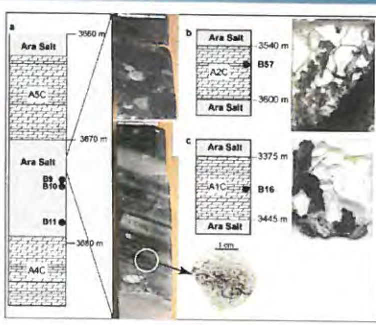
Presentation of J. Hammer (BGR)

14

Observations on ARA salt cores from the OMAN Salt basin



Schoenherr, J., J.L. Urai, P. Kukla, R. Littke, Z. Schleder, J.-M. Larroque, M. Newall, N. Al-bry, H. Al-Siyabi, and Z. Rawahi (2007): Limits to the sealing capacity of rocksalt: A case study of the **Infra-Cambrian Ara Salt from the South Oman Salt Basin**: AAPG Bulletin, v. 91/11, p. 1541-1557.



- Salt is impregnated by oil / bitumen
- contact between carbonate stringers / salt

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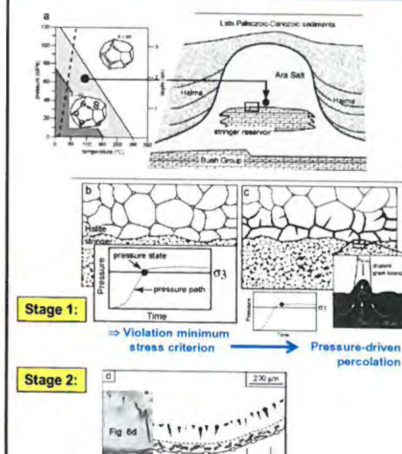
Cartoon of the mechanism of diffuse dilatancy of ARA salt



from Schoenherr et al., 2007

Stage 1: **Diffuse dilation of salt**

- Evidence for decompaction and local damage during uplift
- **Over-pressurisation of Stringer fluids**

⇒ violation of the minimal stress criterion

⇒ Pressure-driven percolation

Stage 2: **Re-sealing**

- After the oil pressure dropped to values equal to s3 in the rock salt **(initial situation)**
- The micro-scale deformation mechanisms (dislocation creep and fluid-assisted grain-boundary-migration recrystallization) results in re-sealing of the fluids

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Is the PT-dependent dihedral angle θ – threshold real?

IfG Kármán pressure cell:

- σ_3 – max = 1000 bar
- T up to 120°C
- Hydrostatic / deformational conditions
- Sample size (natural salt)
  - Length 200 mm
  - Diameter 100 mm
- **Permeability testing with**
  - Gas, brine and oil

✓ Preliminary test results are available

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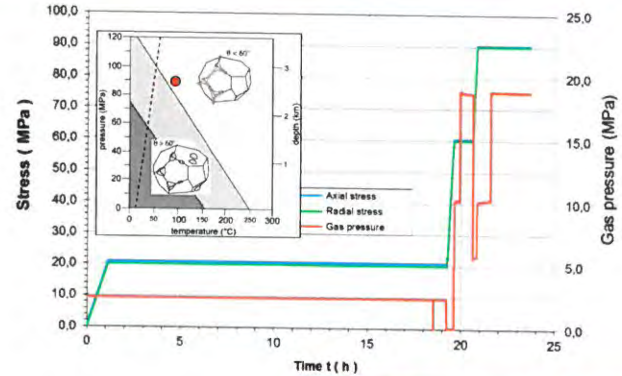
Preliminary lab test results at T = 97°C and increasing confinement



✓ No gas flow was detected!
✓ Resolution better than 10^{-20} m².

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„Deformation assisted fluid percolation in salt"

Conclusions

My personal opinion,

it is a well written and interesting paper but the authors wanted to amplify the public interest by including aspects of nuclear waste storage.

However, there are some remarks regarding the conclusions:

- Sample size and water content are not appropriate to natural salt
- The thesis, that salt becomes permeable if the dihedral angle becomes lower than 60° is only based on theoretical models.
- Porosity resp. fluid content is an important parameter for the porespace network, but not discussed by the authors in the paper.
- The occurence of hydrocarbons is not always an indication of permeability (autochthonous origin is possible)
- It is a well known fact that salt can become permeable so that fluids can migrate through it (especially during the diagnesis or salt dome uplift), but the dilatancy and minimal stress criterion are sufficient to explain the acting processes.

As summary, from our point of view, the integrity of salt as host rock for storage of radioactive waste is out of question.

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Impact of retrieval requirements on repository design

– Results of R&D project funded by BMWi (PTKA) –

Philipp Herold, Sabine Dörr, Eric Kuate Simo, Wilhelm Bollingerfehr, Wolfgang Filbert
DBE TECHNOLOGY GmbH

Washington, DC
September 7-9, 2016

Contents

Final Disposal in Germany

- Disposal in deep rock salt formations was the preferred option for the last decades
- Summer 2013: German parliament (Bundestag) passed new law for restart of site selection process for HLW repository and implemented commission "Storage of HLW"

Exploration Mine Gorleben (DBE, 2016)

Final report commission "Storage of HLW":

- Recommends disposal of HLW in deep geologic formations with the possibility of retrieving waste packages as preferred option in Germany
- Determined site selection criteria, considering salt, clay, crystalline rock as potential host rocks
- Prepared a roadmap for site selection process, which will start in 2017

Retrievability – Regulations

Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste

Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste:

- Mandatory for the design, further exploration, construction, emplacement operations and decommissioning of HLW/SF repository
- Compliance has to be demonstrated (in a verifiable way)
- Demonstration of technical feasibility before or during licensing
- Stipulate retrievability as a design criterion

"Retrievability is the planned technical option for removing emplaced radioactive waste containers from the repository mine."

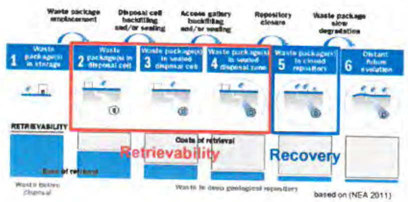
"During the operating phase up until sealing of the shafts or ramps, retrieval of the waste containers must be possible."

Safety Requirements

"The number of open emplacement zones should be kept to a minimum. These should be **promptly loaded, then backfilled** and reliably sealed from the mine building."

→ Operations of emplacement, backfilling, and sealing take place in parallel during complete operational period

"Measures taken to secure the options of recovering or retrieval **must not impair the passive safety barriers and thus the long-term safety.**"



Retrieval Strategy

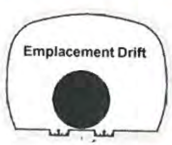
- In the framework of R&D projects (funded by German Federal Ministry for Economic Affairs and Energy), DBE TECHNOLOGY GmbH developed a suitable strategy and technical solutions to retrieve waste packages
- Focus on underground operations
- Waste package management plan after retrieval does not exist

"Re-mining"-strategy:

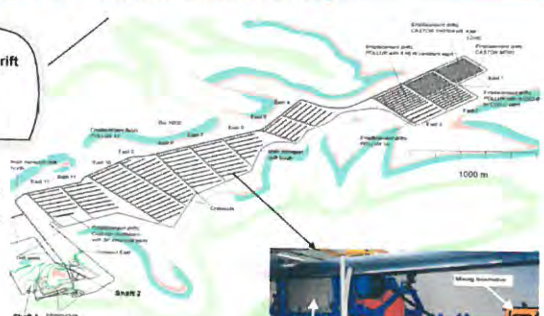
- Emplacement of waste containers, backfilling and sealing as designed
- Conceptual adaptations to facilitate retrieval and improve conditions during potential retrieval period without impacts on long-term safety
- In case of retrievability decision, excavation of new access drifts to the emplacement areas and waste packages, exposal and removal of the waste packages

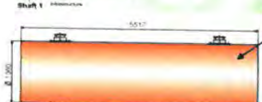
➢ **Transfer of the waste packages from the passive safety system of the repository back into human care**

Drift disposal – Emplacement concept



Emplacement of POLLUX® casks in 250-m-long blind-ending drifts





POLLUX® cask

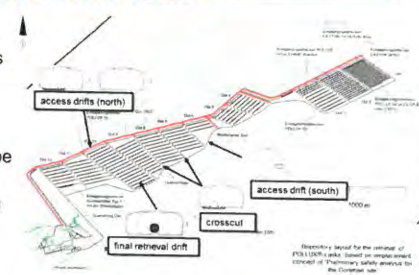
Prototype Emplacement Device

Drift disposal – Layout modifications

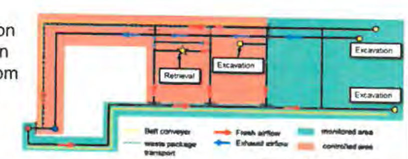
- Removal of all internals before backfilling of emplacement drifts (especially the rails)

During retrieval:

- All emplacement drifts have to be located between two crosscuts
- Additional access drift allows an increase in airflow (first cooling measure) and higher flexibility

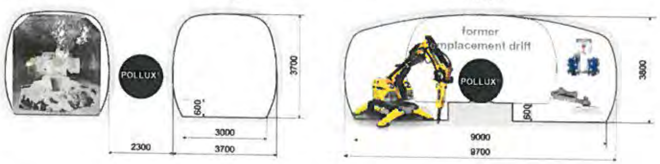


- Re-activation of radiation protection areas during re-excavation of main drifts and cross-cuts or release from controlled area before backfilling



Drift disposal – Excavation

Start of retrieval: **Final retrieval drift:**

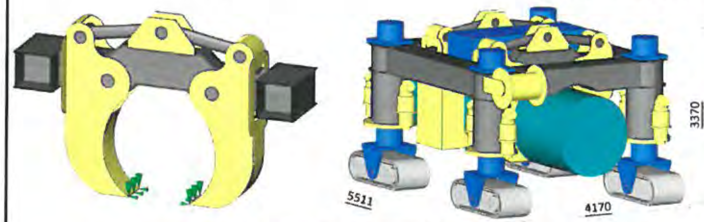


- Stepwise excavation of two sub drifts by means of road header
  - ➢ between two crosscuts
  - ➢ parallel to emplaced waste packages
  - ➢ floor 0.6 m below POLLUX®
- Removal of the remaining pillar and exposure of the POLLUX® cask by means of road header and (remote controlled) demolition robots
- Backfilling after complete retrieval

Drift disposal – Equipment modifications

- Retrieval without rebuilding of rails
  - ➢ automotive drive necessary
- Usability of trunnions after emplacement not guaranteed
  - ➢ alternative bearing structure necessary
- POLLUX® casks lie on a salt base/socket
  - ➢ reduces lifting height

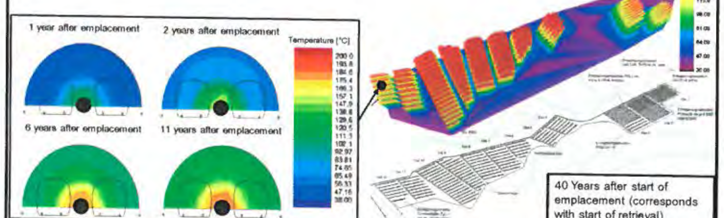
Prototype Emplacement Device



Feasibility Study for Modified Emplacement Device

Drift disposal – Thermal input

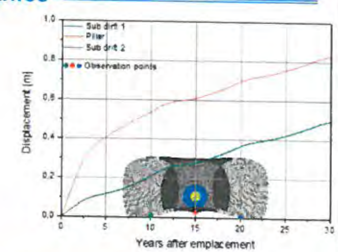
- 200°C design temperature at waste package surface, optimized to densest disposal of waste packages
- Barely manageable conditions inside the access drifts, cross cuts
- Retrieval operation coincides with thermal maximum inside the emplacement fields
- Excavation inside the emplacement fields hardly manageable because of very high technical cooling effort, necessary cooling breaks and geo-mechanics

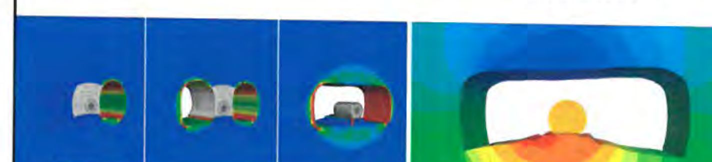


40 Years after start of emplacement (corresponds with start of retrieval)

Drift disposal – Geo-mechanics

- High temperature accelerates salt creep and produces high geo-mechanical stress
- Rise of former drift floor
- High convergence calls for drift re-cutting
- Additional wall and roof stabilization needed





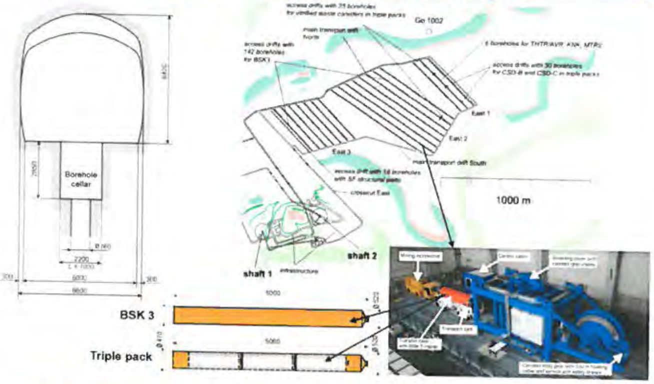
Failure criterion, at excavation of sub drifts 1, 2 and pillar

Displacement, 30 days after complete excavation

Drift disposal – Conclusions

- Retrieval process is designed for total exposure of the POLLUX®-10 casks
- Modified emplacement device with rail-less drive and with new bearing structure
- Thermal input due to densest packaging of the POLLUX®-10 casks produces high rock temperatures and high geo-mechanical stress
- Optimization of thermal repository design would improve conditions during potential retrieval period but increase repository footprint
- Requirement of retrievability changes repository design significantly

Borehole disposal – Emplacement concept



Test facility for borehole disposal of spent fuel canisters with one dummy canister → Unintentional demonstration of canister retrieval

Borehole disposal – Design impacts

Conceptual adaptions from "Preliminary safety analysis for Gorleben site" (based on nse GmbH):

- new canister shape (BSK-R)
- steel liner designed for rock pressure
- non-compactable and incompressible backfill
- stepwise emplacement and backfilling

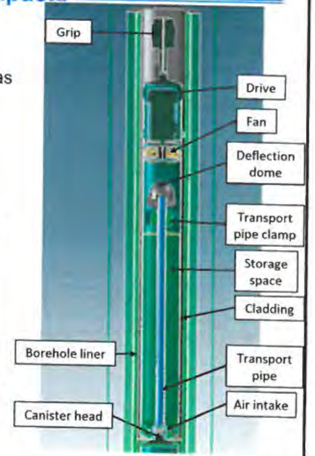
Retrieval concept:

- layout of retrieval drifts corresponds to emplacement drifts
- two parallel drifts in the south improve operation and ventilation
- retrieval corresponds to reversal of emplacement process
- steel liner remains in borehole after retrieval
- removal of backfill (quartz sand) as major technical challenge during retrieval
- development of a suction device

Borehole disposal – Design impacts

Feasibility study on suction device:

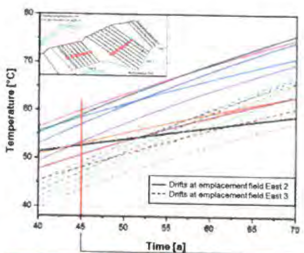
- Remove backfill to free head of the BSK-R
- Suction device with same outer dimensions as BSK
- Integrated drive, fan and storage space
- Two suctions steps per BSK-R
- First pilot tests for air intake design

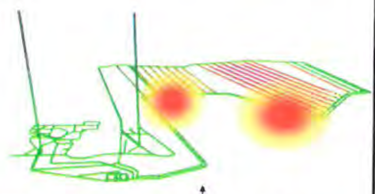


Borehole disposal – Thermal input

Thermal conditions:

- Heat sources below mine level
- Temperatures above 100°C just next to the boreholes
- Steady increase of rock temperature during retrieval period
- Moderate total heat input inside the mine openings expected
- Third main drift improves ventilation conditions and allows higher flexibility
- Additional cooling equipment during excavation necessary





Borehole disposal – Conclusions

- Retrieval process corresponds to reversal of emplacement process
- Unintentional demonstration of canister retrieval at existing test facility
- New suction device for backfill removal, demonstration of technical feasibility still open
- Steady increase of rock temperature but moderate total heat input expected
- No layout modifications necessary

Summary

- Retrievability is required during complete operational period as licensing permission
- Thermal input of the waste will influence retrieval concept and to a certain extent repository design
- Requirement of retrievability could change repository design significantly
- Retrievability is compatible to German safety concept for high-level radioactive waste repository in salt formations
- Technical feasibility of all retrieval concepts and techniques has still to be demonstrated

Thank you for your attention.

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U.S. Deep Borehole Disposal Program for DOE Managed Waste

Timothy C. Gunter
Federal Program Manager, Disposal R&D
Office of Used Nuclear Fuel Disposition R&D

7th US/German Workshop on Salt Repository Research, Design, and Operation
Washington, D.C.
September 7-9, 2016

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Outline

- Office of Nuclear Energy/Fuel Cycle Technologies
- Used Nuclear Fuel Disposition
  - Integrated Waste Management System
  - Used Nuclear Fuel Disposition R&D
- Deep Borehole Disposal
- Conclusions

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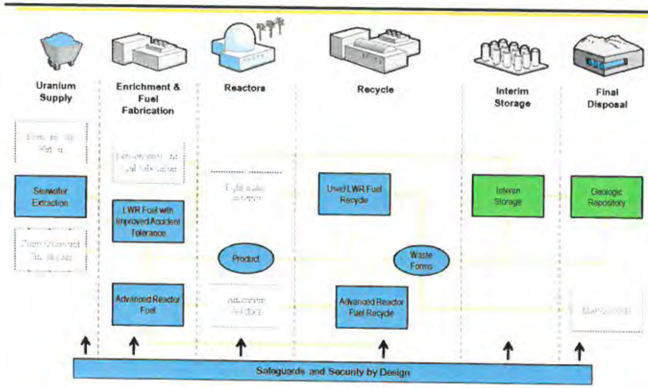
Focus Areas of DOE Fuel Cycle Technologies



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Sources of Nuclear Waste

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How Did We Get Here?

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The Administration's Strategy

"With the appropriate authorizations from Congress, the Administration currently plans to implement a program ... that:

- Sites, designs and licenses, constructs and begins operations of a **pilot interim storage facility** ... with an initial focus on accepting used nuclear fuel from shut-down reactor sites;
- Advances toward the siting and licensing of a **larger interim storage facility** ... that will have sufficient capacity to provide flexibility in the waste management system and allows for acceptance of enough used nuclear fuel to reduce expected government liabilities; and
- Makes demonstrable progress on the siting and characterization of repository sites to facilitate the availability of a geologic repository"

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Used Nuclear Fuel Disposition Mission

- **Develop and implement the design of an integrated waste management system (IWMS) in support of the Administration's strategy for the management and disposal of spent nuclear fuel and high-level radioactive waste.**
- **Conduct generic research and development (R&D) activities related to used nuclear fuel (UNF), nuclear waste management, and disposal issues.**

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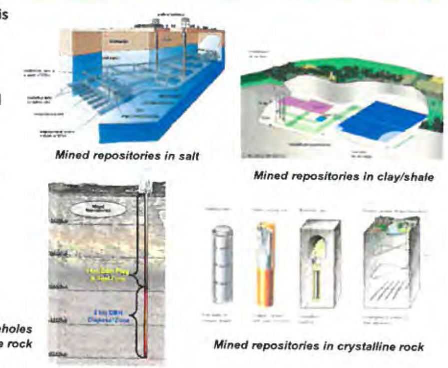
Disposal R&D (Long Term)

- Provide a sound technical basis for multiple viable disposal options in the US
- Increase confidence in the robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation
- Leverage international collaborations



Mined repositories in salt

Mined repositories in clay/shale

Deep boreholes in crystalline rock

Mined repositories in crystalline rock

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Deep Borehole Disposal Concept

- Deep borehole disposal of high-level radioactive waste has been considered in the U.S. and elsewhere since the 1950s and has been periodically studied since the 1970s
- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth
- Waste canisters would be emplaced in the lower 2,000 meters of the borehole
- Upper borehole would be sealed with compacted bentonite clay, cement plugs, and cemented backfill

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Deep Borehole Disposal Concept

- 5,000 m deep borehole(s) in crystalline basement rock, well below fresh groundwater resources
- Waste canisters in lower 2,000 m
- Seals in upper 3,000 m

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Deep Borehole Disposal Concept

Several factors suggest that the disposal concept may provide a technically feasible and cost-effective alternative for safe disposal of some DOE-managed waste forms:

- Crystalline basement rocks are common in many stable continental regions
- Existing drilling technology should permit dependable construction at acceptable cost
- Low permeability and long residence time of high-salinity groundwater in deep continental crystalline basement at many locations suggests very limited interaction with shallow fresh groundwater resources
- Geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides in the waste
- Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection

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Deep Borehole Disposal Concept
Why Deep Borehole Disposal?

- Potential for robust isolation
- Gives DOE the flexibility to consider options for disposal of smaller waste forms in deep boreholes
  - Potentially earlier disposal of some wastes than might be possible in a mined repository
  - Possible reduced costs associated with projected treatments of some wastes

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Deep Borehole R&D

- **Additional research and development is necessary in several important areas for further consideration of deep borehole disposal of radioactive waste, including:**
  - Evaluation of drilling technology and borehole construction to 5 km depth with sufficient diameter for cost effective waste disposal
  - Verification of deep geological, geochemical, and hydrological conditions at a representative location
  - Evaluation of canister, waste, and seals materials at representative temperature, pressure, salinity, and geochemical conditions
  - Development and testing of engineering methods for waste canister loading, shielded surface operations, waste canister emplacement, and borehole seals deployment

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Deep Borehole Field Test

- **The R&D objectives for deep borehole disposal are being met with a deep borehole field test (DBFT) that is conducted to a depth of 5 km in representative geology (without emplacement of radioactive wastes)**
  - Science thrust includes hydrogeological, geophysical, and geochemical investigations of deep borehole environment
  - Engineering thrust includes drilling, canister testing, simulated waste handling, simulated waste emplacement operations, seals design and closure, and operational retrievability

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Deep Borehole Field Test

- **Conducting a Deep Borehole Field Test**
  - Allows further evaluation of the feasibility of the deep borehole disposal concept
  - Is consistent with the UFD Mission
  - Implements a recommended near-term action of the *Blue Ribbon Commission on America's Nuclear Future* (BRC 2012)
  - Is consistent with the Administration's *Strategy for the Management and Disposal of used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013)
  - Economic and scientific benefits of a deep borehole field test are of interest and could be valuable to local, state, and regional stakeholders

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Deep Borehole Field Test

- **The DBFT includes the following major activities:**
  - Obtain a suitable test site
  - Design, drill and construct the Characterization Borehole to requirements
  - Collect data in the Characterization Borehole to characterize crystalline basement conditions and confirm expected hydrogeochemical conditions
  - Design, drill and construct the Field Test borehole to requirements
  - Design and develop surface handling and emplacement equipment systems and operational methods for safe canister/waste package handling and emplacement

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Deep Borehole Field Test
Acquisition of Site and Services

- Request for Information solicited input and interest from States, local communities, individuals, private groups, academia, or any other stakeholders who were willing to host a DBH Field Test
  - Posted to via Federal Business Opportunities (FedBizOps, www.fbo.gov) on October 24, 2014
  - Responses received on December 8, 2014 (45 days)
- Sources Sought and Draft Request for Proposal (RFP)
  - Posted on FedBizOps on April 7, 2015
  - Feedback received on May 5, 2015
- RFP (Solicitation Number DE-SOL-0008071)
  - Pre-solicitation notice posted on June 22, 2015
  - Final RFP posted on FedBizOps on July 9, 2015
  - DBFT contract awarded on January 5, 2016

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Deep Borehole Field Test
Acquisition of Site and Services

- Initial RFP/Award did not establish a suitable test site
- Final RFP (Solicitation Number DE-SOL-0010181)
  - Pre-solicitation notice posted on August 5, 2016
  - Final RFP posted on FedBizOps on August 22, 2016
  - Proposals due October 21, 2016
  - Contract award anticipated in early 2017

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Potential Wastes for Deep Borehole Disposal

- Several DOE-managed small waste forms are potential candidates for deep borehole disposal (SNL 2014) including some DOE spent nuclear fuel, high-level radioactive waste, or other specialized waste types
  - Cesium and strontium capsules. 1,936 cesium and strontium capsules stored at the Hanford Site
  - Untreated calcine HLW currently stored at the Idaho National Laboratory in sets of stainless steel bins within concrete vaults
  - Salt wastes from electrometallurgical treatment of sodium-bonded fuels could be packaged in small canisters as they are produced
  - Some DOE-managed SNF currently stored in pools at DOE sites
- Commercial SNF is not being considered
- DOE has made no decision to dispose of any waste in deep boreholes

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Conclusions

- Evaluation of the feasibility of deep borehole disposal Is consistent with the Administration's Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste
- Conducting a Deep Borehole Field Test Implements a recommended near-term action of the ***Blue Ribbon Commission on America's Nuclear Future***
- Several DOE-managed small waste forms are potential candidates for deep borehole disposal
- The next step in evaluating this disposal option is a Deep Borehole Field Test
- DOE had made no decision to dispose of any waste in deep boreholes

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Questions

Questions/Comments?

Additional information at
www.energy.gov

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References

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- DOE (U.S. Department of Energy) 2013. *Strategy for the Management and Disposal of used Nuclear Fuel and High-Level Radioactive Waste*, January 2013
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7th US/German Workshop on Salt Repository Research, Design, and Operation

Issues on Aging of Spent Fuel Storage Systems

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SAND2016-8277 C

Contents

- Background of SNL-BAM collaboration
- BAM research activities associated with extended interim storage issues and aging management
- SNL activities associated with extended interim storage issues and aging management

Background of SNL-BAM collaboration

- SNL and BAM collaborate in the areas associated with the back-end of the commercial nuclear fuel cycle; specifically on packaging, transportation, and storage of spent nuclear fuel.
- A Memorandum of Understanding (MOU) between SNL and BAM was established by 2012. Bilateral meetings/workshops take place twice a year.
- Extended interim storage of spent fuel and HLW needs to be addressed as a major issue in both countries due to delayed disposal siting procedures.
- Various technical issues concerning degradation effects of casks and inventories during extended periods of interim storage have been identified and specific investigations are being performed.

BAM Research Activities

- BAM Research Activities related to Extended Interim Storage Issues
- BAM Seal Investigations
  - Metal Seal Systems
  - Elastomer Seal Systems
- Polymer Degradation Effects investigated by BAM

BAM research activities related to extended interim storage: General remarks

- The need for the extended interim storage of SNF and HLW casks towards disposal implicates additional challenges for the nuclear waste management strategy in Germany.
- Improved knowledge and data bases about the long term performance of casks and their inventories is essential for future extended storage licenses.
- Recently, governmental research programs have been adjusted in Germany to address technical and scientific issues in this area.
- BAM has identified the need for demonstrating the extended long term performance of seals and polymers used in dual purpose casks and has already initiated specific R&D programs. Additional or extended R&D programs are scheduled.

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BAM research activities related to extended interim storage (1)

Long term performance of metal seals, elastomeric seals, and polymers for neutron shielding purposes

- Preliminary investigations and laboratory tests performed by BAM for many years
- Project **"LaMEP"** (Long term investigations on **metal seals, elastomer seals**, and **polymers**) funded by BMWi/GRS for 3 years (2015-2018).

  Major Goals are:
  - Extension and continuation of initial test series to gain further systematic material data,
  - Development and validation of analytical approaches for the extrapolation of selected material or component properties to longer periods of time.

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BAM research activities related to extended interim storage (2)

Project „New Developments in the Long term Dry Interim Storage of Spent Nuclear Fuel and Vitrified High-Level Waste“

- **Funded by BMUB for 3 years (2015-2018)**
  Project Lead: GRS   Sub-contractors: BAM and Öko-Institut
- **Main topics:**
  1. State of the art and review of national and international developments in interim storage of spent nuclear fuel and HLW
  2. Aging management
  3. International activities
  4. Non-accessible areas (cask inventories)
  5. Organizational and ethical aspects
- **BAM key topics:**
  - National and international regulations and guidance
  - Aging Management: technical aspects, integrated approach, gap analyses
  - Evaluation of international activities in the area of long term dry interim storage

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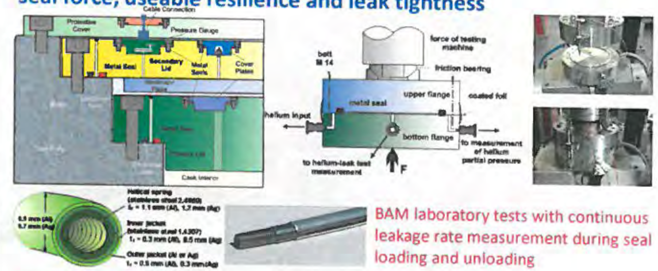
BAM metal seal investigations (1)

Long term performance of Helicoflex® metal seals concerning seal force, useable resilience and leak tightness



BAM laboratory tests with continuous leakage rate measurement during seal loading and unloading

Test Parameters

Temperatures:	+20°C	+75°C	+100°C	+125°C	+150°C
Holding times since:	02/2009	01/2014	11/2010	01/2014	02/2009
Seal type	Al + Ag	Al + Ag	Al + Ag	Al + Ag	Al + Ag

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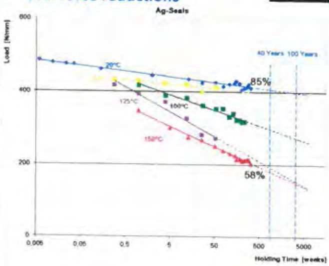
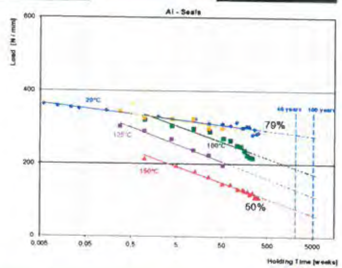
BAM metal seal investigations (2)

Restoring seal force (Load F_r) reduction depending on holding time and temperature

Major outcome so far:
Seal function and leak tightness are not affected by seal force reductions

Computer tomography scan of an Al-seal after 3 months at 150°C





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BAM elastomer seal investigations (1)

Relevance for:

- **Auxiliary seals in spent fuel and HLW casks**
- **Primary seals in LLW/ILW casks**

Major topics:

1. Investigation of the low temperature behavior down to -40°C

Results published by Matthias Jaunich, Wolfgang Stark, and Dietmar Wolff:

- *Low Temperature Properties of Rubber Seals* Kgk-Kautschuk Gummi Kunststoffe, 2011. **64**(3): p. 52-55.
- *A new method to evaluate the low temperature function of rubber sealing materials* Polymer Testing, 2010. **29**(7): p. 815-823.
- *Comparison of low temperature properties of different elastomer materials investigated by a new method for compression set measurement* Polymer Testing, 2012. **31**(8): p. 987-992.

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OPT2

BAM elastomer seal investigations (2)

2. Aging of elastomer O-rings under thermo-mechanical loads

Investigation program with selected rubbers (HNBR, EPDM and FKM) tested as O-rings with an inner diameter of 190 mm and a cross sectional diameter of 10 mm since May 2014.

The O-rings are oven-aged at four different temperatures (75 , 100 , 125 , 150 °C). They are examined after various times between one day and 5 years.

- ➢ In order to be able to compare between compressed and relaxed rubber, the samples are aged in their initial O-ring state (Fig. 1)
- ➢ As well as compressed between plates (Fig. 2) with a deformation of 25 % corresponding to the actual compression during service
- ➢ Furthermore, we are aging samples in flanges that allow leakage rate measurements (Fig. 3).

Fig. 1 Undeformed O-rings

Fig. 2 Half O-rings compressed between plates

Fig. 3 O-ring in flange for leakage measurements

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OPT3

BAM elastomer seal investigations (3)

Selected results from aging investigations of elastomer O-rings under thermo-mechanical loads

Kömmling A, Jaunich M, Wolff D, Effects of heterogeneous aging in compressed HNBR and EPDM O-ring seals, Polymer Degradation and Stability (2016), doi: 10.1016/j.polymdegradstab.2016.01.012.

- The test set-up can lead to heterogeneous aging caused by diffusion-limited oxidation (DLO) effects. These effects depend on material, dimensions, time and temperature. Heterogeneous aging results in distorted bulk properties such as compression stress relaxation and compression set (CS) suggesting that HNBR has better performance than EPDM at 150 °C but which is not the case at 100 °C.
- CS represents the resulting permanent deformation after the load is removed (CS=100% means no elastic recovery anymore).
- The presence of heterogeneous material properties due to thermo-mechanical aging was shown by hardness measurements across the seal cross-section.
- If DLO-affected data is excluded, extrapolations of CS data are possible using time-temperature shifts and Arrhenius graphs.
- According to the extrapolations to 23 °C, exemplary CS values of 50 % and 80 % would be reached after approx. 10 years and 29 years, respectively for HNBR and after approx. 400 years and 1100 years, respectively for EPDM.

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Polymer degradation effects investigated by BAM (1)

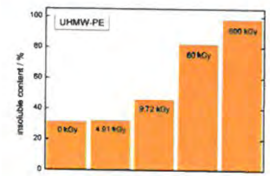
Basic requirement: Sufficient long term neutron radiation shielding without safety relevant degradation

Degradation effects to be considered:

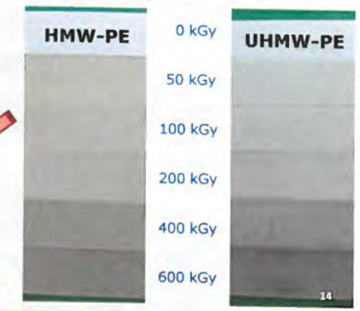
- Temperatures (max. 160 °C and decreasing during storage)
  - Thermal expansion
  - Structural changes from semi-crystalline to amorphous
- Gamma radiation (decreasing during storage)
  - Structural damages and/or crosslinking
  - Hydrogen separation
- Mechanical assembling stresses
  - Stress relaxation
- Gamma irradiation tests by BAM (at room temperature)
  - Low dose irradiation (60Co source): 0.5 – 60 kGy
  - High dose irradiation (conservative max. storage dose): 600 kGy

Polymer degradation effects investigated by BAM (2)

Exemplary outcomes for UHMW-PE show an increase of the insoluble, crosslinked fraction after high dose gamma irradiation



Further gamma irradiation tests with material blocks of 10*10*50 cm³



Further investigations planned:

- Thermal aging of(U)HMW-PE at elevated temperatures
- Combination of radiation and thermal aging
- Development of adequate prognostic methods to allow extrapolation of long term material performance

SNL activities associated with the BAM/SNL collaboration

- **DOE Program Objectives: Storage and Transportation R&D**
- **Closing the High Burnup Spent Fuel Cladding Technical Gap**
  - These activities are funded through the U.S. Department of Energy, Office of Nuclear Energy. BAM and SNL meet on a regular basis to collaborate on technical issues, and development and analysis of data
  - BAM and SNL are also collaborators on a DOE/Euratom sponsored International Nuclear Energy Research Initiative (I-NERI) entitled:

    Assessing the Integrity of High Burnup Spent Nuclear Fuel in Long Term Storage and Transportation

DOE Program Objectives: Storage and Transportation R&D

- Preparing for extended storage and eventual large-scale transport of spent nuclear fuel (SNF) and high-level waste (HLW)
- Developing the technical basis for:
  - Extended storage of used nuclear fuel
  - Fuel retrievability and transportation after extended storage
  - Transportation of high burnup used nuclear fuel

Closing the high burnup used fuel technical gap associated with fuel cladding

What is the fuel cladding issue?

- Reactor operations
  - Hydrogen is absorbed into the cladding
  - Fission gas build-up increases rod internal pressures → cladding hoop stress
  - Longer operating times and high burnup fuel (> 45 GWd/MTU) increase these effects
- Dry storage
  - The drying cycle creates a thermal spike that brings H back into solution
  - H precipitates preferentially with radial orientation under subsequent cooling and cladding hoop stresses
  - Degradation of cladding mechanical properties due to re-oriented hydrides
- Transportation loadings
  - Normal conditions of transport induce cladding stresses due to over-the-road (rail) loadings
  - Cladding integrity during transport needs to be demonstrated

Billone, "Update on Testing to Evaluate Radial Hydrides", U.S. NWTRB Meeting Presentation, Feb 17, 2016, ANL

Hanson, "DOE R&D in Support of High Burnup Spent Fuel Dry Storage and Transportation", EPRI ESCP Int'l Subcommittee Meeting, Apr 14, 2016, PNNL

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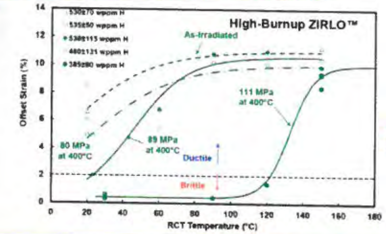
Closing the high burnup used fuel technical gap associated with fuel cladding

Mechanical testing on high burnup fuel cladding:

- **Ring compression testing at Argonne National Laboratory**
  Determines Ductile-to-Brittle Transition Temperature (DBTT) of cladding, an indicator of material brittleness
  - Highly dependent on internal rod pressure
  - Dependent on maximum temperatures seen during drying



Billone, "Update on Testing to Evaluate Radial Hydrides", U.S. NWTRB Meeting, Presentation, Feb 17, 2016, ANL

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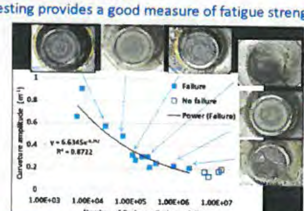
Closing the high burnup used fuel technical gap associated with fuel cladding

Mechanical testing on high burnup spent fuel:

- **Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) at Oak Ridge National Laboratory**
  - Determines the flexural stiffness of the cladding/fuel "system"
    - Stiffness provides a measure of fuel/cladding strength under mechanical loads
    - CIRFT testing provides valuable insights regarding
      - Pellet-Clad interactions
      - Pellet-Pellet interactions
    - CIRFT testing provides a good measure of fatigue strength



All figures and picture: Wang, et al., "CIRFT Testing of High-Burnup Used Nuclear Fuel from PWRs and BWRs", U.S. NWTRB Meeting, Presentation, Feb 17, 2016, Oak Ridge National Laboratory

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Closing the high burnup used fuel technical gap associated with fuel cladding

Thermal analyses on high burnup spent fuel in storage:

- **Thermal analyses on the DOE/EPRI Confirmatory Demonstration Project cask loading with high burnup fuel:**
  - Best estimate given fuel vendor data and current drying processes
  - Regulatory thermal analyses penalty factors removed
  - Best estimate maximum cladding surface temperatures are much less than the regulatory limit of 400 °C
  - Indicating:
    - Less Hydrogen going into solution that can re-precipitate in a radial orientation
    - Lower internal rod pressures that effect H radial hydride reorientation (PV=nRT)

	238	247	244	234	
234	257	269	268	256	235
241	268	255	271	269	246
247	268	268	260	269	247
238	255	269	269	257	238
	239	248	246	235	

Maximum cladding surface temperature for each assembly in the demo cask

Hanson, "DOE R&D in Support of High Burnup Spent Fuel Dry Storage and Transportation", EPRI ESCP International Subcommittee Meeting, Apr 14, 2016, PNNL.

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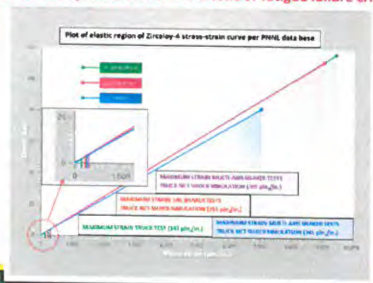
Closing the high burnup used fuel technical gap associated with fuel cladding

Normal Conditions of Transport (NCT) Loadings:

- **Shaker table and Over-the-Road Truck and Rail (shaker table only) tests** were conducted on a surrogate PWR assembly to estimate realistic loadings that a spent fuel assembly may see during transport.
  - Accelerations and strains were obtained on both the surrogate assembly and the conveyance
  - Placement of instrumentation was informed by analyses

→ **Large margin of safety relative to either elastic or fatigue failure criteria**



McConnell, "Sandia Shaker Table and Over-the-Road Vibrations Studies", US NWTRB Meeting, Feb 17, 2016, SNL.

Closing the high burnup used fuel technical gap associated with fuel cladding

FY16 Activities:

- **Ring Compression Tests:** Conduct additional RCTs to better understand DBTT Zirlo results at 350 °C:
  - Higher H content?
  - Lack of radiation-hardening annealing at 350 °C?
- **CIRFT Tests:**
  - Tests on TMI (low Sn Zirc) and Surry (Zirc) samples
  - Tests on lower sections of fuel rod
- **Thermal Analyses:**
  - Conduct best estimate analyses of other licensed storage designs
- **Thermal Tests:**
  - Conduct thermal benchmark test to obtain maximum cladding surface temperatures using higher design temperatures/pressures
- **Transportation NCT:**
  - Plans are underway to conduct a full-scale ENSA ENUN-32P rail cask with surrogate assemblies to obtain over-the-rail loading data

Summary

- **SNL and BAM collaboration addresses various technical issues regarding aging effects on spent fuel storage systems and regular workshops are held to share information.**
- **BAM investigations on aging effects of metal seals, elastomer seals and polymers don't indicate a major safety issue regarding the long term performance of such materials and components so far. Investigations are going to be continued and expanded.**
- **SNL focusses on the technical gap associated with fuel cladding:**
  - Further testing will focus on cladding response and performance under realistic temperatures, hoop stresses, and external stresses,
  - Indications are that cladding, including for high burnup fuel, will continue to perform its safety functions during extended storage and normal conditions of transport.