KIT SCIENTIFIC REPORTS 7569

Projektträger Karlsruhe (PTKA-WTE) – Wissenschaftliche Berichte 12

US-German Workshop on Salt Repository Research, Design, and Operation

May 25 – 27, 2010
Mississippi State University, CAVS
Canton, MS
USA

A joint workshop organized by

Projektträger Karlsruhe (PTKA-WTE)

SANDIA National Laboratories

DBE TECHNOLOGY GmbH

Walter Steininger (ed.)

KIT Scientific Publishing

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Scientific Publishing

Report-Nr. KIT-SR 7569

Wissenschaftliche Berichte - FZKA-PTE

Der vorliegende Band dient der aktuellen Unterrichtung der auf dem Gebiet der Entsorgung gefährlicher Abfälle arbeitenden Institutionen und der zuständigen Behörden. Verantwortlich für den Inhalt sind die Autoren.

Impressum

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Table of Contents

Foreword

Most countries using nuclear power face the problem of safe disposal of the radioactive wastes. Although for highly radioactive wastes (spent fuel, high-level waste, and some types of long-lived radioactive waste) a repository is still pending, there is international consensus that the preferred solution is disposal in deep geological repositories (DGR). Therefore, during the past 45 years many types of geological media have been studied around the world regarding its suitability to host such a repository.

Currently the three most favored DGR host-rock media are crystalline rocks, evaporitic / salt rocks, and argillaceous / "clay" rocks. Besides, a volcanic / tuffaceous rock-sequence was also held suitable to host a DGR.

For more than 30 years, both the USA and Germany have studied rock salt as a medium to host a repository for high-level radioactive waste. In both countries deep-geological repositories for both radioactive and chemical-toxic wastes are safely operating, and a thorough knowledge and a sound expertise have been acquired. Hence, the German and U.S. financial and intellectual investments in rock-salt repositories are unique, state-of-the-art global assets.

Recent developments in Germany and the USA have renewed efforts in salt repository investigations and related studies. Both the German rock salt repository program and the U.S. waste management program currently face challenges that may adversely affect their respective current state-of-the-art core capabilities in rock salt repository science and technology. Therefore, it seems congruously that Germany and the U.S. renewed joint efforts in salt repository investigations.

There was a desire on both sides

- to renew collaborations and cooperation on overall salt repository science and technology,
- to coordinate a potential research agenda of mutual interest,
- to leverage collective efforts for the benefit of their respective programs, and
- to form a basis for providing an attractive, cost-effective insurance against the premature loss of virtually irreplaceable scientific expertise and institutional memory.

It was felt that appropriately coordinated, closer collaborations between the principal scientists and investigators of both countries representing the expertise in deep geological disposal science and technology in salt could provide a joint remedy to these challenges. This was the motivation to organize a joint workshop to map out a potential research agenda and to renew working relationships at the institutional and individual levels.

Representatives of institutions in both countries met at the workshop in Canton, Mississippi USA. The workshop was a joint undertaking of Sandia National Laboratories, DBE TECHNOLOGY GmbH and the Project Management Agency Karlsruhe in the Karlsruhe Institute of Technology, and was kindly hosted by Mississippi State University (CAVS) and Sandia National Laboratories (Please see the website address in the reference list).

Besides seventeen U.S. invited attendees from academia, industry, and the State of Mississippi, fifteen representatives/scientists of U.S. organizations and sixteen German representatives from eight different German organizations involved in the radioactive waste management programs were attending. These key investigators in salt repository science and engineering presented material pertinent to the state-of-the-art in R&D. Predicated on these presentations and other material, par-

ticipants identified several potential coordinated research areas and agreed in principle to pursue such research individually or in concert with others.

As the German/U.S. salt repository programs move forward in their respective countries, the intent is to maximize individual resources for the mutual benefit of each program. The workshop basically reinitiated previous collaborative research activities that had been waning for about ten years.
It was agreed to collect the excellent presentations and to publish it in proceedings, not only to document the outcomes of this event, but also to make this information accessible to a larger community and spread among concerned scientists ideas or proposals for still open RD&D issues.

We greatly acknowledge the contributions of all participants.

Frank D. Hansen
Enrique Biurrun
Walter Steininger

Workshop Presentations

OVERVIEW OF GERMAN R&D ACTIVITIES

Walter Steininger
Karlsruhe Institute of Technology (KIT)
Project Management Agency Karlsruhe
Water Technology and Waste Management (PTKA-WTE)

Since the 2009-General Elections the Federal Government is formed by a coalition between the Christian Democrats and the Liberal Party. In their coalition agreement nuclear topics are explicitly mentioned: *"The responsible use of nuclear energy necessitates safe final storage for radioactive waste. This is why we will immediately lift the moratorium on exploration at the Gorleben salt dome in order that exploration can be continued in an open-minded fashion. We want an international peer review group to investigate whether Gorleben meets the latest international standards. The entire process will be conducted in a public and transparent fashion."* And further*" This is why we are prepared to extend the operating life of Germany's nuclear power plants on condition that strict German and international safety standards are met."*

Nuclear energy is regarded *as a bridging technology* till the renewables can produce enough energy. No nuclear power plants are to be built. Yet, 17 reactors at 12 nuclear power plants (NPP) are in operation with an total output power of about 135 TWh in 2009. Still nearly 25 % of the total electricity production is contributed by the German NPP. The lifetime of the NPPs, still determined by the limited electrical output and fixed in the Atomic Energy Act (AEA), is a matter of discussions and will be on the agenda for the Government's planned energy concept. This concept will address all energy issues in a broader scope against the background of fossil energy shortage, change and challenges in national and international energy supply, and climatic change.

With regard to disposal of heat generating waste, a final decision about the rock type that will finally host the repository is still pending. Nevertheless, in Germany, rock salt still is the favorite rock type. This opinion is supported not only by the results of decade-long successful R&D that lead to a sound base of knowledge about the features of this host rock, but is also supported by years of experience in mining and the operation of salt mines, and the technological state-of-the-art in disposal technology. What is more, up to now there are no indications that this material is not suitable to accommodate the repository. Therefore, the stop of the Gorleben moratorium and the decision to resume the exploration work is a very positive development. This is accompanied by making a preliminary safety analysis during the next two years to have all the necessary information available for the final evaluation of the suitability of the site.

With regard to R&D in the field of HLW disposal, the 5th Energy Research Program of the Federal Government "Innovation and New Technology" is the general and overall frame. The Ministry of Economics and Technology (BMWi), the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Ministry of Education and Research (BMBF) use this Program for their particular responsibilities and competences. BMBF - as a partner associate of BMWi - is funding primarily basic research conducted by the national research scientific-technical and biological-medical centres that constitute the Helmholtz-Association. Research on waste disposal is carried out in the national research centres Karlsruhe and Jülich.

Non-site specific R&D projects are funded by BMWi on the basis of its Research Concept that comprises two main topical areas: *Repository concepts and repository subsections,* and *Data and tools for safety analysis*. The priorities for R&D activities are firstly rock salt, secondly argillaceous rocks and thirdly - on a minor scale - crystalline rocks. This rock type R&D prioritization emphasizes on the one hand the different levels of advancement in knowledge about these rock types, respectively, their significance as potential host rocks. On the other hand, it mirrors the conceptual and geological reasoning concerning the selection of potential host rock types.

Besides R&D on rock salt, and based upon the 2001 decision of the then Federal Government, argillaceous rock and crystalline rock still are under investigation if only with different intensity. Most of these activities are integrated in international programs and activities in underground research laboratories in Switzerland (crystalline, argillaceous rocks), France (argillaceous rocks) or Sweden (crystalline rock). During the last years the knowledge increased substantially. The project results achieved so far allow a better and more qualified estimation and evaluation of the pros and cons of HLW disposal esp. in argillaceous rock. Besides substantial progress in developing a deeper understanding of this host rock, essential progress in concept design has been made. The activities in crystalline are mainly concentrated on the behavior of the engineered barrier system.

Although, for disposal in rock salt a lot of know-how is available, technologies have been developed, conceptual progress has been made, and scientific expertise has been developed and accumulated, a number of projects were started. These key projects were performed and successfully finished and contributed to further improve the knowledge on rock salt behaviour, engineering and conceptual questions, and to improve the toolbox for safety analyses. Some of these projects are key for the use in future safety assessment (safety case) exercises.

All R&D activities are related to three areas: national cooperation, international cooperation, and the participation in the European Framework Programs. This triangle offers the unique chances for acquiring competence, for getting external expertise and offer expertise, to bear the burden of expensive large projects by cost sharing, and by offering the chance for education and training. What is more, there is an important contribution in communication with the public.

The German R&D activities are mirrored both by this triangle and the subject areas and topics of BMWi´s Research Concept. The main goal for all this R&D efforts is lately to demonstrate the safety of the disposal system. This is a real challenge, because it requires a multidisciplinary and interdisciplinary approach. Issues like material behaviour, modelling, conceptual and engineering must be addressed. The processes occurring in the system in space and time must be understood to be integrated in safety evaluations of the system, etc.(A lot of projects covering these areas are currently performed.)

To tackle this challenges national and international cooperation in bilateral, multilateral projects, is and will be indispensable. For Germany this always played an important role during the decades of research which is documented by several cooperation agreements, the involvement of German scientist in many international projects, in initiatives (e.g. Technology Platform *Geological Disposal of Radioactive Wastes*) and projects within the Framework Programs of the European Commission.

To summarize, it can be stated: the status of knowledge on HLW disposal in rock salt is well advanced, techniques (e.g. for shaft and drift emplacement as well as for borehole emplacement of spent fuel) are developed, instruments and tools for modeling and safety analysis were substantially further developed and are about to be applied in a safety case.
The status achieved and questions to be answered yet are mirrored in BMWi´s Research Concept. This is also reflected by the rock type dependent prioritization (SALT, claystone, crystalline). In the last years knowledge on other host rock types increased substantially. However, R&D will continuously contribute to enlarge the scientific-technological know-how and provide the necessary basis for future decision making and R&D activities. Within this frame international cooperation plays an important part.

Karlsruhe Institute of Technology

US-German Workshop on Salt Repository Research, Design, and Operation

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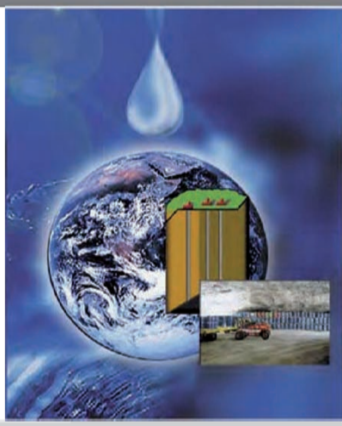
Jackson, MS

PROJEKT MANAGEMENT AGENCY KARLSRUHE
WATER TECHNOLOGY AND WASTE MANAGEMENT (PTKA-WTE)

PTKA
Project Management Agency Karlsruhe
within Karlsruhe Institute of Technology



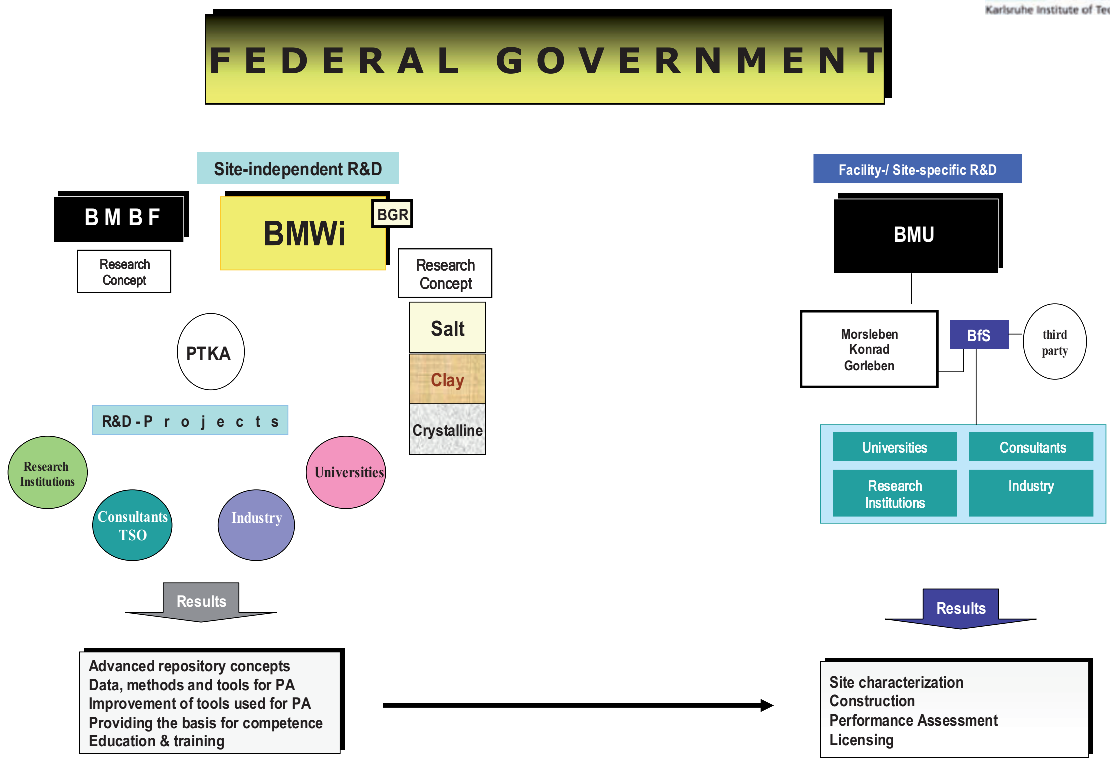
Federal Ministry of Economics and Technology

Karlsruhe Institute of Technology

OVERVIEW OF GERMAN R&D ACTIVITIES

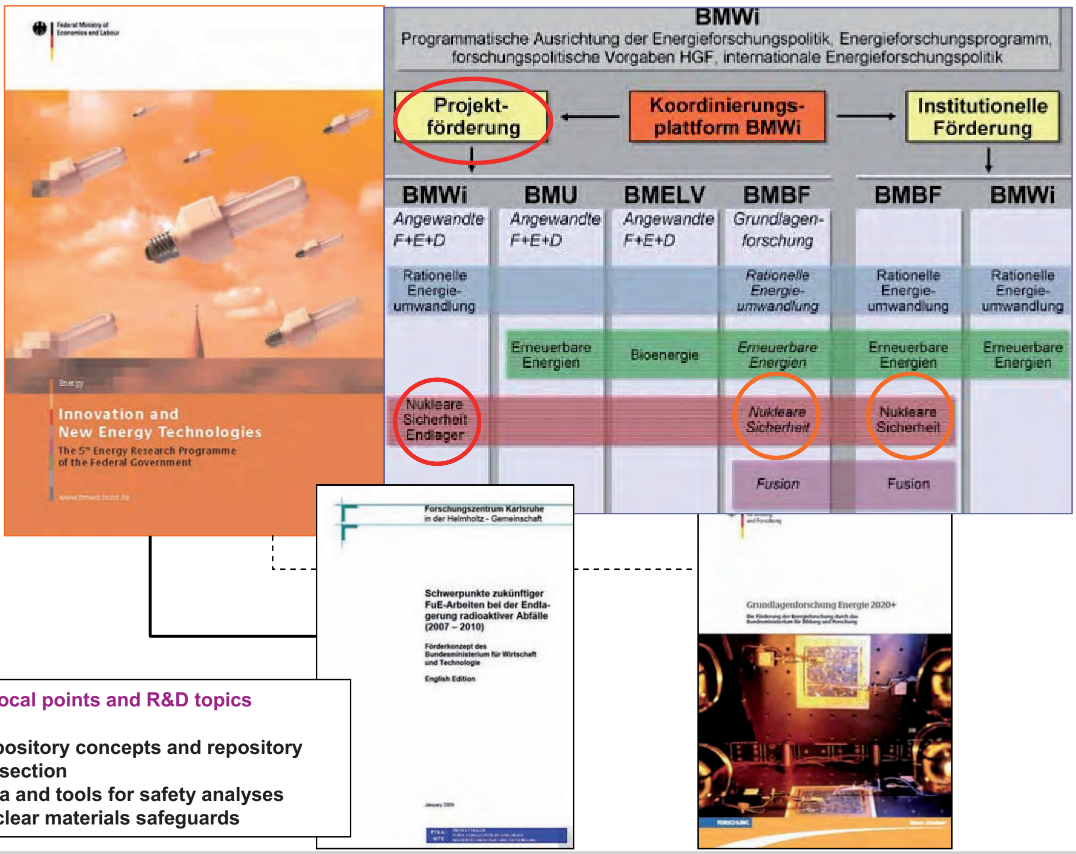
- Nuclear facts
- Responsibilities for R&D
- Programmatic frame
- Achievements
- Cooperation in R&D
- Summary

RESPONSIBILITIES IN R&D



BMWi Ministry of Economics and Technology
BMBF Ministry of Education and Research
BMU Ministry of the Environment

PROGRAMMATIC FRAME



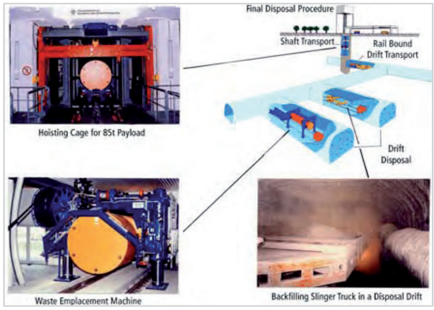
R&D focal points and R&D topics

A Repository concepts and repository subsection
B Data and tools for safety analyses
C Nuclear materials safeguards

ACHIEVEMENTS

Development of the German disposal concept "Direct Disposal" (1985 – 1995)

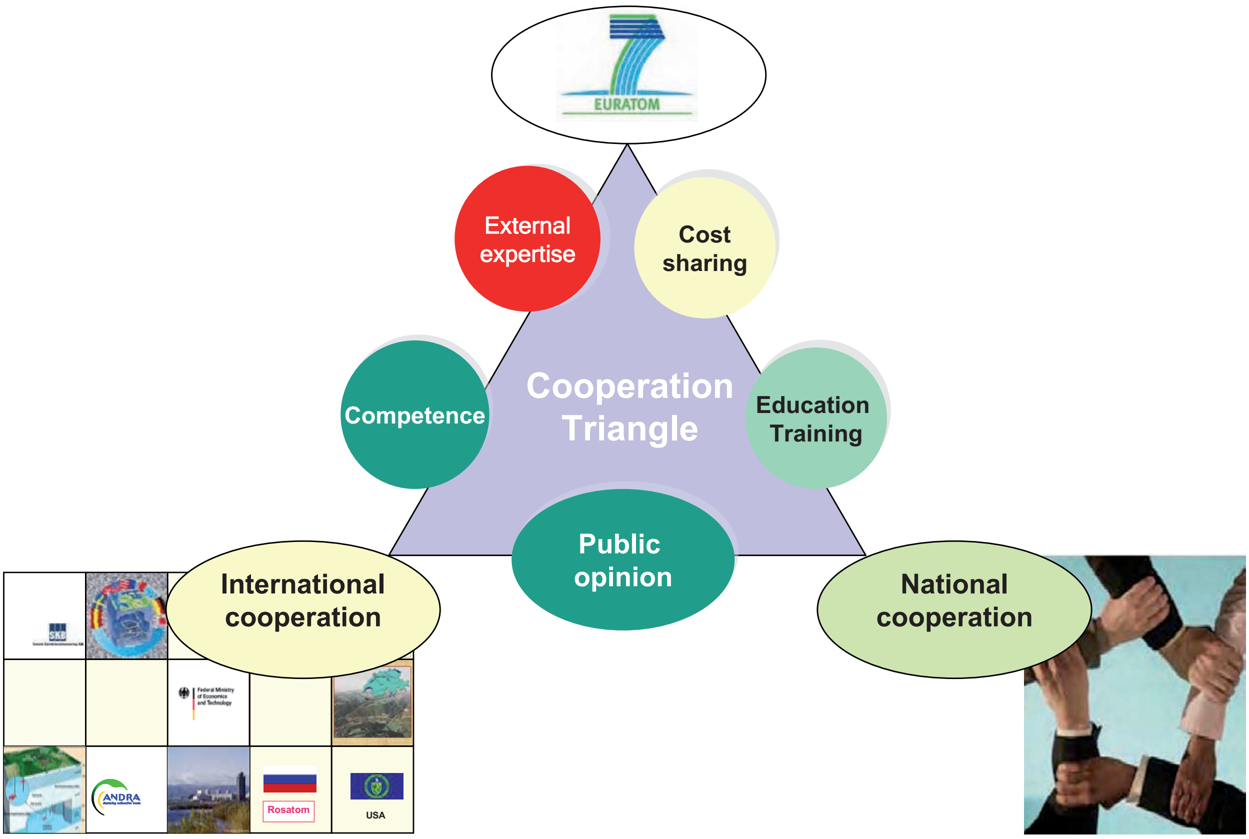
- Techniques for handling, transportation, and disposal were tested, their feasibility was shown.
- Direct Disposal is the only legal disposal option.
- Large-scale in-situ projects (technology development), laboratory experiments and modeling (all activities with international cooperation), e.g. Brine Migration Test, HAW-project, MHV-project, Dam construction project, BAMBUS-project. Additionally accompanying R&D.



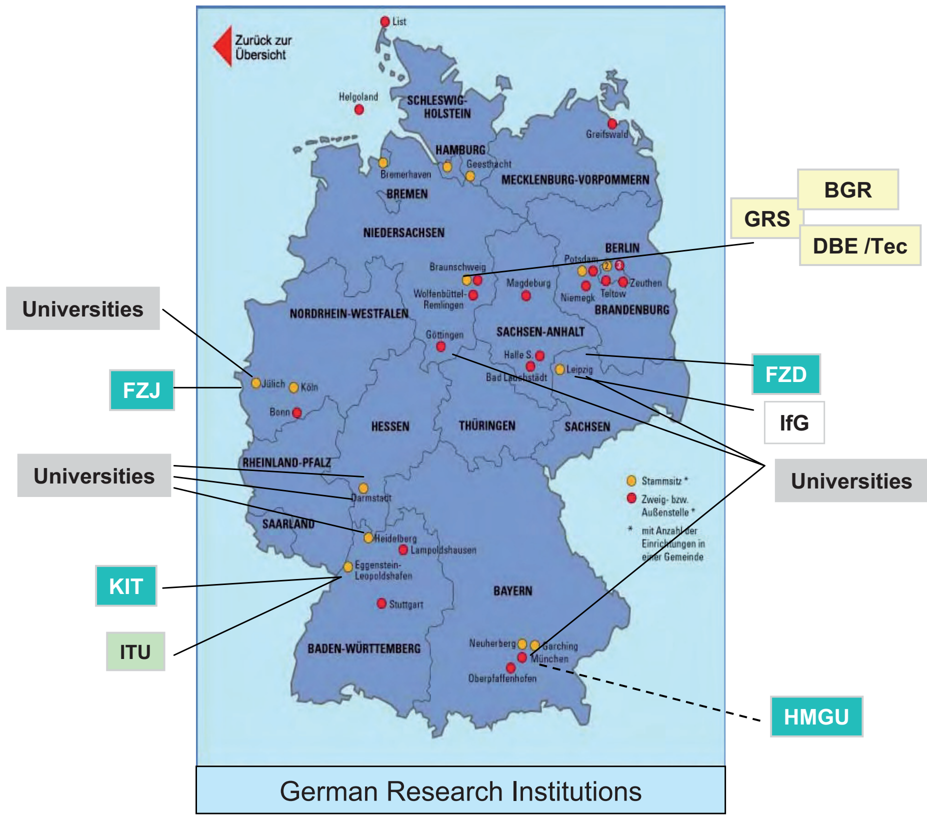
Despite drawbacks and standstills, projects were initiated driven by the requirements to identify open questions, to define R&D solutions, and to support and to foster future decisions

- Development of an advanced safety proof concept for a HLW – repository in rock salt
- Optimizing the direct disposal concept by developing the technology for vertical borehole emplacement
- Development of a reference concept for a generic German deep geologic repository in clay
- Further development of sophisticated models and computer software
- Improving the understanding of systems behavior

COOPERATION IN R&D



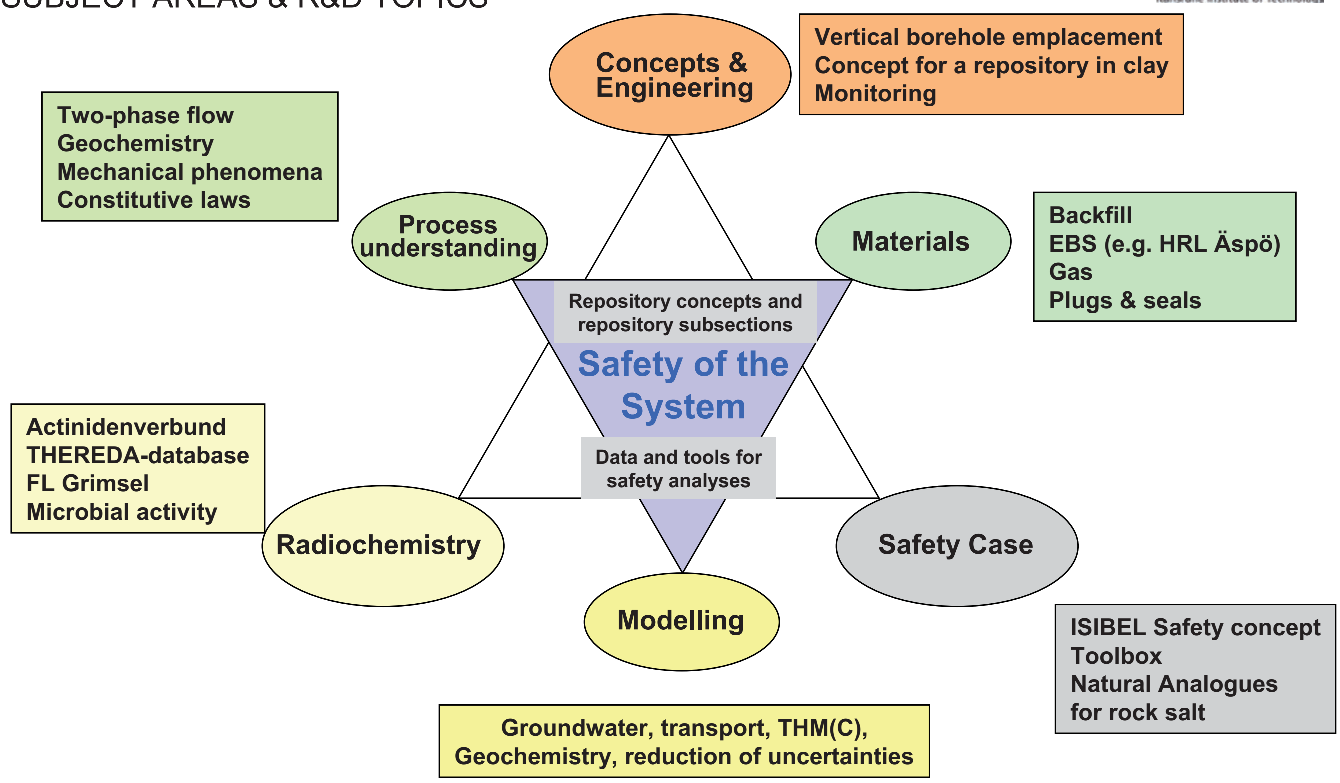
COOPERATION IN R&D



German Research Institutions

COOPERATION IN R&D

SUBJECT AREAS & R&D TOPICS



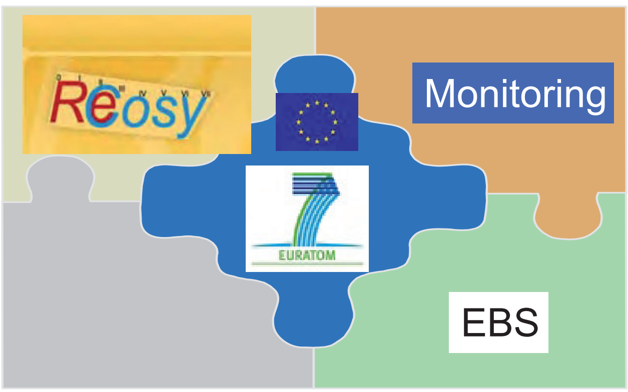
COOPERATION IN R&D

- identify parameters of potential host rocks in addition to rock salt (Coalition agreement 1990)
- develop and test investigation methods and demonstrate their applicability transfer data to other sites
- exchange experiences and develop international standards
- consider the state of the art
- maintain flexibility with different host rock options

COOPERATION IN R&D

Implementation-oriented R&D on all remaining key aspects to establish a sound scientific and technical basis for demonstrating the technologies and safety of geological disposal to underpin the development of a common European view on the main issues

Studies on relevant near field processes, understanding of the repository environment, bedrock and pathways to biosphere, developments of robust PA/SA methodologies (modelling tools), engineering studies and demonstration of repository designs, In situ characterisation of host rocks in generic & site specific URLs, investigation of governance and societal issues related to public acceptance

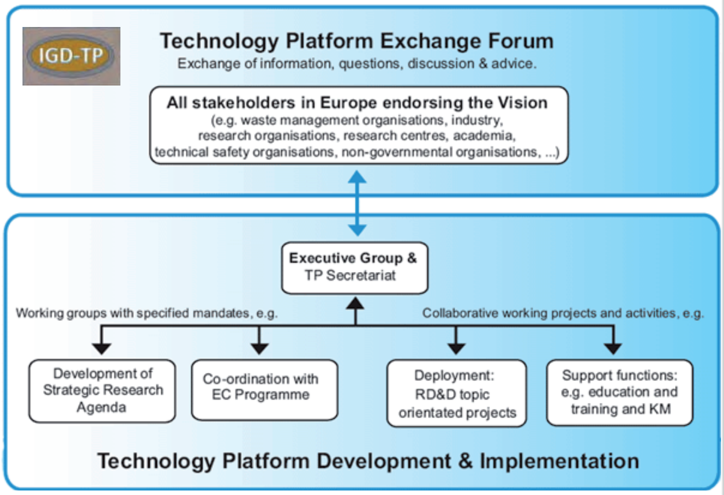


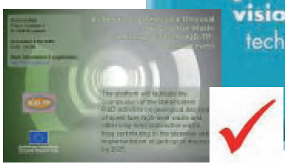
COOPERATION IN R&D

Technology Platforms
a 3-step process

Webpage: www.igdtp.eu

1. R&D stakeholders, led by "end users", come together around a common vision for the technology
2. SH define a Strategic Research Agenda setting out medium to long-term research priorities to realise the vision
3. SH implement the SRA with the mobilisation of significant human and financial resources ("Deployment Strategy")
   - Better align EU research priorities to end users' needs
   - Positive impact on Europe's growth, competitiveness and sustainability
   - Increased efficiency & effectiveness and reduced fragmentation of R&D efforts
   - Mobilisation of public and private funding sources





SUMMARY

- A lot of know-how, technological, and scientific expertise has been accumulated during the past decades
- practical experience and skills from salt mining and disposal of chemotoxic wastes
- The status of knowledge on HLW disposal in rock salt is well advanced
  - Techniques for shaft and drift emplacement are principally available
  - Borehole emplacement of spent fuel is developed
  - Instruments and tools for modeling and safety analysis were substantially further developed and are about to be applied

→ Knowledge for building a repository in rock salt is at hand

- The status achieved is mirrored in BMWi´s research concept
- R&D-priorities are rock type dependent (SALT, claystone, crystalline)
- Knowledge on other host rock types increased
- R&D will continuously contribute to enlarge the scientific-technological know-how and provide the necessary basis for future decision making and R&D activities
- International cooperation plays an important part in BMWi´s R&D concept

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

A BRIEF CHRONOLOGY OF SANDIA ACTIVITIES SUPPORTING SALT SCIENCE

Andrew Orrell
Director of Nuclear Energy Programs
Sandia National Laboratories

A Brief Chronology of Sandia Activities Supporting Salt Science

US-German Salt Workshop
Jackson, Mississippi, USA

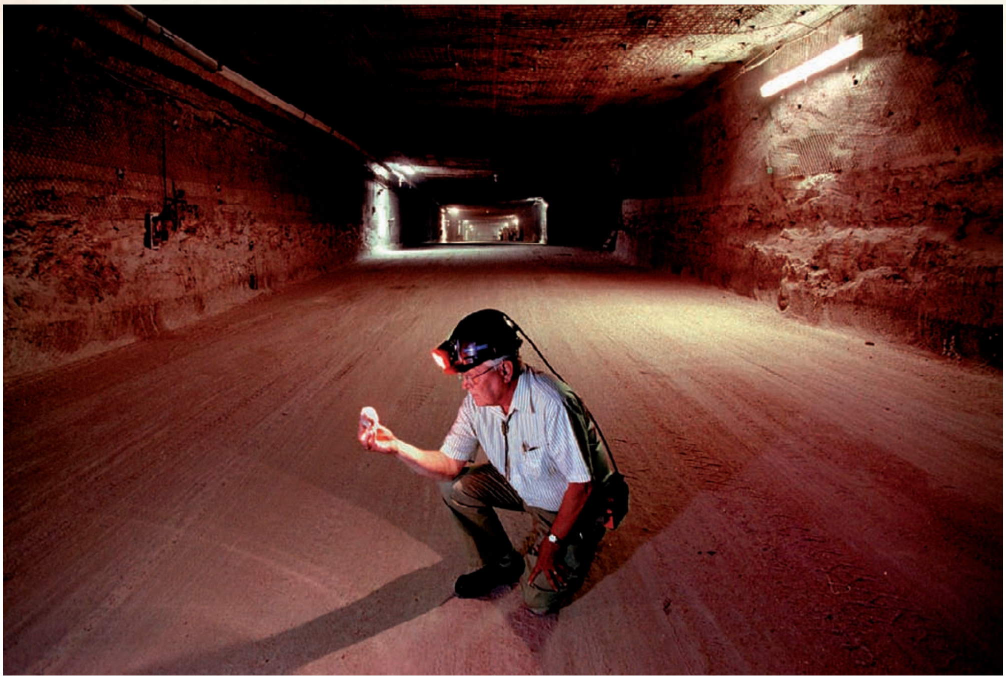
Andrew Orrell
Director of Nuclear Energy Programs
Sandia National Laboratories

May 25 - 28, 2010

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

Sandia National Laboratories

The Venerable Wendell Weart



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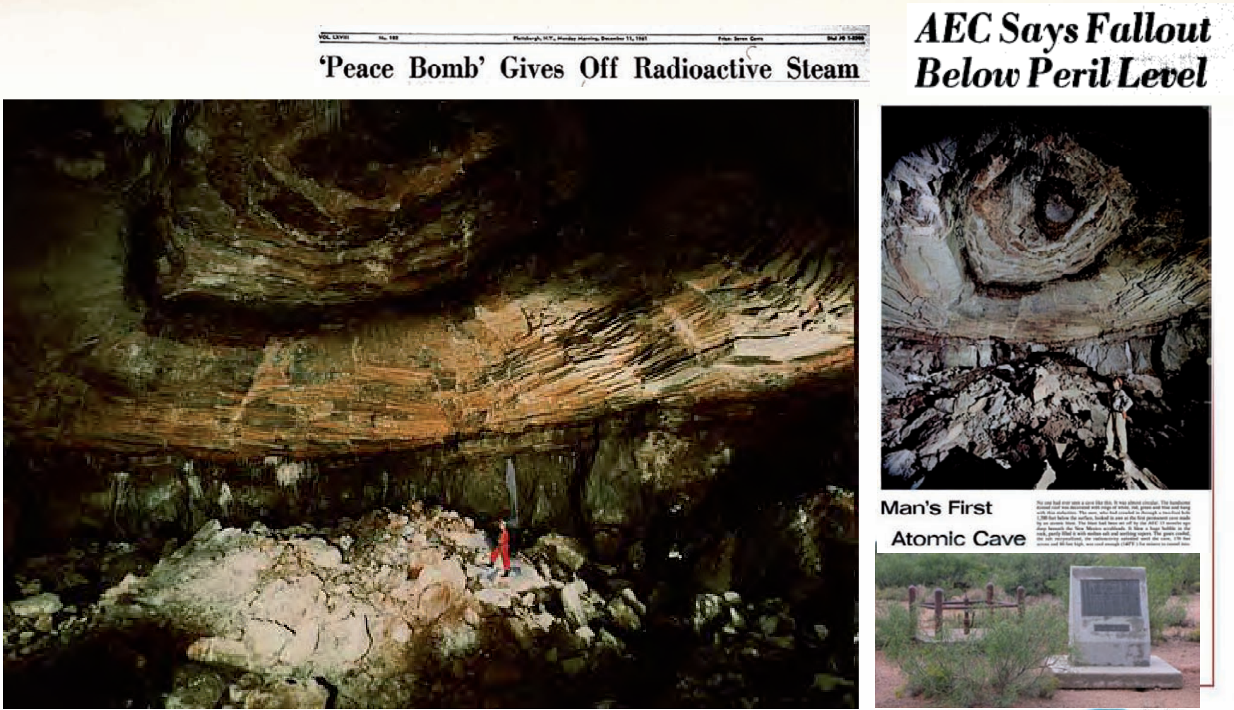
Project Gnome
December 10, 1961



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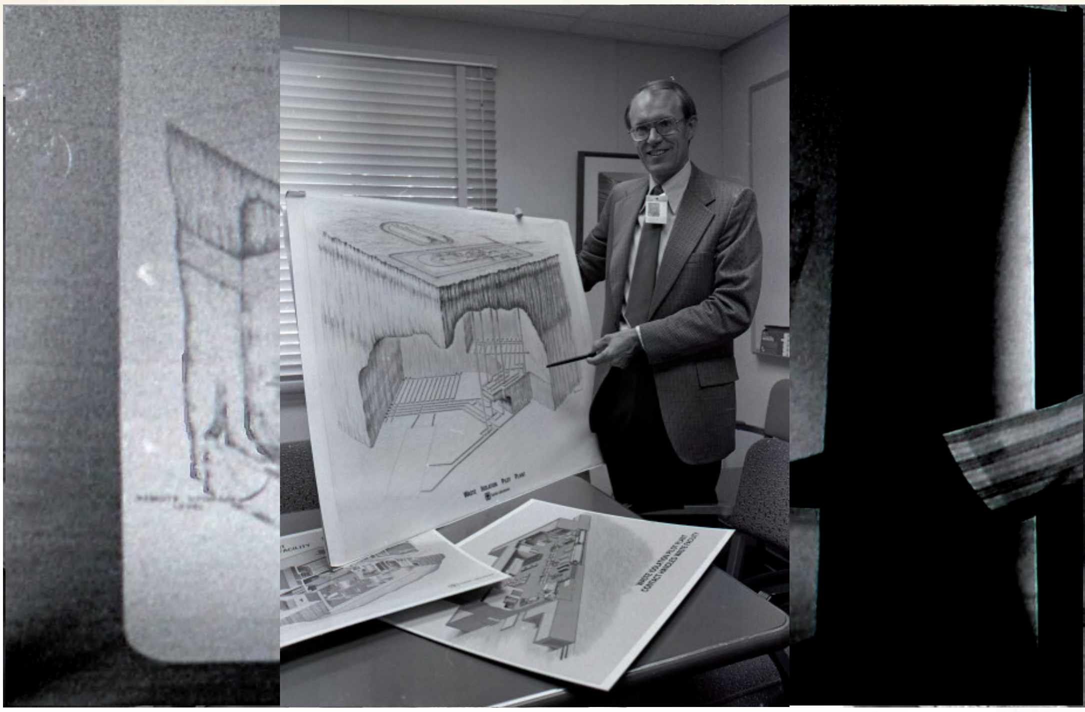
The WIPP Scientific Advisor Role since mid-70's



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Waste Isolation Pilot Plant Chronology 1975-2009

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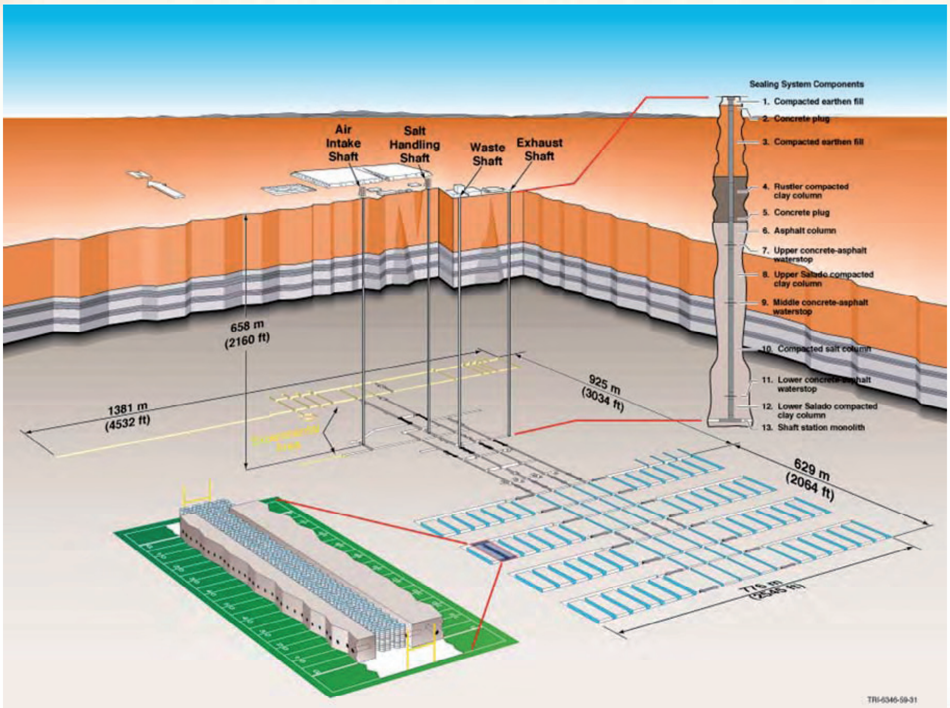
Isometric View



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Starting in the Lab to In-Situ…

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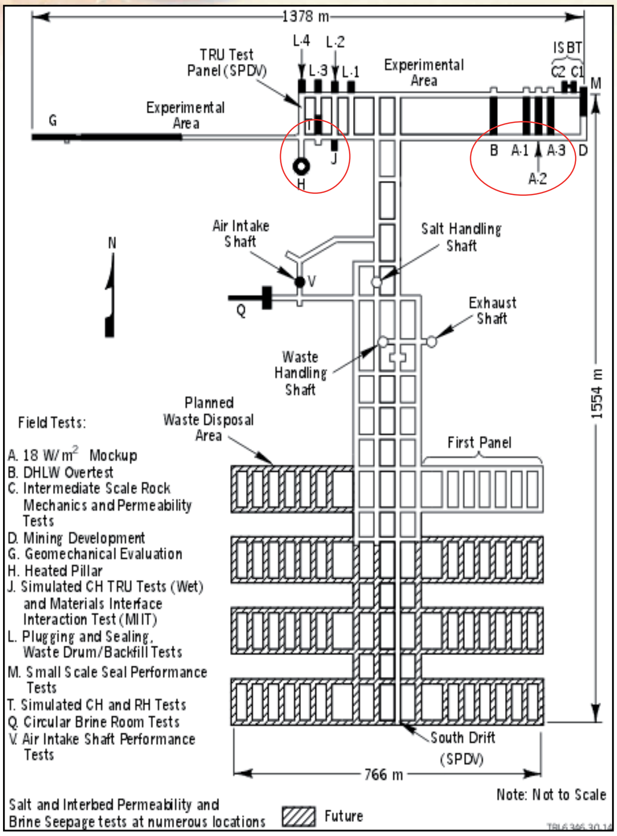
Major Tests in the WIPP



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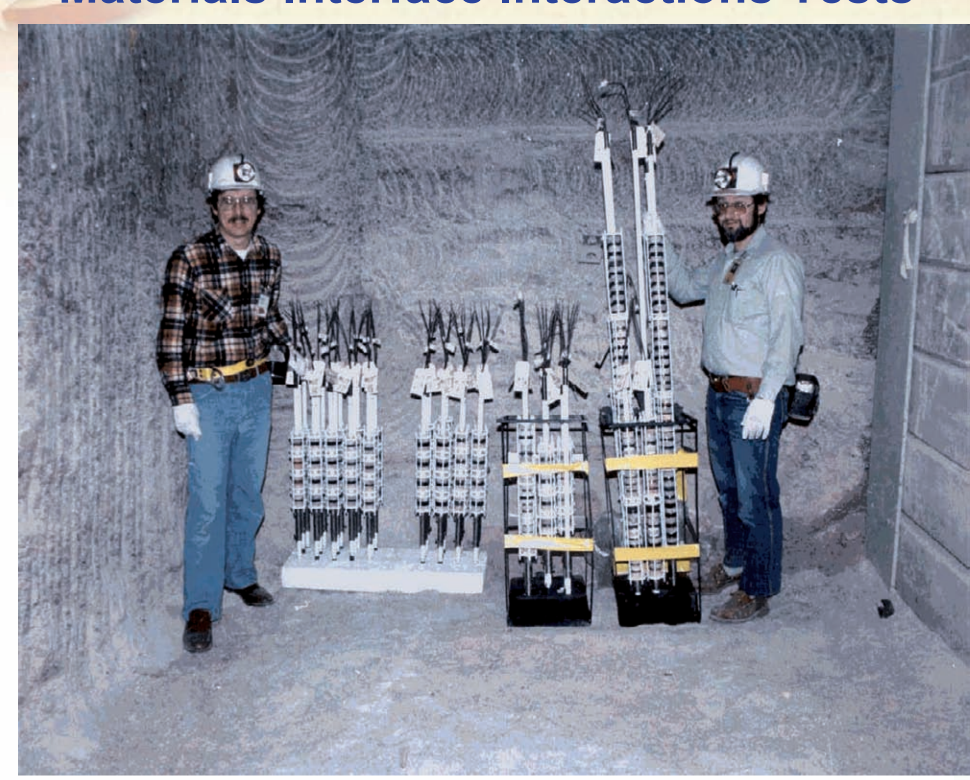
Heated Axisymmetric Pillar Test

Materials Interface Interactions Tests



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Thermal-Mechanical Test

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29

Waste Package Performance Tests (Room B)

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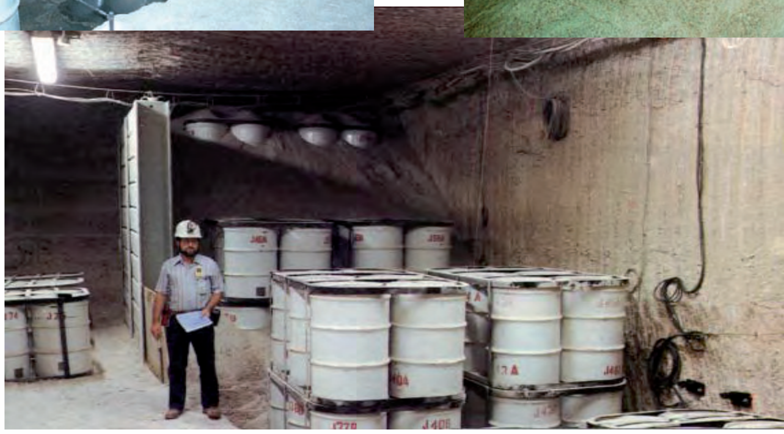
Waste Package Performance Tests (Room J)



Reports

SAND92-1921C

Submitted for presentation at the Workshop on
In Situ Tests on Radioactive Waste Forms and Engineered Barriers
Corsendonk, Belgium, October 1992

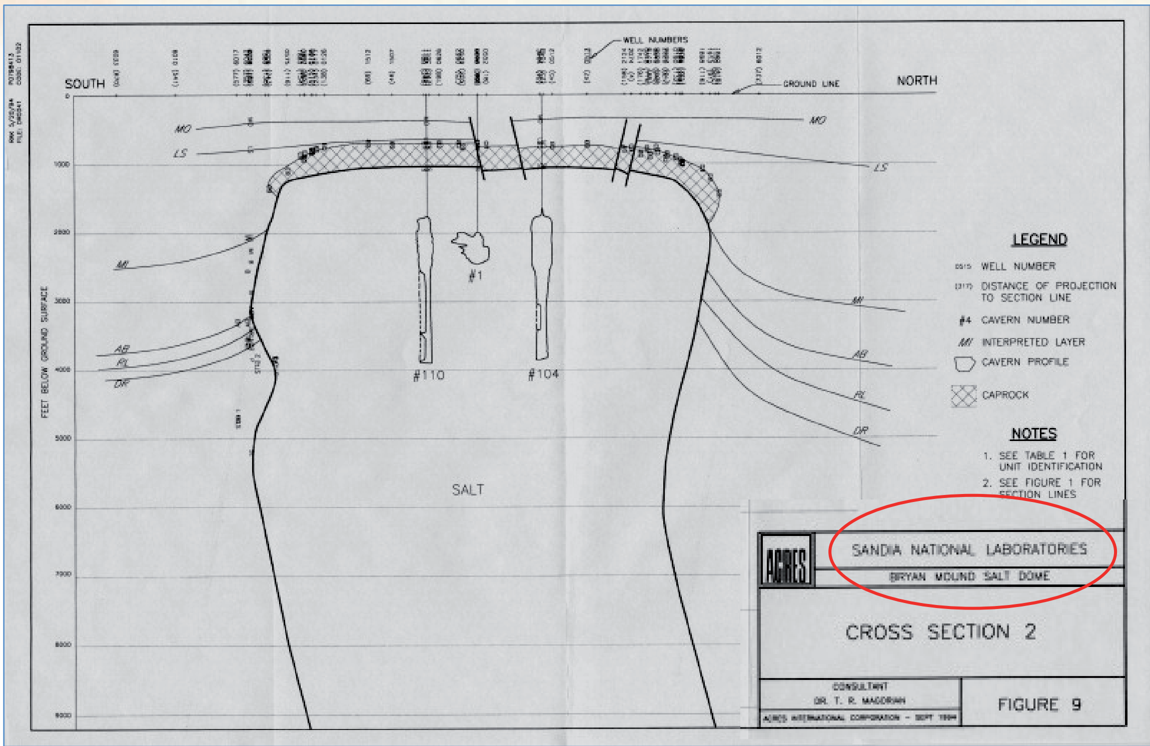
SUMMARY OF THE WIPP MATERIALS INTERFACE INTERACTIONS TEST - METAL CORROSION

N. Robert Sorensen and Martin A. Molecke
Sandia National Laboratories*
Albuquerque, NM 87185 USA

Compliance Certification Application

Sandia National Laboratories

Other Salt Programs



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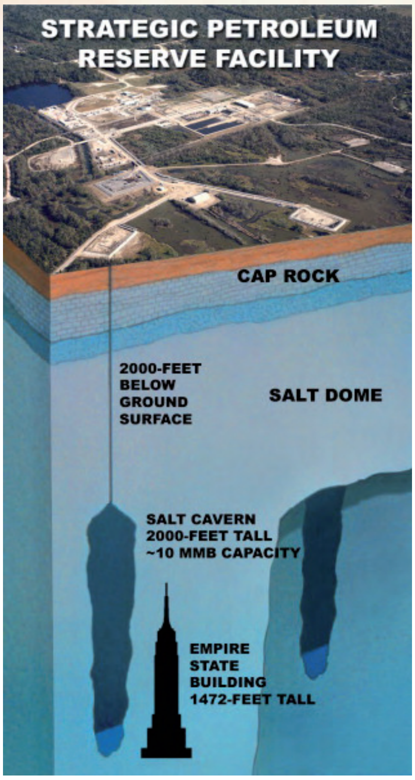
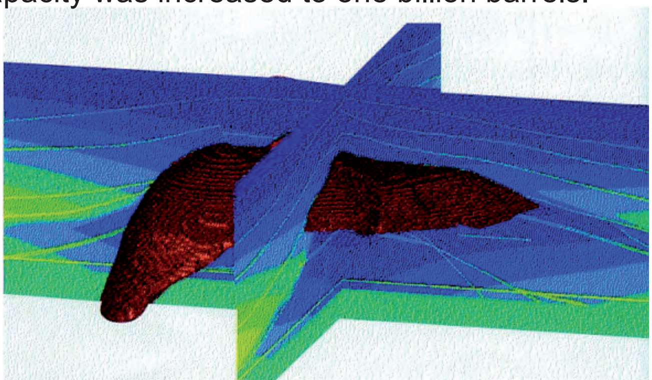
Strategic Petroleum Reserve



- America's emergency crude oil is stored in salt caverns along the Gulf Coast at depths up to 5,000 feet. Since 1977 Sandia has provided the Department of Energy with scientific and engineering assistance on the Strategic Petroleum Reserve, including helping DOE evaluate and choose additional storage sites when SPR capacity was increased to one billion barrels.



Three-dimensional seismic image of a salt diapir based on SEG/EAGE dataset.

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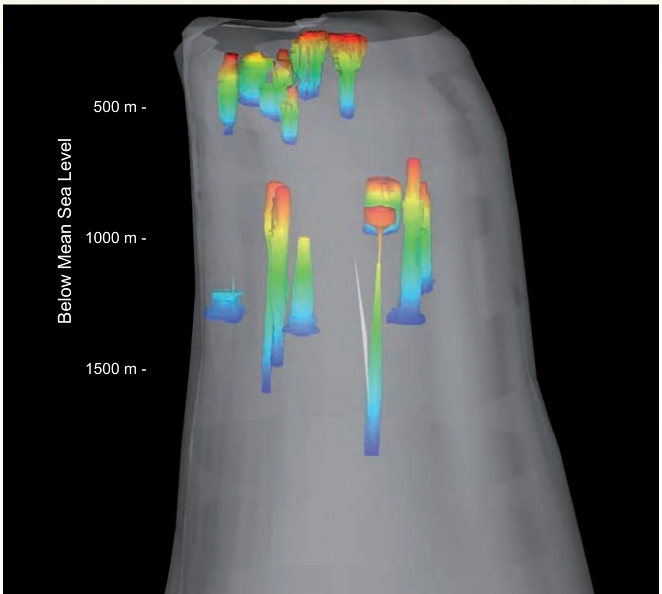
Sandia's Strategic Petroleum Reserve (SPR) Program

- **Active Continuously Since 1977**
- **62 caverns at four sites holding 727 million barrels of oil**
- **Sandia is the lead for underground geomechanical and oil process engineering R&D**
- **500+ journal articles, conference papers, Sandia Reports, and letter reports**
- **Impacts: For example, Sandia developed the CAVEMAN tools to integrate cavern data continuously. This tool has shown well leakage before standard tools have.**
- **CAVEMAN has influence state regulation in Kansas, Texas and Louisiana**



Bayou Choctaw Dome, LA
One of the 4 SPR Storage Sites

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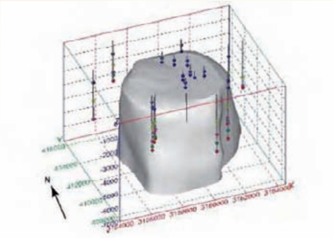
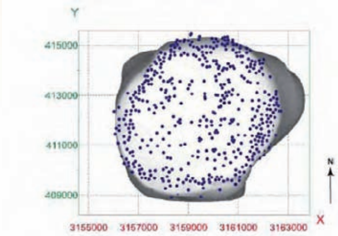
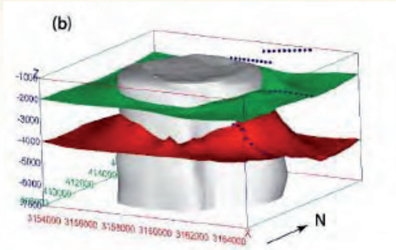
Geologic Characterization of SPR Salt Domes Sites



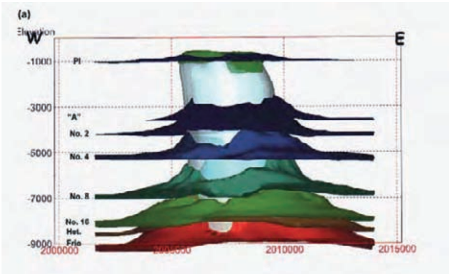
1. Obtain Existing Well Logs



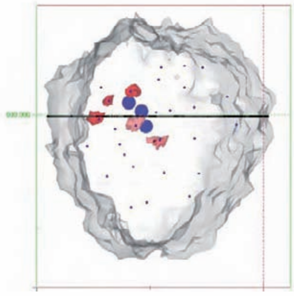
2. Define Caprock



3. Map boundary sediments and fault traces



4. Construct 3-D Model of Dome and Surrounding Geology



5. Incorporate 2-D or 3-D Seismic Imaging Of the Dome and Surrounding Geology

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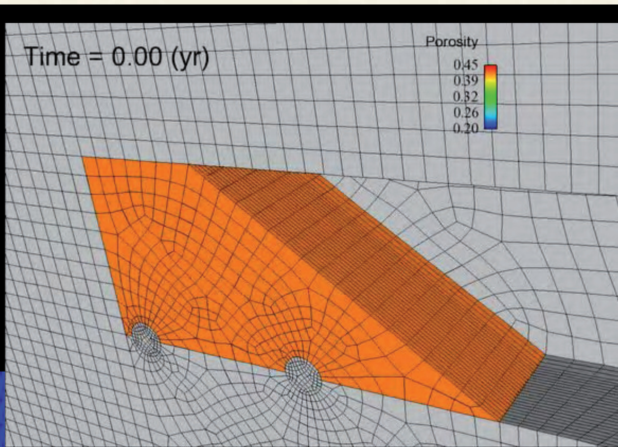
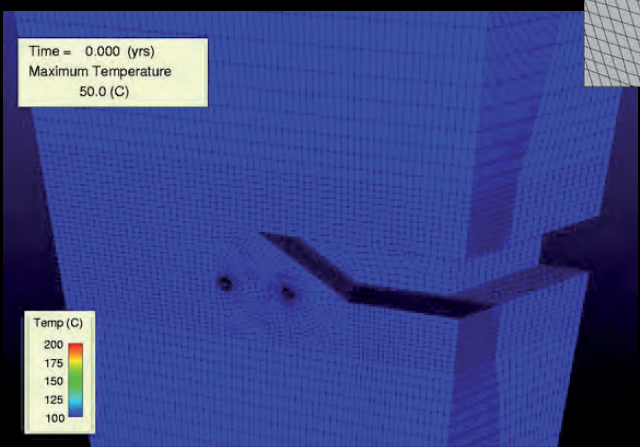
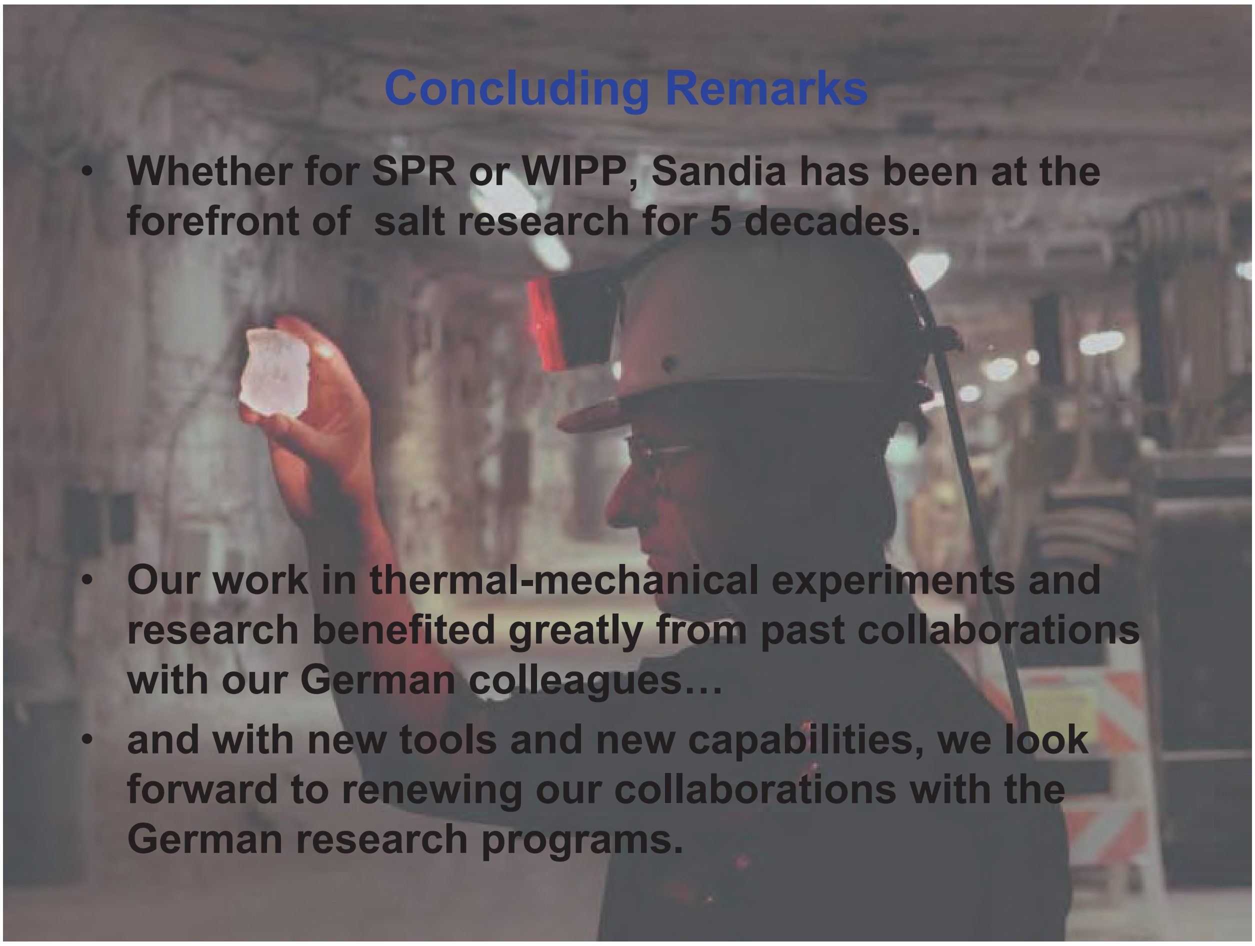
Salt Simulations






Concluding Remarks
• Whether for SPR or WIPP, Sandia has been at the forefront of salt research for 5 decades.
• Our work in thermal-mechanical experiments and research benefited greatly from past collaborations with our German colleagues…
• and with new tools and new capabilities, we look forward to renewing our collaborations with the German research programs.

39


Vielen Dank!

40

Backup

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Aerial View of WIPP (1999)

Sandia National Laboratories

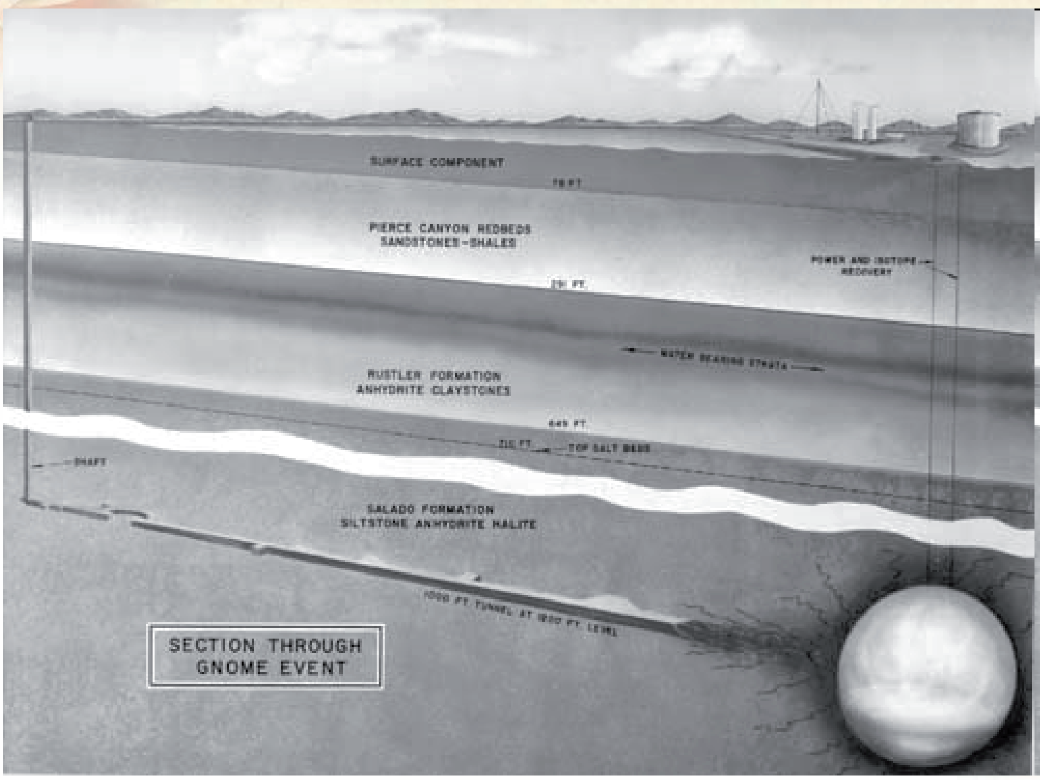

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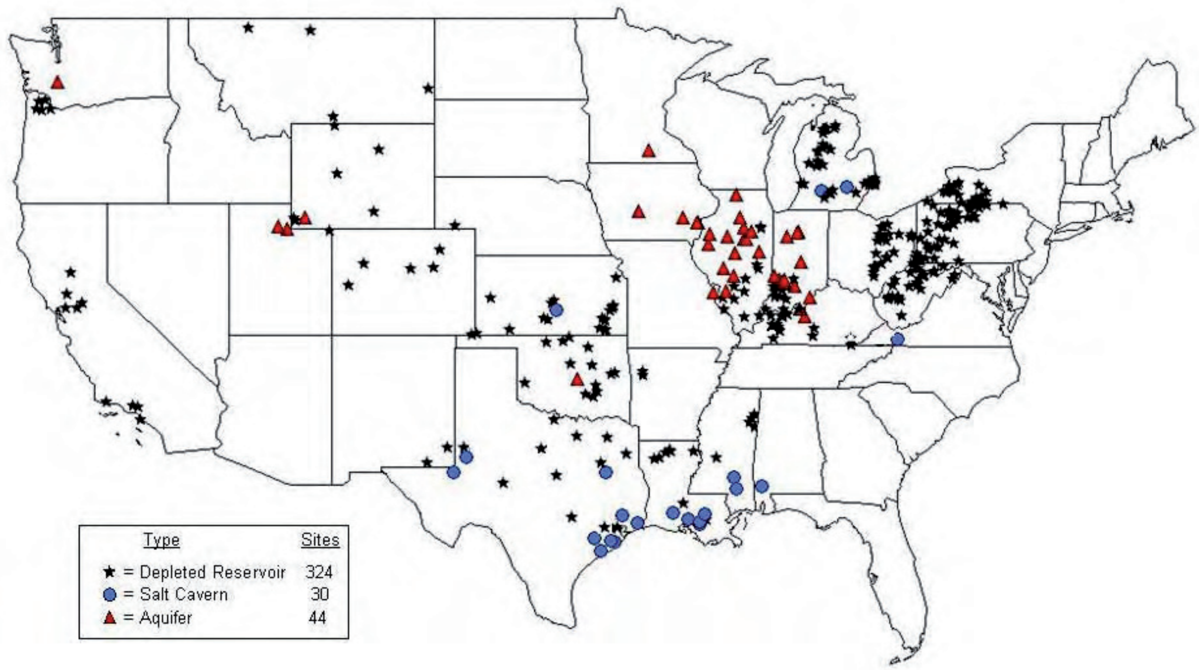
Figure 14. Locations of Existing Natural Gas Underground Storage Fields in the United States, 2008



Source: Energy Information Administration (EIA), Form EIA-191A, “Annual Underground Gas Storage Report.”

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Newly Excavated Test Drift

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WIPP Disposal Room Evolution

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US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

SAFETY CASE APPROACHES - AN AMERICAN PERSPECTIVE

Clifford Hansen
Sandia National Laboratories

Safety Case Approaches

An American Perspective

May 25, 2010

Clifford Hansen
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Safety Case vs. Safety Assessment
- PAMINA project
- Points to consider

Safety Case (IAEA 2006)

- A collection of arguments and evidence to demonstrate the safety of a facility
- Developed in concert with the facility as scientific understanding advances
- Includes:
  - Pre- and post-closure safety assessments
  - Descriptions of barriers and their performance
  - Supporting evidence (e.g., geologic analogues)
- Acknowledges unresolved issues

- Somewhat site and design independent for a common geologic environment

Post-Closure Safety Assessment

- Systematic analysis of:
  - the hazards associated with the facility and
  - the ability of the site and the design of the facility to provide for the safety functions and meet technical requirements
- Quantifies performance and associated uncertainties
- Compares to relevant safety standards

- Safety assessments are site and design specific
- Constructed to address regulatory requirements

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Examples

- Safety Case: Compliance Certification Application for the Waste Isolation Pilot Plant (and applications for recertification)

- Safety Assessment: 1996 (and 2004 and 2009) Performance Assessment for the WIPP

- Suggests an action: Begin to compile the (general) safety case for disposal in salt

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PAMINA

The PAMINA Project

Jörg Mönig

PAMINA Final Workshop

Schloss Hohenkammer, 28.09.2009

IP PAMINA – General information

- Performance Assessment Methodologies in Application to Guide the Development of the Safety Case
- October 1, 2006 – September 30, 2009
- www.ip-pamina.eu

- Germany: GRS, BGR, DBETec, FZK, TUC
- France1: ANDRA, CEA, IRSN, Univ. Lyon
- Spain: Enresa, UPV, UDC, Amphos 21
- UK: NDA, Galson Sciences
- Belgium: ONDRAF, SCKCEN, Bel-V
- Switzerland: NAGRA, AF-Colenco
- Netherlands: NRG
- Czech Republic: NRI
- Finland: Posiva, VTT
- Sweden: SSM, Facilia
- EC: JRC Petten

PAMINA General Objectives

- **promote a common understanding of the techniques and methods for performance assessments and the development of a safety case within the European countries**
  - **notable differences in methodologies to demonstrate the safety of a repository owing to specific national regulations as well as the geological and technical framework**
- **adaptation to the state of the scientific and technical knowledge**
  - **improvement of integrated performance assessment methodologies and tools**
- **innovation in a couple of topics**

A Few PAMINA Observations

- Approaches to safety assessments are more common than different
  - Safety functions / indicators

  or

  - Barrier capabilities / performance

- There are important differences
  - Stylized scenario analysis
  - Fully probabilistic analysis

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Points to Consider

- Role of Safety Indicators and Safety Functions
  - Safety Indicators are quantities compared to regulatory standards
  - Safety Functions are those features, events and processes which contribute to safety of the repository
- Safety indicators support judgments about compliance
- Safety functions evince understanding of the system and its robustness

- Common ground here for technical collaboration

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Points to Consider (cont.)

- Treatment of human intrusion
  - 'most speculative potential disruption' 40 CFR 191
  - In the U.S. analysis circumscribed by regulation
  - Quite different for WIPP and for Yucca Mountain
    - WIPP – probabilistic treatment
    - Yucca Mtn – separate scenario with separate protection standard
  - New regulatory criteria (e.g., 10 CFR 194) will be needed for a future repository

- Need for safety case developers to communicate with those drafting regulatory guidance

- Discussions will be organized around national regulations

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Summary

- Opportunities for collaboration

  - Compile safety case for disposal in salt
  - Develop safety functions and safety indicators

- Scenario development will likely remain a national discussion

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Towards a German Safety Case – The ISIBEL Project

Jörg Mönig
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH,
Theodor-Heuss-Str. 4, D-38122 Braunschweig, Germany

Abstract

Introduction

The research project ISIBEL aims at developing a novel approach to prove safety for a high-level waste repository in a salt formation, to refine the safety concept and to identify open scientific issues and and to define necessary R&D work. The yardstick for the work is the ability to develop a safety case according to the state-of-the-art.

The project is funded by the German Ministry of Economics (BMWi) and it is concertedly executed by DBE Technology (DBETec), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS). The first project phase covered October 2005 to March 2010; the follow-up project has just started. The work was split into specific work packages. Several individuals were involved from each project partner who are not explicitly mentioned here but contributed significantly to the results. Even though each work package was carried out by a lead contractor, all results were discussed jointly within the project team. The presentation summarises the main findings and common conclusions of the first project phase [1], which are partly published in English [2].

The Fundamentals

In Germany, rock salt formations are regarded as suitable for hosting a HLW repository. Owing to the specific objectives of the research project ISIBEL, boundary conditions were chosen that match as closely as possible the current understanding of geological features and processes at salt domes in Northern Germany and the technical developments with respect to repository design options.

The amount of waste to be disposed off results from the present status of the German Atomic Act, i.e. the decision to phase-out nuclear energy production. The different wastes from reprocessing spent fuel elements are disposed off in thin-walled stainless steel casks having 440 mm diameter and a length of about 1.441 mm. In total 3767 canisters with high-level vitrified waste (CSD-V), 6902 canisters with compacted technological waste (CSD-C) and 560 canisters with medium level vitrified waste (CSD-B) are to be disposed off. Two different disposal options were considered for spent fuel, drift disposal in thick-walled POLLUX casks (2045 casks) and borehole disposal in thin-walled BSK3 casks (6817 casks).

The work in ISIBEL concerns a stylised reference site [3] featuring the geological situation at the Gorleben site, which has been investigated intensively as a possible site for the HWL repository. However, the site investigation at Gorleben has not been completed yet. The ISIBEL reference site is a salt dome of Permian age. The diapirism of the salt dome is virtually completed and the long-term subrosion rates are very low. The reference site possesses large areas of homogeneous salt rock of the Staßfurt series (z2HS), which contains only very small amount of solution. The anhydrite layer of the Leine series is fractured into isolated blocks, which have no hydraulic connection. This implies that the release of radionuclides via the main anhydrite, often regarded as an all-encompassing reference scenario in the past, is irrelevant for the safety assessment.

The repository concept was developed by DBETec [4]. It is based on the German reference concept of 1998 and includes new waste types, such as the thin-walled stainless steel canister for

spent fuel rods (BSK3) and a more detailed design of geotechnical barriers, i.e. the shaft and drift seals. The repository layout features two shafts and an infrastruture area located in salt formations of the Leine series at a depth of about 840 m. Two access drifts that are 300 m apart connect the infrastructure area with the disposal areas, which are fully situated in the Staßfurt rock salt z2HS. The access drifts embrace the disposal areas and they are connected by cross-cuts, from which the disposal galleries are accessible. In order to accommodate the waste several disposal areas for spent fuel, one for CSD-V canisters and one for CSD-C canisters are required.

Upon repository closure high performance shaft and drift seals with dedicated hydraulic properties will be built. The drift seals are located in the Staßfurt rock salt at the transition zone to the salt of the Leine Series in order to seal off the disposal areas from the infrastructure area. These geotechnical barriers have to meet specific requirements that can be derived from the tasks and functions of the respective component within the safety concept. In this context, the focus is on demonstrating safe containment during undisturbed repository development. The shaft and drift seals are to be placed and designed in such a way that brine intrusion to the waste via the shaft and the drifts that are backfilled with crushed salt and a subsequent forcing out of contaminated solutions via the same pathway will not occur. Additional requirements may arise from the relevant release scenarios determined in the scenario analysis. The mine workings will be backfilled with crushed salt. Owing to the salt creep the remaining void volume will decrease gradually by and by.

Elements of the Concept to Demonstrate Safety

A concept for a safety assessment was developed and applied for the very first time which takes full account of the advantages of the final disposal of HLW in rock salt and thus of its safe containment. Consequently, the long-term safety assessment focuses on the systematic demonstration of the safe long-term containment of the waste by demonstrating the integrity of the geotechnical barriers and of the geological main barrier. The evaluation of radionuclide releases is carried out on a complementary basis for those evolutions of the final repository for which an impairment of the integrity of the barrier system resulting in the creation of a continuous pathway for radionuclides cannot be ruled out. The assessment whether these evolutions are to be considered as likely, little likely, very unlikely or whether they can even be excluded is the result of the scenario analysis.

Integrity of the Geological Barrier

The assessment of the integrity of the salt barrier is primarily based on the results obtained from mechanical and thermo-mechanical model calculations, e.g. using the finite elements method, which accurately describe the physical processes in the rock that are to be expected in the long term. As part of a holistic approach, geological and geo-engineering explorations, laboratory analyses of petrophysical properties, geotechnical in-situ measurements and surveys, on-site observations, and mining experience from comparable geologic media and mines are to be taken into account in addition to purely numerical calculations [5]. Generally, large-scale three-dimensional predictive models are to be used, depending on the objective.

The functionality and integrity of the salt barrier is considered to be mathematically proven if the formation of pathways can be ruled out from a geomechanical point of view. For salt rock areas capable of creep, two criteria may be applied according to current scientific knowledge [6]:

- Dilatancy criterion: The integrity of the barrier is ensured if no damage in the rock mass occurs. Comprehensive laboratory analyses of the petrophysical properties of rock salt showed that stress states below the dilatancy limit do not cause any damages, not even in the long term, which means that for stress states in this range, the impermeability of the salt rock is ensured. Only stress states above the dilatancy limit cause a loosening of the microstructure, which in turn leads to the gradual formation of a network of microfissures if such conditions persist.

- Brine pressure criterion: The integrity is ensured if the lowest main compressive stress does not drop below the value of the hydrostatic pressure to be assumed at the corresponding depth. This pressure is calculated from a hypothetical column of liquid that extends to the surface. Usually, the liquid is assumed to be a brine solution with a density of 1.2 kg/l.

Practical application of these two criteria, which initially were assumed to be equally important, showed that as a rule (primarily intact outer fringe area), conditions enabling the intrusion of brines from the overburden or the surrounding rock are only possible if the dilatancy criterion is not met.

Integrity of the Geotechnical Barriers

The demonstration of the integrity of the geotechnical barriers, such as the drift and shaft seals, involves the consideration of the integrity of the barrier structure itself and of the hydraulic properties and their corresponding evolution over time of the barrier structure, the excavation damage zone (EDZ) and the contact zone between both [7]. The requirements on the hydraulic resistance of the barriers are determined by the calculations on radionuclide transport carried out in the long-term safety analysis.

The proof of the integrity of the barrier structure is based on three components, i.e. the proof of the structural and mechanical stability of the barrier structure, the proof of limited fractures and the proof of the long-term chemical durability. Possible impacts on the barrier structure, as derived in the scenario development, have to be taken into account. Furthermore, is has to be demonstrated that the seals can be built as specified.

The requirements on the hydraulic resistance as well as on the design life of the shaft and drift seals are directly correlated with the compaction behaviour of the crushed salt backfill material. In-situ experiments and analogies suggest that it is possible to achieve complete containment. However, the processes taking place can currently not be described in full detail. The most important parameters that determine the behaviour of the crushed salt backfill are the geometric values porosity and grain size, which is generally specified through the grain-size distribution curve, the compaction rate, the stress level and the stress state, the temperature, the moisture content or saturation, and the mineralogical composition. Usually, several parameters influence the physical effect of the material behaviour to be described. In the case of thermal conductivity, the factors are the porosity and the degree of saturation in the pores, and possibly the stress level. Thus, when describing the material behaviour, these parameters need to be taken into account. Currently it is possible to provide a detailed description of the material behaviour and thus of the compaction behaviour down to a residual porosity of 10%; for porosities below 10%, however, there is still need for further research in order to be able to carry out substantiated predictive calculations.

Scenario Development

The identification and subsequent quantitative analysis and evaluation of scenarios, each of which represents one of the possible future developments of the final repository system, are essential components of the long-term safety assessment of a final repository. The individual scenarios are characterised by features, events, and processes (in short FEP) that may influence the future evolution of the final repository system. Salt rock has one integral characteristic that distinguishes it from other types of rock analyzed worldwide as potential host rocks. As salt is an impermeable type of rock with only a few brine inclusions of macroscopic relevance, high-level radioactive waste emplaced in salt can only come into contact with large amounts of brines under very specific circumstances. However, the presence of ample brine quantities is the central characteristic that may lead to a release of radionuclides from the waste and to the transport of these nuclides into the biosphere. Thus, experience in scenario development and FEP identification made in other countries can only be transferred to a limited extent.

Based on the geological situation at the reference site, the repository concept and the different types of waste, a FEP catalogue for a final repository for HLW in a salt diapir was systematically compiled for the very first time in the ISIBEL project. Different methodical approaches were pursued and finally consolidated in order to contribute towards the completeness of the FEP catalogue. The different methodical approaches each have their advantages as well as inherent disadvantages. One approach had the goal of identifying all the FEPs that, principally, may have an impact on the geological evolution at the reference site or on the geosphere of the final repository system, as well as their potential consequences on the waste emplaced. This method may be designated as a 'bottom-up' approach. Another methodical approach for the development of scenarios to be assessed and for the identification of FEPs to be considered focused on the issue of if and how brines could be able to come into contact with the waste. Based on this top-down approach, conceivable scenarios were identified that could lead to the failure of one or more geological or geotechnical barriers. The starting point of these considerations was that as a consequence of such sequences of events, radionuclides might be released from the waste and even be transported into the biosphere. In a second step, all FEPs that play a role in these scenarios were identified and described. The main difficulty of this method is to prove that the list of scenarios is complete and that all relevant FEPs have been identified. As a result it was concluded that for scenarios concerning a final repository in a salt formation, a procedure which suitably combines elements of a bottom-up approach with those of a top-down approach seems to be the most appropriate.

In a final repository in salt rock, the waste emplaced can only come into contact with brines from the overburden and surrounding rock if one or more barriers have failed. Due to the choice of the site and the design and layout of the final repository mine with its geotechnical barriers, a failure of the geological barrier or of the geotechnical barriers can only occur under specific boundary conditions. Although the probability that such events occur is generally very low, these events cannot be completely ruled out. Therefore, they need to be taken into account when defining the scenarios. A detailed understanding of the conditional probabilities of occurrence of the individual FEPs and of their interdependencies and interactions is therefore required for the safety assessment of the scenarios. Pertinent information has been included, therefore, in the descriptions of FEP in the FEP catalogue.

Starting with the identification of FEP that may impair the barriers that provide effective containment and considering the likelihood of their occurrence and of their individual characteristics, scenarios are developed by taking the interdependencies of FEP and their chronological sequence into account. This method has been successfully employed to derive the reference scenario. Owing to the many different pieces of information, which result mainly from the consideration of the FEP interdependencies, this method is very elaborate. In principle, however, it provides the opportunity to develop scenarios in a transparent and traceable way. Regarding the clarity of the method applied for the development of scenarios, further testing of the procedures and their descriptions is required.

Proof of Safe Containment

One methodological challenge is to demonstrate the safe containment of the radioactive waste within the isolating rock zone (IRZ). This complements the demonstration of the integrity of the geological and the geotechnical barriers. A method has been developed in ISIBEL [8] which allows the qualitative and quantitative evaluation of radionuclide transport processes for those scenarios, where a continuous pathway for solutions from the waste to the biosphere is existent. It includes the numerical evaluation whether radionuclide releases from the isolating rock zone are radiologically insignificant. The method involves an applicable definition of the IRZ as well as the definition of suitable indicators.

The isolating rock zone lies within that part of a salt dome which is not affected by geological processes, such as subrosion or erosion, at the given time. Within the IRZ all mine workings have sufficient distance to geological strata which could develop pathways to groundwater bearing formations

The qualitative and quantitative evaluation of solution and radionuclide transport processes yields a staged assessment. Complete containment is regarded as the most stringent form of safe containment. Complete containment is given when no contact between intruding solution and waste occurs or when no radionuclides are released from the IRZ, respectively. In order to demonstrate safe containment, a radiological pettiness index (RPI) has been defined, which is a dimensionless number calculated as follows. Annual radionuclide fluxes from the IRZ are taken up in a defined low volume of groundwater yielding a calculated radionuclide concentration. By applying a generic, rather conservative biosphere model potential radiation exposures are calculated from this radionuclide concentration. The RPI is then calculated by relating these calculated potential exposures to a limit value of 0.1 mSv/a. As long as the RPI is below 1, the radionuclide releases from the IRZ can safely be considered to be radiologically insignificant.

Conclusions

In the research project ISIBEL, for the first time, a consistent concept for the safety assessment was developed that takes full account of the advantages inherent in the disposal of high-level radioactive waste in salt formations. This concept focuses on the systematic demonstration that safe containment of the emplaced waste is achieved. The demonstration is based on proving the integrity of both the geological barrier as well as the geotechnical barriers in the likely evolutions of the repository system. It is complemented by the assessment of system evolutions for which an impairment of the integrity of the barrier system, and thus the formation of a continuous pathway for radionuclide formation cannot be excluded. Whether such evolutions are to be regarded as being likely, little likely or even unlikely is the result of a scenario development. A comprehensive FEP catalogue for a final repository for HLW has been compiled for the first time. It forms the basis for a transparent and traceable identification of scenarios, each of which represents one of the possible future evolutions of the repository system. Finally, a scheme has been developed which allows assessing that radionuclide releases from the isolating rock zone are insignificant. In addition to this, the methods and documents to demonstrate operational safety and compliance with the non-radiological protection goals in the post-closure phase were considered. It is expected that the results from the research project ISIBEL provide the basis for future safety cases for a HLW repository in a salt formation in Germany.

References

[1] Überprüfung und Bewertung des Instrumentariums für eine sicherheitliche Bewertung von Endlagern für HAW – ISIBEL. – Gemeinsamer Abschlussbericht von BGR, DBE TECHNOLOGY GmbH und GRS. Hannover, Peine, Braunschweig, April 2010.
[2] English translation: Review and Examination of the Tools available for a Safety Assessment of Final Repositories for HLW – ISIBEL. – Joint report by DBE TECHNOLOGY GmbH, BGR, and GRS. DBE TECHNOLOGY GmbH, Peine, April 2008.
[3] Langzeitsicherheitsanalyse für ein HAW-Endlager im Salz – Geologisches Referenzmodell für einen HAW-Endlagerstandort im Salz – Technischer Bericht. Beitrag für das Projekt ISIBEL. BGR, Hannover, Tagebuchnummer 11614/05, Juli 2007.
[4] Konzeptionelle Endlagerplanung und Zusammenstellung des endzulagernden Inventars. – DBE TECHNOLOGY GmbH, Peine, April 2008.
[5] Nachweis der Integrität der geologischen Barriere. – BGR, Hannover, Tagebuchnummer 10403/08, September 2007.
[6] Heusermann, S.: Beurteilung der geomechanischen Stabilität und Integrität von Endlagerbergwerken im Salzgebirge auf der Grundlage geologischer und ingenieurgeologischer Untersuchungen. – Geologische Beiträge Hannover, 2, 159-174. 2001.
[7] Nachweiskonzept zur Integrität der einschlusswirksamen technischen Barrieren. – DBE TECHNOLOGY GmbH, Peine, April 2008.

[8] Nachweis und Bewertung des Isolationszustandes „Sicherer Einschluss“. – Gemeinsamer Bericht von BGR, DBE TECHNOLOGY GmbH und GRS. Hannover, Peine, Braunschweig, April 2010.

Towards a German Safety Case
The ISIBEL Project

Jörg Mönig

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Theodor-Heuss-Str. 4
D-38011 Braunschweig, Germany

US-German Workshop on Salt Repository Research, Design and Operation
May 25-28, Jackson, Mississippi, USA

The ISIBEL project

Objectives

- refinement of safety concept for HLW disposal in rock salt
- development of a novel approach to demonstrate safety
- identification of necessary R&D

Project partners

- Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover
- DBE Technology, Peine
- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

Research project

- funded by German Ministry of Economics (BMWi)
- duration: Oct. 2005 – Mar 2010, second phase started Apr 2010

yardstick

- ability to develop a safety case according to state-of-the-art

Fundamentals

Waste amount and characteristics

- amount according to present status of German Atomic Act (phase-out decision)
  - spent fuel
    - 2045 POLLUX casks or 6817 BSK3 casks
  - vitrified waste from reprocessing
    - 3767 CSD-V
    - 6902 CSD-C + 560 CSD-B

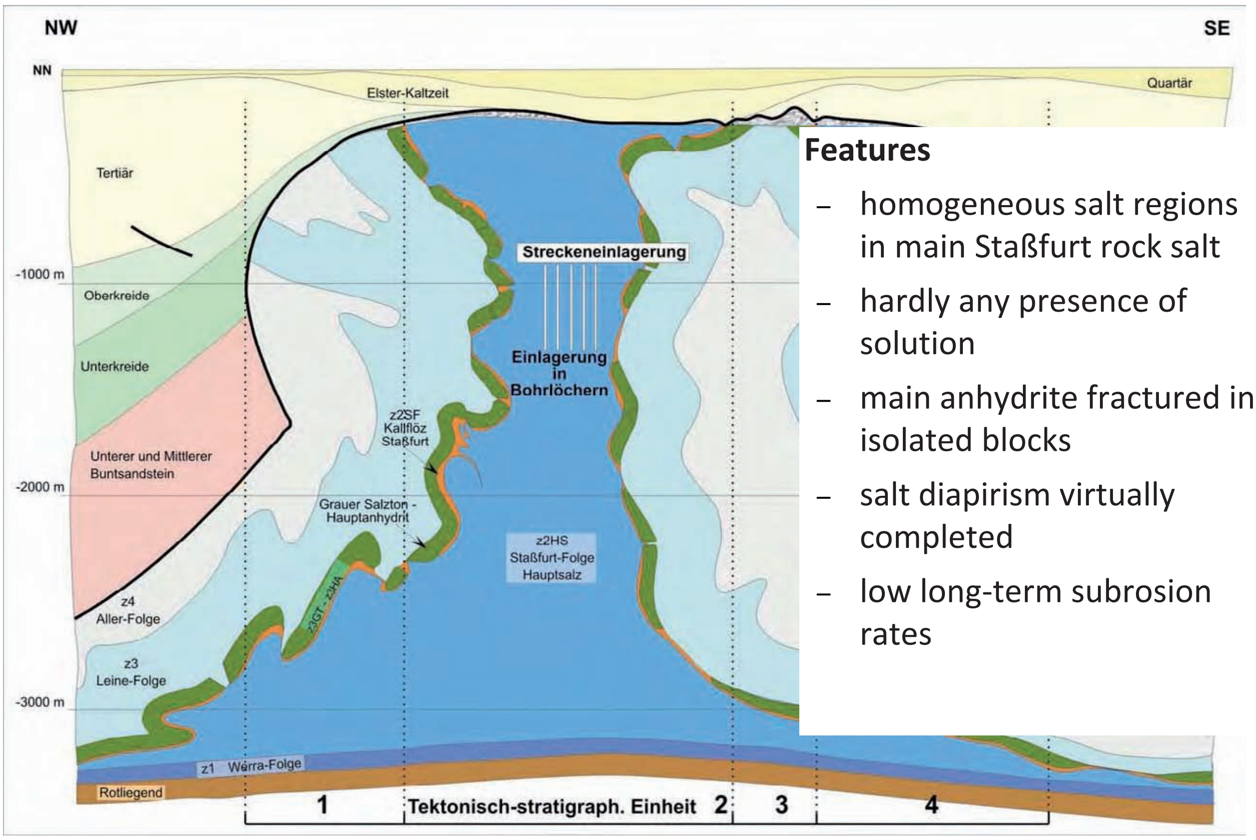
Geology

- available knowledge concerning salt domes in Northern Germany potentially suitable (stylized site model)

Repository concept

- based on reference repository concept of 1998
- including new waste types (BSK3) and more detailed design of geotechnical barriers

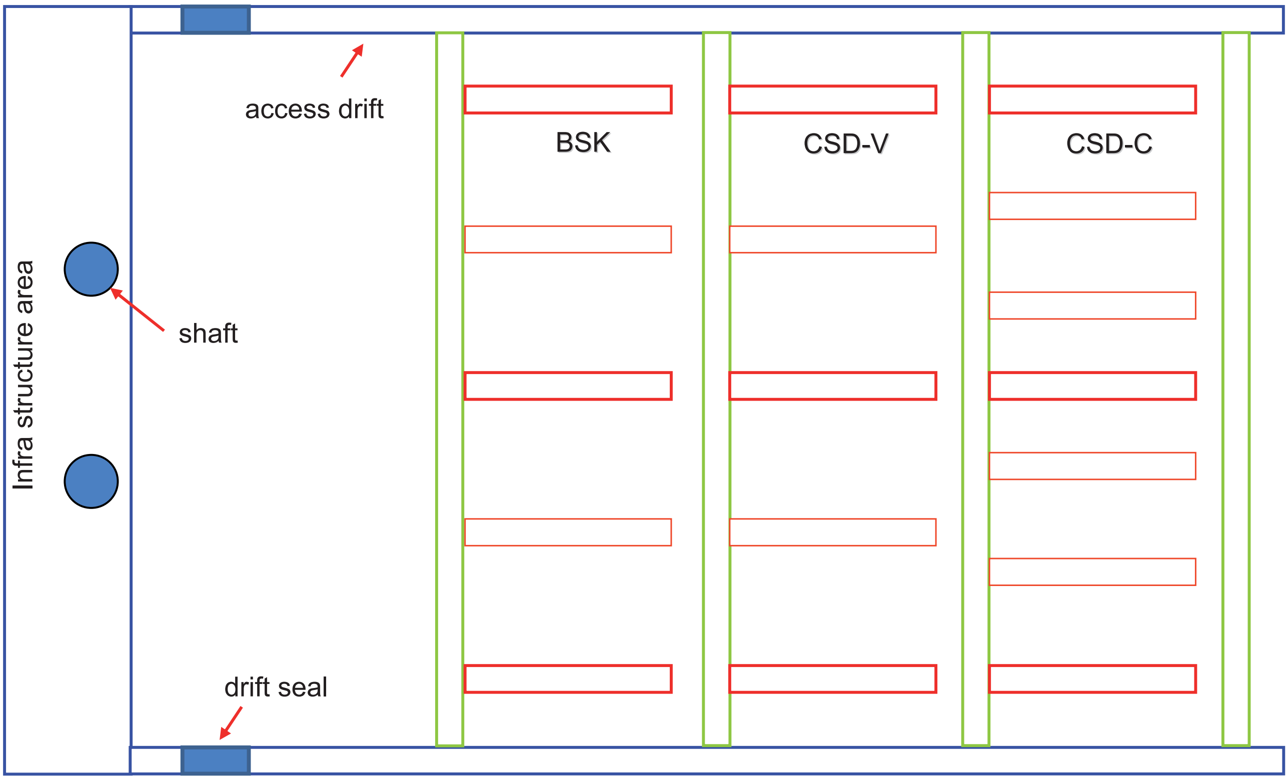
Stylized site model



Features

- homogeneous salt regions in main Staßfurt rock salt
- hardly any presence of solution
- main anhydrite fractured in isolated blocks
- salt diapirism virtually completed
- low long-term subrosion rates

Schematic repository layout



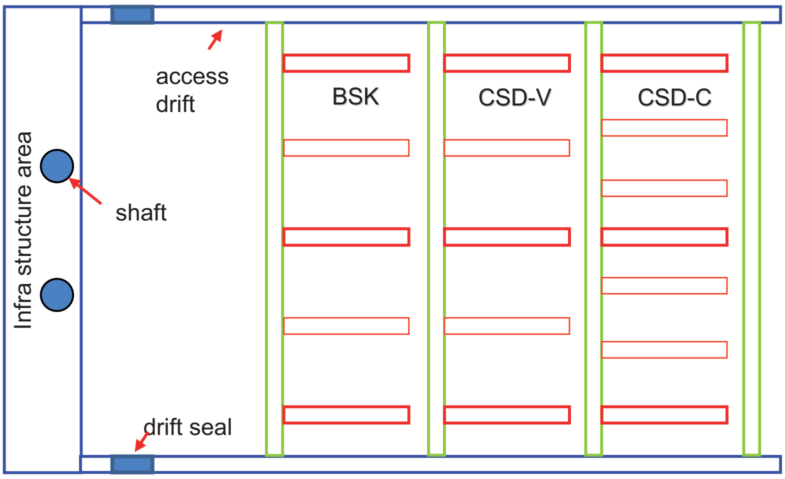
Schematic repository layout

infrastructure area wih two shafts

- located in Leine salt facies (z3)

two access drifts embracing disposal areas, connected by cross cuts

- located in Staßfurt main rock salt (z2HS)
- several disposal areas
  - 8 BSK3, 1 CSD-V, 1 CSD-C

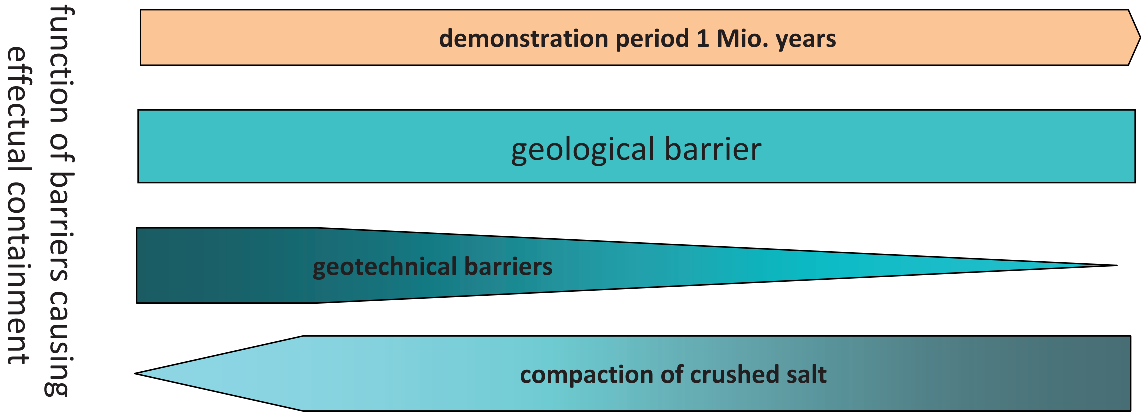


designed high-performance shaft and drift seals

repository void volume is backfilled with crushed salt

repository void volume will fade away due to salt creep

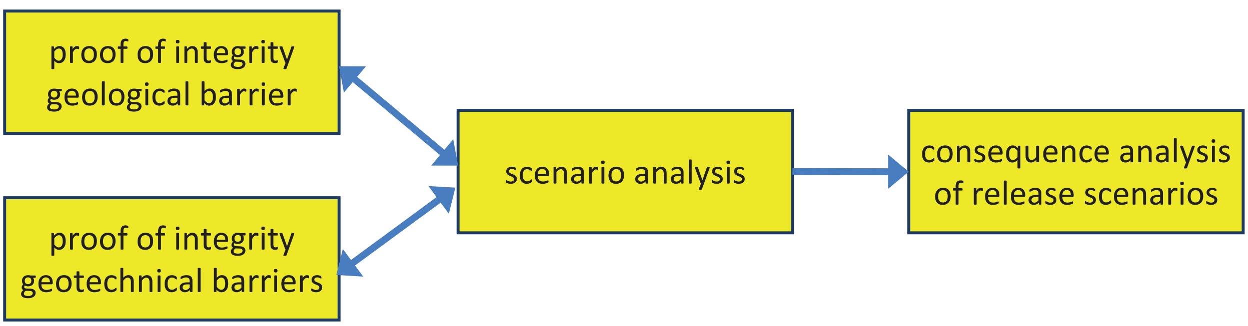
Functional requirements to demonstrate safety



New approach to demonstrate safety

proof of
safe containment

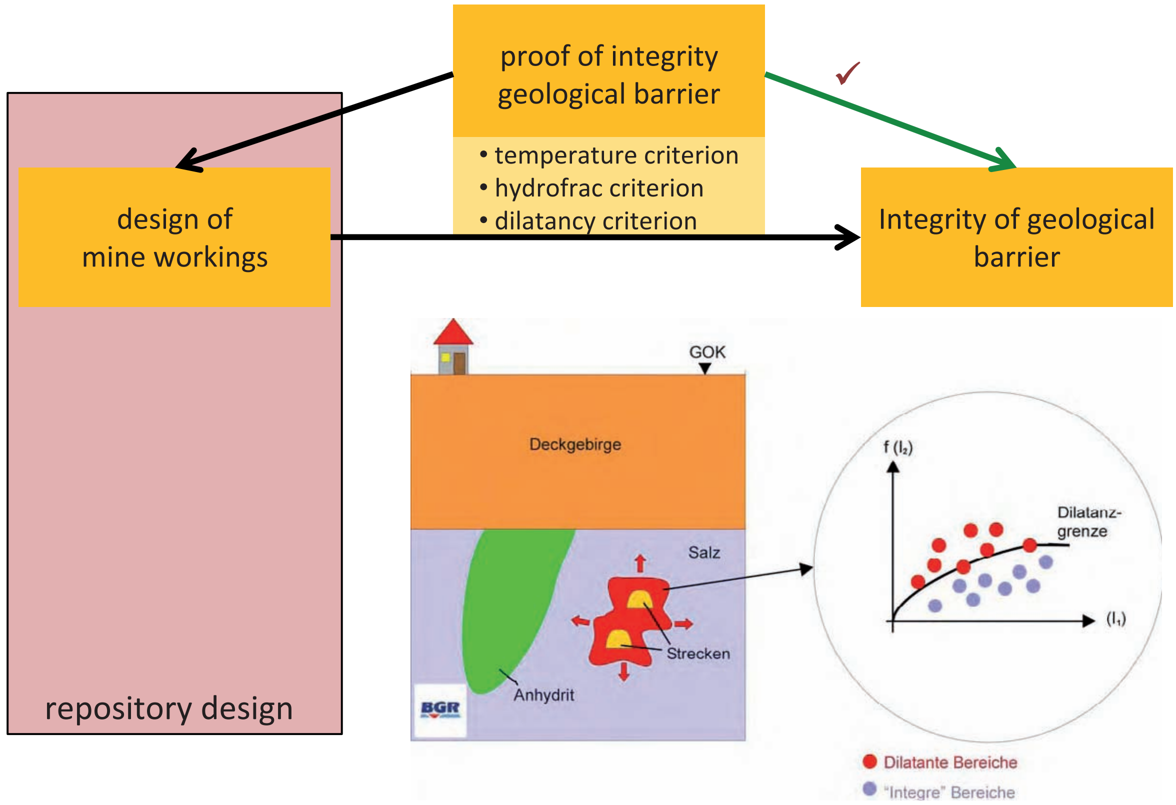
assessment of
radionuclide releases



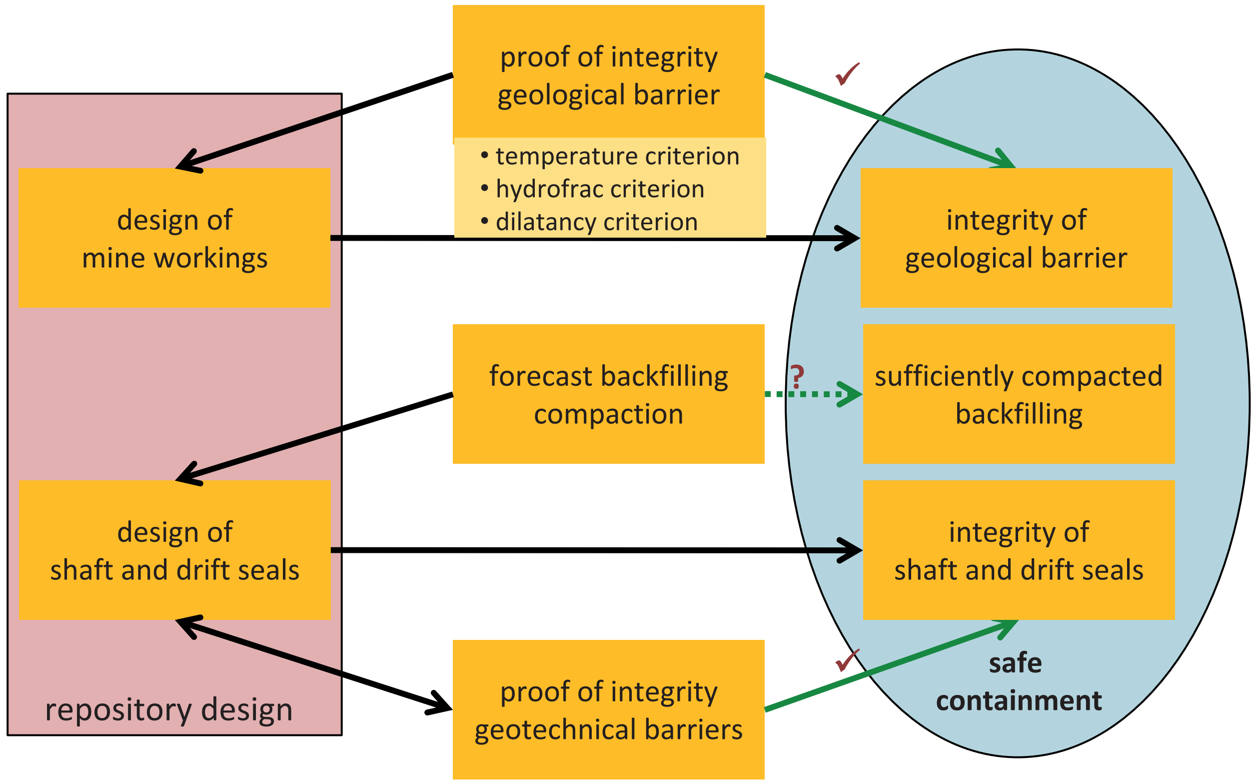
normal evolution

altered evolutions

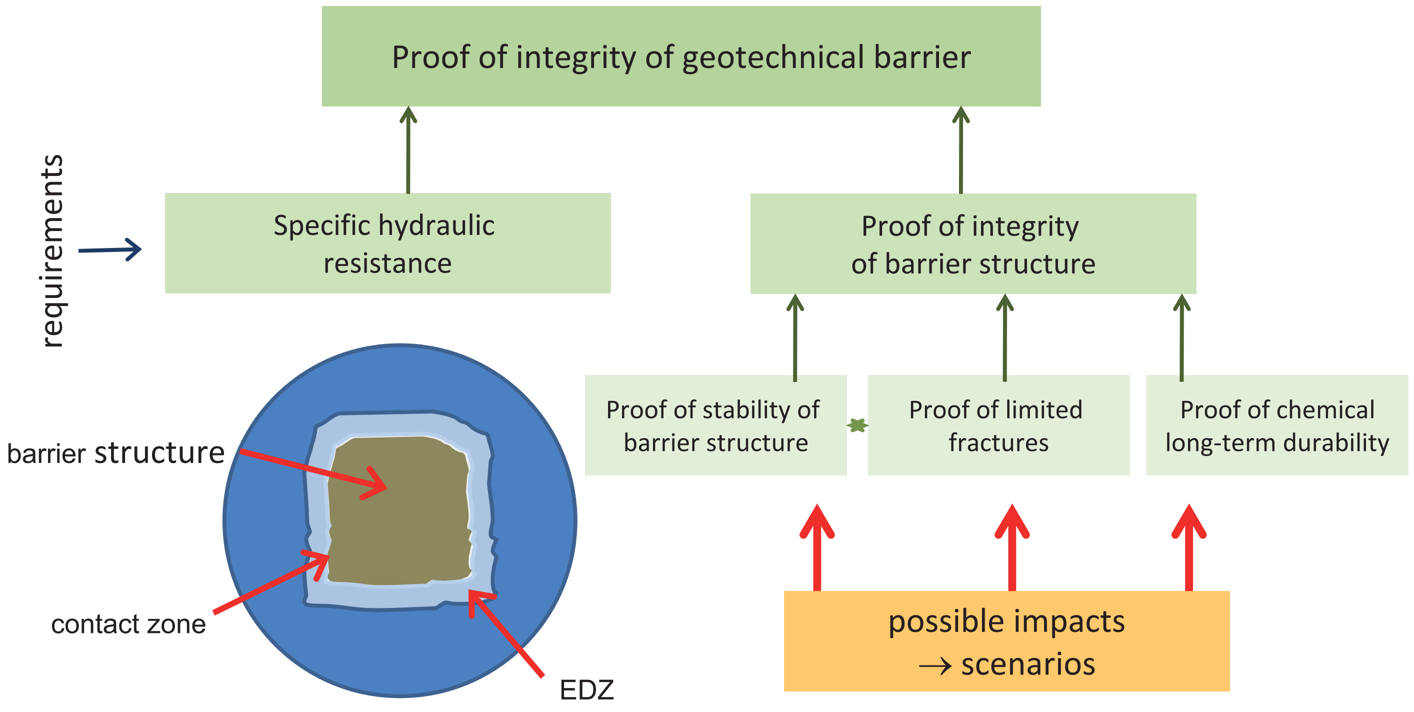
Concept to demonstrate safety



Concept to demonstrate safety



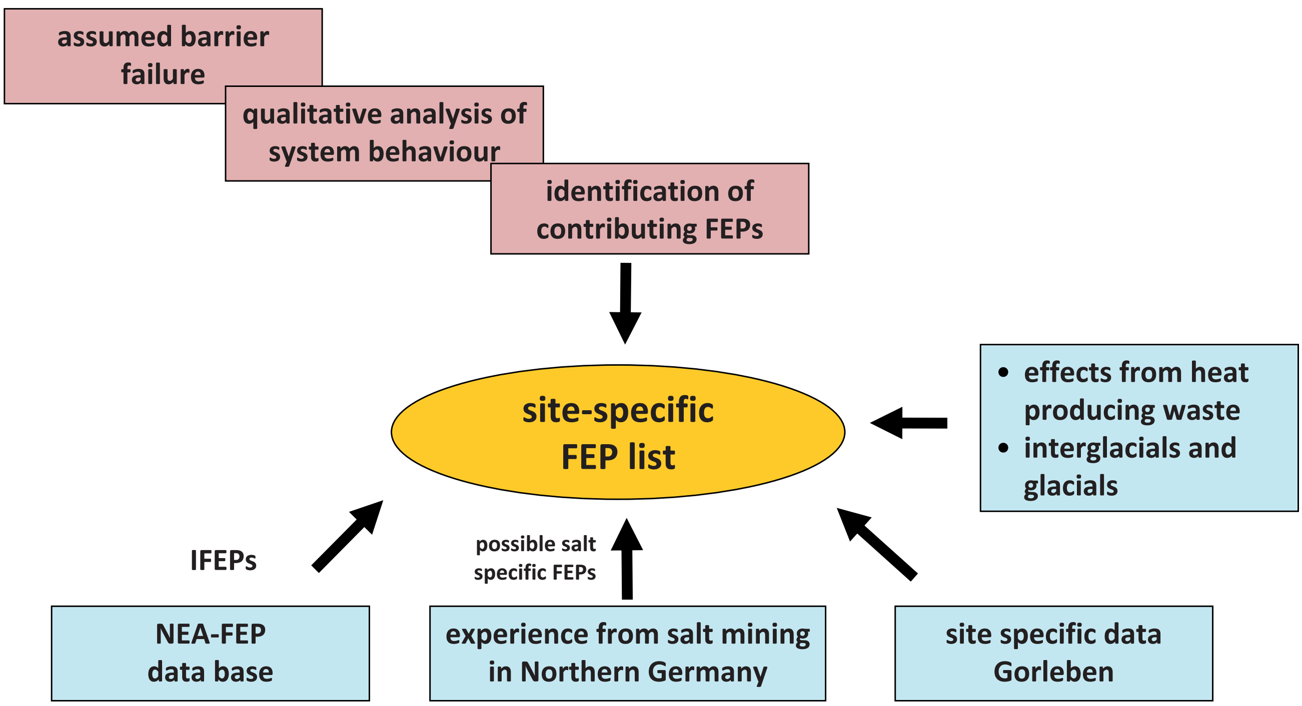
Integrity of geotechnical barriers



Development of Scenarios

Development of a comprehensive FEP catalogue

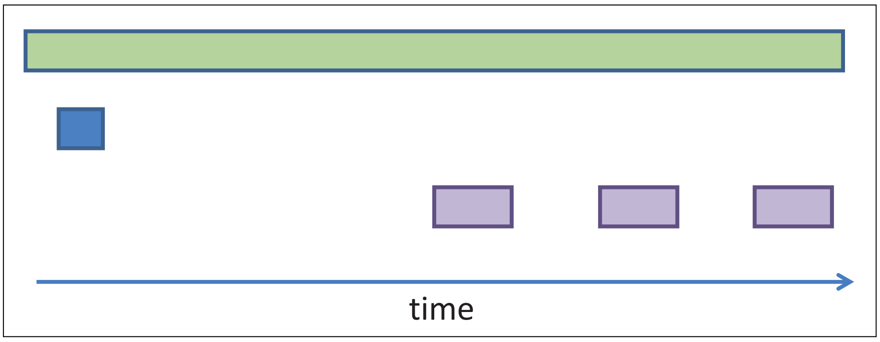
- combined top-down and bottom-up approach to identify relevant FEP



Development of Scenarios

Development of a comprehensive FEP catalogue

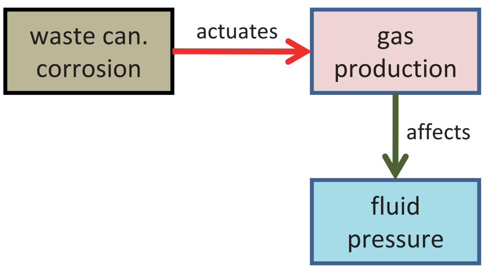
- combined bottom-up and top-down approach to identify relevant FEP
- systematic description of each FEP
  - detrimental effects of containment relevant barriers?
  - time frame of action



Development of Scenarios

Development of a comprehensive FEP catalogue

- combined bottom-up and top-down approach to identify relevant FEP
- systematic description of each FEP
  - detrimental effects of containment relevant barriers
  - time frame of action
  - interaction with other FEPs
    - actuating FEPs ⇔ resulting FEPs
    - affecting FEPs ⇔ affected FEPs



  - conditional probability of occurence
    - probable / less probable / not to be regarded / boundary condition
  - unresolved issues
- realised in database format

Development of Scenarios

Reference scenario

- selection of all probable FEPs from FEP database
- selection of FEPs with detrimental effects on containment relevant barriers
- selection/consideration of actuating and resulting as well as influencing FEPs
- consideration of time frame of action
- consideration of probable characteristics of FEPs

Altered evolution scenarios

- same principal procedure
- inclusion of less probable FEPs and less likely characteristics of probable FEPs

Safe Containment in the IRZ

Staged approach to proof safe containment of radionuclides in the IRZ

Definition of isolating rock zone necessary (duty of implementer)

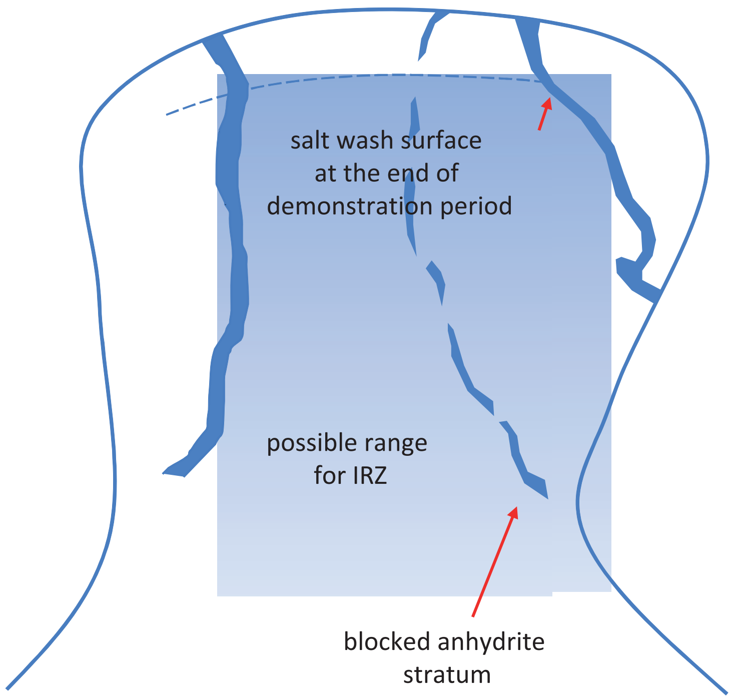
Formation of a continuous pathway from the waste to the biosphere for solutions

- evaluation of transport processes quantitatively and qualitatively
  - measures?

Impact of radionuclide release from IRZ

- release of radionuclides is sufficiently low
  - measures?

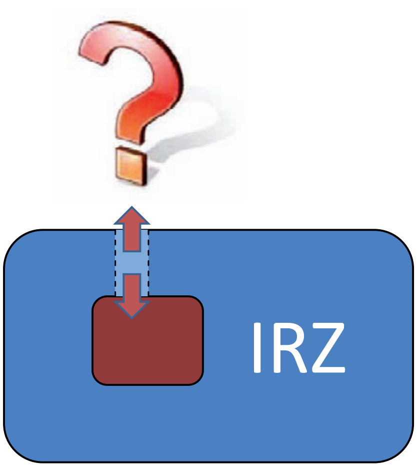
Isolating rock zone



The isolating rock zone lies within that part of a salt dome which is not affected by subrosion or erosion processes at the given time

Within the IRZ all mine workings have sufficient distance to geological strata which could develop pathways to groundwater bearing formations

Evaluation of transport processes



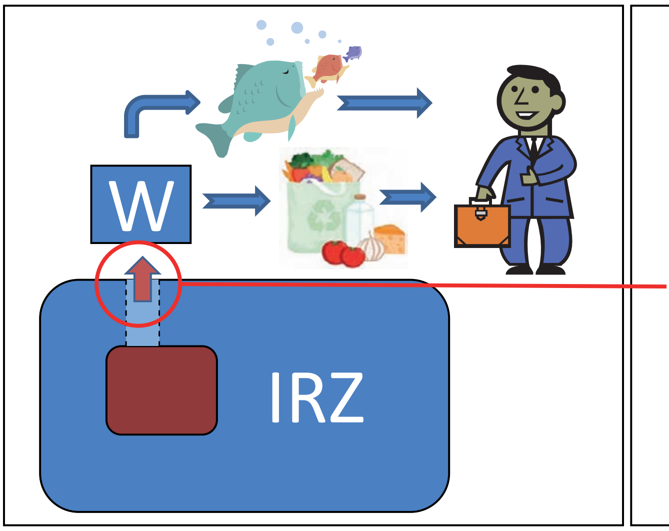
Indicators used:

- amount of solution released from IRZ after 10^6 a [m^3]
- start of solution release [a]
- start of radionuclide mobilisation [a]
- start of radionuclide release from disposal area [a]
- end of salt creep, i.e. of convergence process [a]
- dominating transport pathway for radionuclides

very illustrative, flexibly applicable (grading of safe containment)

no complete quantification possible

Radiological pettiness index



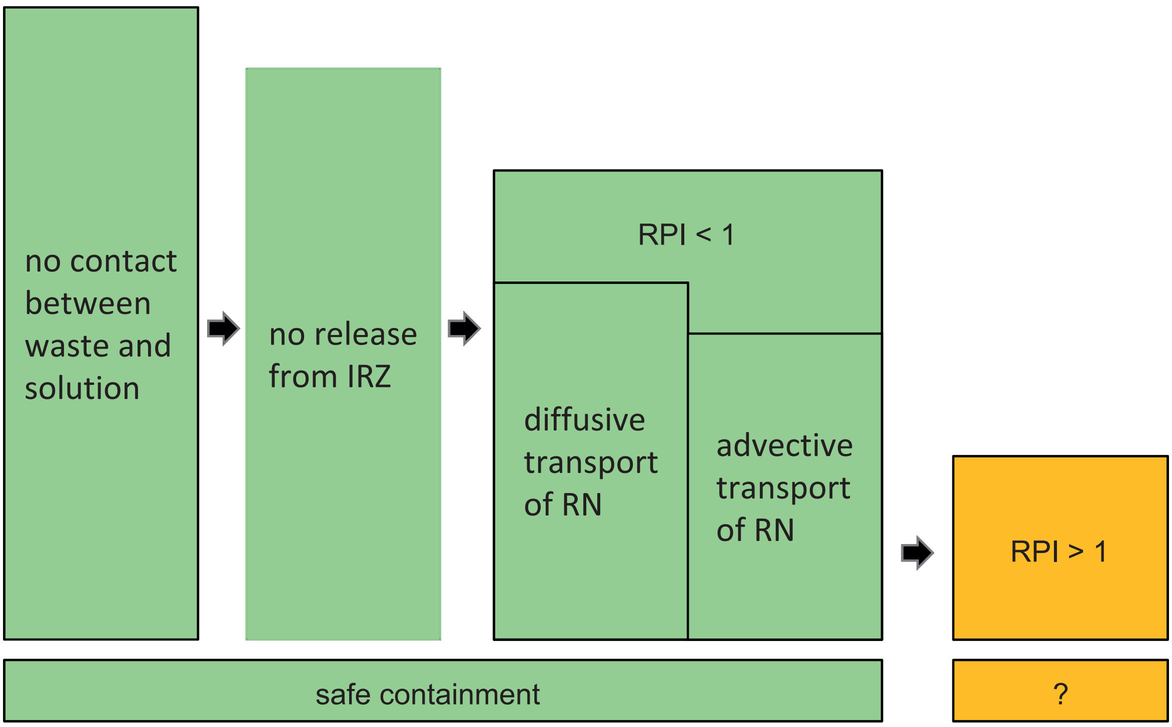
activity fluxes [Bq/a] — dose conversion factors

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

500 m³/a — inspection level: 0,1 mSv/a

- 👍 safety relevance, comparison with radiation exposure in biosphere
- 👎 stylised scenario is used

Safe Containment



Conclusions

A novel concept to demonstrate safety has been developed, tested and shown to be applicable for the disposal of HLW in a repository in rock salt

- primary focus is to proof the safe containment of the waste within IRZ
    - integrity of geological and geotechnical barriers important aspect
- proof compliance with safety requirements for possible radionuclide releases

Methods have been developed and tested

- for developing scenarios (based on a comprehensive FEP catalogue)
- for proving integrity of geological and geotechnical barriers
- for addressing uncertainties comprehensively in the Safety Case
- for calculating radiological consequences of radionuclide releases from the IRZ
- for evaluating non-radiological consequences

Necessary R&D has been identified

Tools are at hand which are suitable to develop a Safety Case for the Gorleben Site

FROM RELEASE SCENARIO TO SAFE CONFINEMENT - EVOLUTION OF THE SAFETY CASE FOR HLW DISPOSAL IN ROCK SALT

Klaus-Jürgen Röhlig, TU Clausthal, J. Krone, DBE TECHNOLOGY GmbH

In the 80ies and 90ies post-closure safety demonstrations were focused on numerical compliance with radiological protection objectives. Despite of the fact that confinement is the ultimate objective of disposal, modelling was focused on release and migration as well as on radiological considerations. Moreover, in some cases the linkage to the factual bases of assessment (site investigation and R&D results, design development etc.) was rather loose – parameter values and assumptions underlying the calculations were not always justified. Lack of confidence in this approach as well as backlashes of a number of national programs have lead to contemporary demonstration methods often described as “Safety Case”. A Safety Case takes a holistic view on site investigation, R&D, the safety concept, repository layout and engineering, and the safety assessment in which assessment calculations form one (central) of multiple lines of evidence. Many Safety Cases utilize – in various ways – the concept of “Safety Functions” which establish the linkages between the above mentioned components but are also an important tool for scenario development.

Similarly to the international practise at that time, early German safety assessments for HLW/SNF disposal in rock salt were, despite of the (postulated) objective of confining the radionuclides, focussed on calculating releases e.g. via anhydrite veins. The realism of the underlying scenarios was often not questioned, while the normal or expected evolution (confinement) was not further addressed in safety assessments. Over the years, a number of factors including

- investigation results from the Gorleben site indicating the weak factual basis of release scenarios and
- regulatory developments focussing on the requirement to confine the radionuclides by geologic and geotechnical barriers

have lead to an evolution of the assessment approach. E.g. the primary goal of the approach followed in the ISIBEL project is to demonstrate safe confinement as undisturbed evolution by evidencing the integrity of the geologic and geotechnical barriers. The question about potential disturbances of this integrity leads – via scenario development – to disturbed evolutions (release scenarios) for which – as a secondary goal – compliance has to be demonstrated.

The ISIBEL FEP database (the first FEP database for HLW/SNF disposal in rock salt) was designed to aid this demonstration. In order to increase the confidence in the database, it underwent an external review by independent experts in which advice for further improvements was provided.

Future R&D has to be focused on the performance of geotechnical barriers, in particular on the compaction behavior of salt grit (backfill material) and the demonstration of the long-term integrity of seals. Since the latter have to be designed in order to prevent early brine intrusions and to protect the backfill material as long as compaction is still insufficient, there is a relationship between the two issues which has to be explored by means of scenarios development and safety assessment.

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

References

[1] Larsson A. 1992. The international projects INTRACOIN, HYDROCOIN and INTRAVAL. *Advances in Water Resources*, vol. 15, 85-87.

[2] SKI and NEA, 1987. The International INTRACOIN Project, Background and Results. OECD, Paris.

[3] SKI and NEA, 1992. The International HYDROCOIN Project, Summary Report. OECD, Paris.

[4] SKI and NEA, 1996. The International INTRAVAL Project, Final Results. OECD, Paris.

[5] NEA, 1995. GEOVAL ’94: Validation through model testing, Proceedings of an NEA/SKI Symposium, Paris, France, 11-14 October 1994.

[6] Konikow L.F. & Bredehoeft J.D. 1992. Ground-water models cannot be validated. *Advances in Water Resources*, vol. 15, 75-83.

[7] de Marsily G., Combes P. & Goblet P. 1992. Comment on ‘Ground-water models cannot be validated’, by L. F. Konikow & J. D. Bredehoeft. *Advances in Water Resources*, vol. 15, 367-369.

[8] Bredehoeft J.D. & Konikow L. F. 1992. Reply to Comment. *Advances in Water Resources*, vol. 15, 371-372.

[9] Oreskes N., Shrader-Frechette K. & Belitz K. 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science*, New Series, vol. 263, No. 5147, 641-646.

[10] KFK 1984. Systemstudie Andere Entsorgungstechniken (SAE), Kurzfassung, KWA Nr. 2190/1, Kernforschungszentrum Karlsruhe GmbH.

[11] KFK 1989. Systemanalyse Mischkonzept (SAM), Abschlussbericht Hauptband, KWA Nr. 2190A1, Kernforschungszentrum Karlsruhe GmbH.

[12] DBE 1996. Systemanalyse Endlagerkonzepte (SEK) , Abschlussbericht BMFT FE-Vorhaben FKZ 02E820, Hauptband, DEAB T59.

[13] Storck, R., Aschenbach J., Hirsekorn, R.-P., Nies, A. & Stelte, N. 1988. Performance Assessment of Geological Isolation Systems for Radioactive Waste (PAGIS): Disposal in Salt Formations. EUR 11 778 EN, GSF-Bericht 23/88. Commission of the European Communities, Gesellschaft für Strahlen-und Umweltforschung mbH München, Brussels-Luxembourg.

[14] Hirsekorn R.-P., Nies A., Rausch H. & Storck R. 1991. Performance Assessment of Confinements for medium-level and α-contaminated Waste (PACOMA Project). Rock Salt Option. Final Report. EC, EUR 16634 EN, Luxembourg.

[15] Becker A., Fischer H., Hofer E., Kloos M., Krzykacz B., Martens K.-H. & Röhlig K.-J. 1997. **EV**aluation of **E**lements **R**esponsible for the effective **E**ngaged dose rates associated with the final **ST**orage of radioactive waste: EVEREST project, Volume 3a: Salt Formation, site in Germany. EC, EUR 17449/3a EN, Luxembourg.

[16] Martens K.-H., Fischer, H., Hofer, E. & Krzykacz-Hausmann, B. 2000. Stochastic and deterministic analyses for a generic repository in rock salt in the EU Project SPA "Spent Fuel Performance Assessment". BMU-Schriftenreihe Reaktorsicherheit und Strahlenschutz, BMU-2000-550.

[17] NEA, 2002. Establishing and Communicating Confidence in the Safety of Deep Geologic Disposal (“Confidence Paper”). OECD, Paris.

[18] NEA, 2004. Post-closure Safety Case for Geological Repositories. Nature and Purpose (“Safety Case Brochure”). OECD, Paris.

[19] IAEA, 2006. Safety Standards WS-R-4 „Geological disposal of radioactive waste“. Safety Requirements. Vienna.

[20] NEA, 2008. “Safety cases for the deep disposal of radioactive waste: Where do we stand?” Symposium Proceedings, 23-25 January 2007, Paris, France. OECD, Paris.

[21] NAGRA 2002. Project Opalinus Clay, Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Wettingen/Switzerland. [22] ANDRA, 2005. Evaluation of the feasibility of a geological repository in an argillaceous formation (“Dossier 2005 Argile”). Châtenay-Malabry.

[23] SKB, 2006. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main Report of the SR-Can project. TR-06-09, Stockholm.

[24] Langzeitsicherheitsanalyse für ein HAW-Endlager im Steinsalz; Geologisches Referenzmodell für ein HAW-Endlager im Salz; Technischer Bericht: Beitrag für das Projekt ISIBEL, BGR, Hannover, Juli 2007

[25] Überprüfung und Bewertung des **I**nstrumentariums für eine **si**cherheitliche **B**ewertung von **E**nd**l**agern für HAW -ISIBEL, AP5: Nachweis der Integrität der einschlusswirksamen technischen Barrieren, DBE TECHNOLOGY GmbH, April 2008

[26] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU): Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste. Final version, July 2009, http://www.bmu.de/files/pdfs/allgemein/application/pdf/endfassung_sicherheits anforderungen_en.pdf

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From Release Scenario to Safe Confinement

Evolution of the Safety Case for HLW disposal in Rock Salt

Klaus-Jürgen Röhlig, Institute of Disposal research
J. Krone, DBE TECHNOLOGY GmbH

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-28, 2010
Jackson, Mississippi USA

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Outline

- International developments:
  - Demonstrating compliance for the post-closure phase in the 80ies and 90ies
  - The Safety Case
  - Safety functions
- Developments in Germany:
  - Demonstrating compliance … in the 80ies and 90ies : Early German safety assessments for disposal in rock salt
  - R&D, Gorleben site investigation
  - Site selection (AKEnd), the concept of a "confining rock zone" and regulation development
  - The ISIBEL demonstration concept
  - The ISIBEL FEP catalogue
- Conclusions & outlook

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Demonstrating compliance for the post-closure phase in the 80ies and 90ies

- Numerical compliance with dose / risk / release criteria of particular interest
- Safety assessment focused on modeling release and migration
- Linkage with site characterization, science, design development, R&D rather loose
  (input parameters for SA sometimes rather claimed than derived / justified)

➢ Questions / problems:
  - Despite of considerable national and international efforts (the "…VALs" and the "…COINs"):
    "Groundwater problems cannot be validated"
    (Konikow & Bredehoeft 1992)
  - Predictability of biosphere (and upper aquifers)
  -

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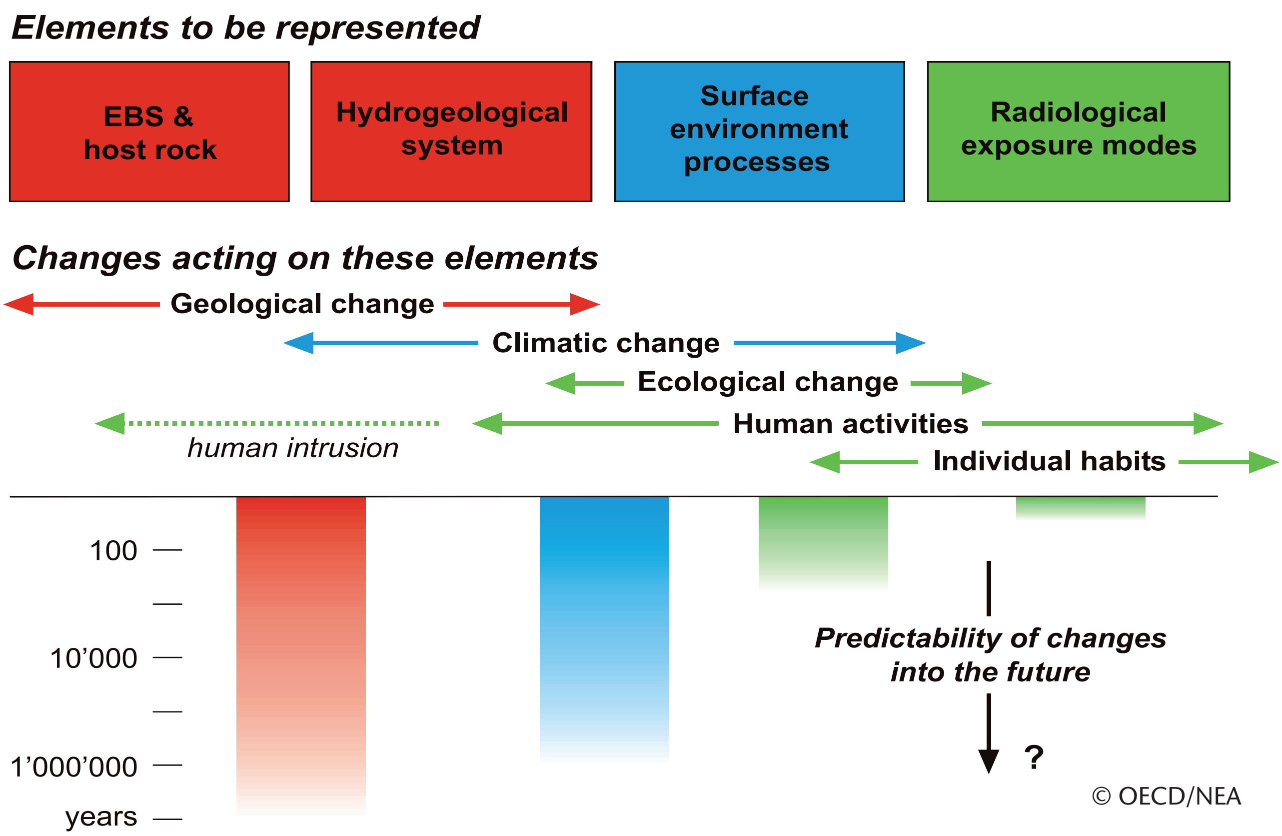
Timescales and predictability



Demonstrating compliance for the post-closure phase in the 80ies and 90ies

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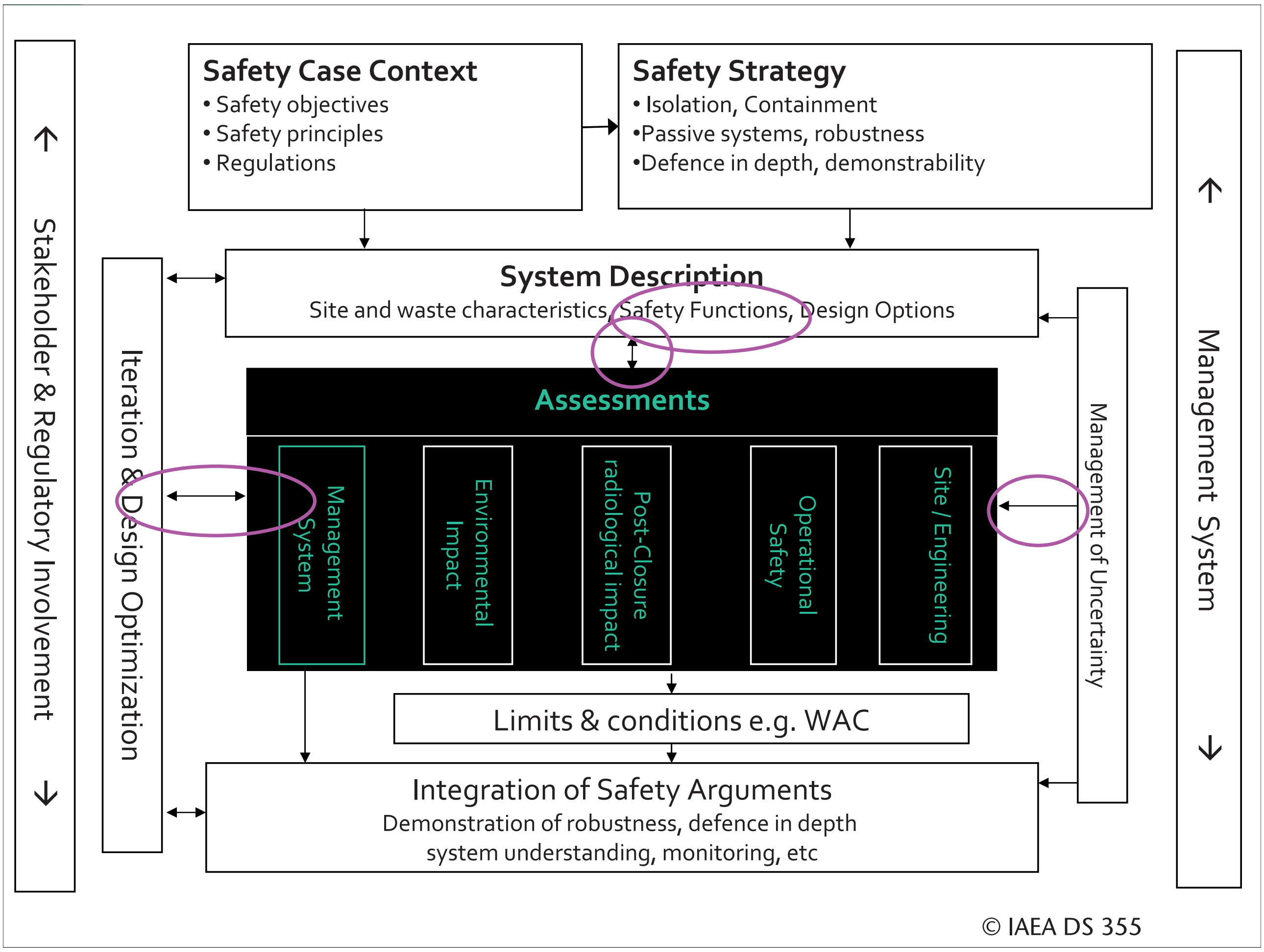
➢ Questions / problems:
- Despite of considerable national and international efforts (the "…VALs" and the "…COINs"):
  "Groundwater problems cannot be validated"
  (Konikow & Bredehoeft 1992)
- Predictability of biosphere (and upper aquifers)
- **More fundamentally: Is there a contradiction (or inconsistency): protection objective (confinement) vs. criteria (release-orientated)**

International developments: The Safety Case

- The Konikow paper as one of the bases
  for criticizing the assessment approaches in general
- At the same time: acceptance problems and backlashes
  for some major programmes (France, UK, Canada, Germany)

- Lessons learnt:
  1. Establish better linkages between components of evidence
     (site investigation, R&D, safety concept, repository layout & engineering, safety assessment)
  2. Establish decision process which is better structured and transparent
  3. Better stakeholder information / involvement

➢ The concept "Safety Case" evolves in national programmes and internationally
- Integration aspect (linkage of arguments) → Lesson no. 1
- Dynamic aspect (SC as evolving basis for decisions in stepwise repository development) → Lesson no. 2



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Safety functions …

- … are expressions of the objectives of disposal
- … establish linkages between safety case components and involved disciplines ("lingua franca") – example France (Dossier 2005):
  - "limiting water circulation"
  - "limiting the release of radionuclides and immobilising them in the repository"
  - "delay and attenuate radionuclide migration"
- … give rise to definition of scenarios → next slide

Safety functions …

- … give rise to definition of scenarios – example France:

  - Normal evolution
    (functions as intended, diffusion-dominated migration)

  - "limiting water circulation“ → seal failure scenario (altered evolution)
  - "limiting the release of radionuclides and immobilising them in the repository“ → failure of thermal waste containers (altered evolution)
  - "delay and attenuate radionuclide migration“
    → intrusive borehole (altered evolution)
  - "generalised failure of all safety functions“
    → severely degraded evolution (altered evolution)

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Definitions (SR-Can, SKB)

- A safety function is a role through which a repository component contributes to safety.

- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.

- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

High-level functions (IAEA WS-R-4) and components

Function	Isolation from biosphere, reduce likelihood of human intrusion	Stability (mechanical, hydraulic, chemical)	Contain waste	Attenuate / delay migration
Granite	Host rock	Canister, buffer	Canister	Fuel matrix, buffer
	Overburden	Host rock		Host rock
Indurated clay	Host rock	Host rock	[Canister] – limited in time!	Host rock [Overburden] Seals
	Overburden			
Rock salt	Host rock	Host rock	Host rock Seals / compacted backfill	Host rock [Overburden] Seals / compacted backfill
	Overburden			

Anthropogenic component (green)	
Geologic component (grey)	

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Examples of lower-level safety functions & corresponding indicators (SR-Can)

Canister

- **C1. Provide corrosion barrier** – Copper thickness > 0
- **C2. Withstand isostatic load** – Strength > isostatic load
- **C3. Withstand shear load** – Rupture limit > shear stress

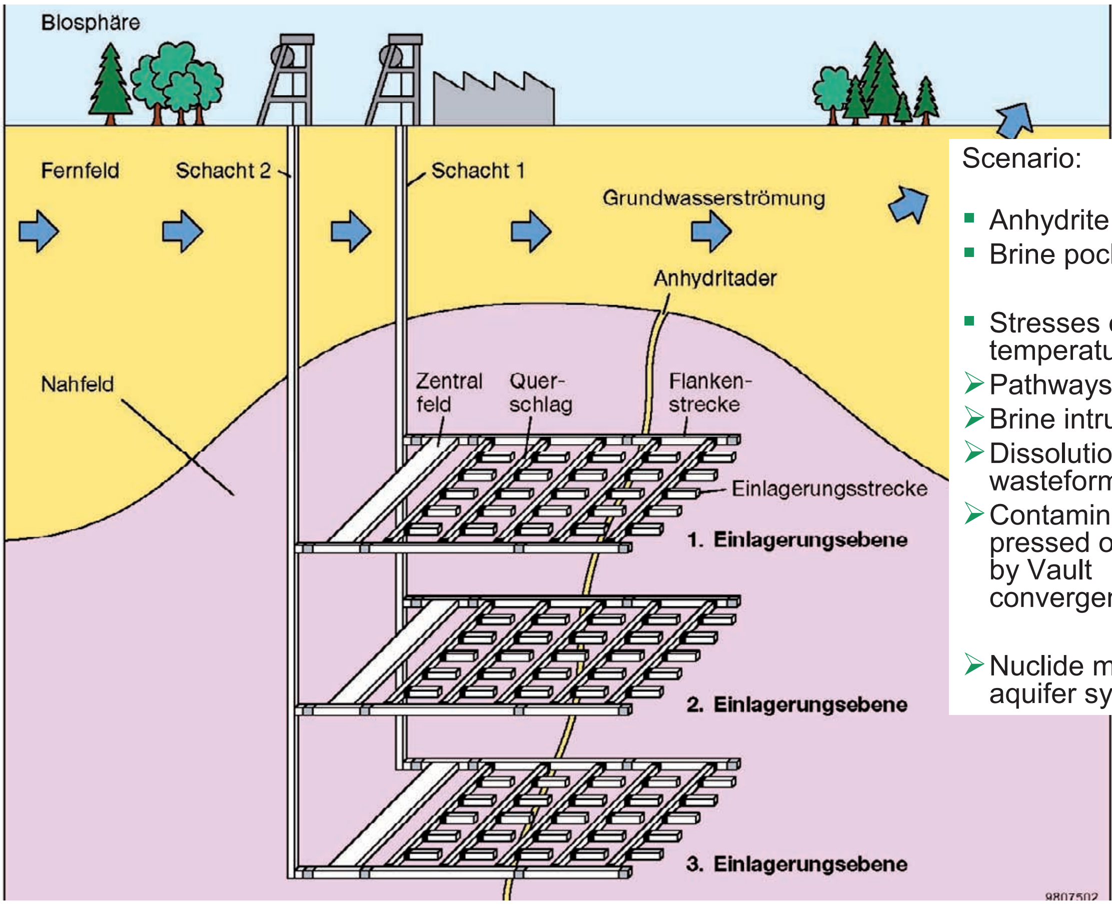
Buffer

- **Bu1. Limit advective transport** – a) Hydraulic conductivity < 10^{-12} m/s; b) Swelling pressure > 1 MPa
- **Bu2. Filter colloids** – Density > 1,650 kg/m^3
- **Bu3. Eliminate microbes** – Swelling pressure > 2 MPa
- **Bu4. Damp rock shear** – Density < 2,050 kg/m^3
- **Bu5. Resist transformation** – Temperature < 100 °C
- **Bu6. Prevent canister sinking** – Swelling pressure > 0.2 MPa
- **Bu 7. Limit pressure on canister and rock** – Temperature > −5 °C

Color coding:
Functions with contribution to canister functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow)

Demonstrating compliance … in the 80ies and 90ies : Early German safety assessments for disposal in rock salt

- Carried out in national studies (SAE 1984, PSE 1985, SAM 1989, SEK 1996) and EU projects (PAGIS 1989, PACOMA 1991, EVEREST 1997, SPA 2000)
- Confinement identified as objective of disposal in rock salt is **postulated**, but not addressed in assessment calculations:
  - Focus on flow and migration in repository mine and overburden
  - Considerable effort re. hydrogeological modeling of Gorleben erosion channel, also via participation in NEA validation projects (e.g. INTRAVAL)
  - Emphasis on development of assessment tools rather than on linkage to site investigation and R&D results
  - regulatory background: dose criterion & recommended 10,000 a timeframe
  - underlying scenario → next slide



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Scenario:

- Anhydrite vein
- Brine pockets

- Stresses caused by temperature increase
- ➢ Pathways
- ➢ Brine intrudes
- ➢ Dissolution of wasteform
- ➢ Contaminated brine pressed out (driven by Vault convergence)

- ➢ Nuclide migration in aquifer system

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Developments in Germany: R&D, Gorleben site investigation

- Details about salt geology
- Demonstration methods to show integrity of salt barrier
- Understanding of salt compaction
- Engineering-based demonstration concepts for drift and shaft seals

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Details about salt geology (Gorleben)

- Sources
  - Deep drillings investigating salt dome
  - Seismics
  - Drilling samples: geochemistry, petrography
  - Shafts Gorleben 1 and Gorleben 2
  - Underground exploration area (mine) EB 1
  - Geophysical (e.g. electro-magnetic reflection measurements EMR) and geochemical investigations from underground

- Results
  - New high-resolution stratigraphic characterization
  - Large homogeneous volumes in Z2 (old rock salt - Staßfurt), extension of fracture systems limited
  - Z2 almost without brine inclusions (only some cm^3 at a time) → “brine pockets” (release scenarios) do not exist
  - Main anhydrite Z3HA broken into isolated blocks → no continuous pathway
  - Uplift of salt dome almost finished
  - Low subrosion rates in the long run (some 10^{-2} mm/a)

  ➢ Geologic integrity of the main barrier
  ➢ Drift excavation preserving barrier possible

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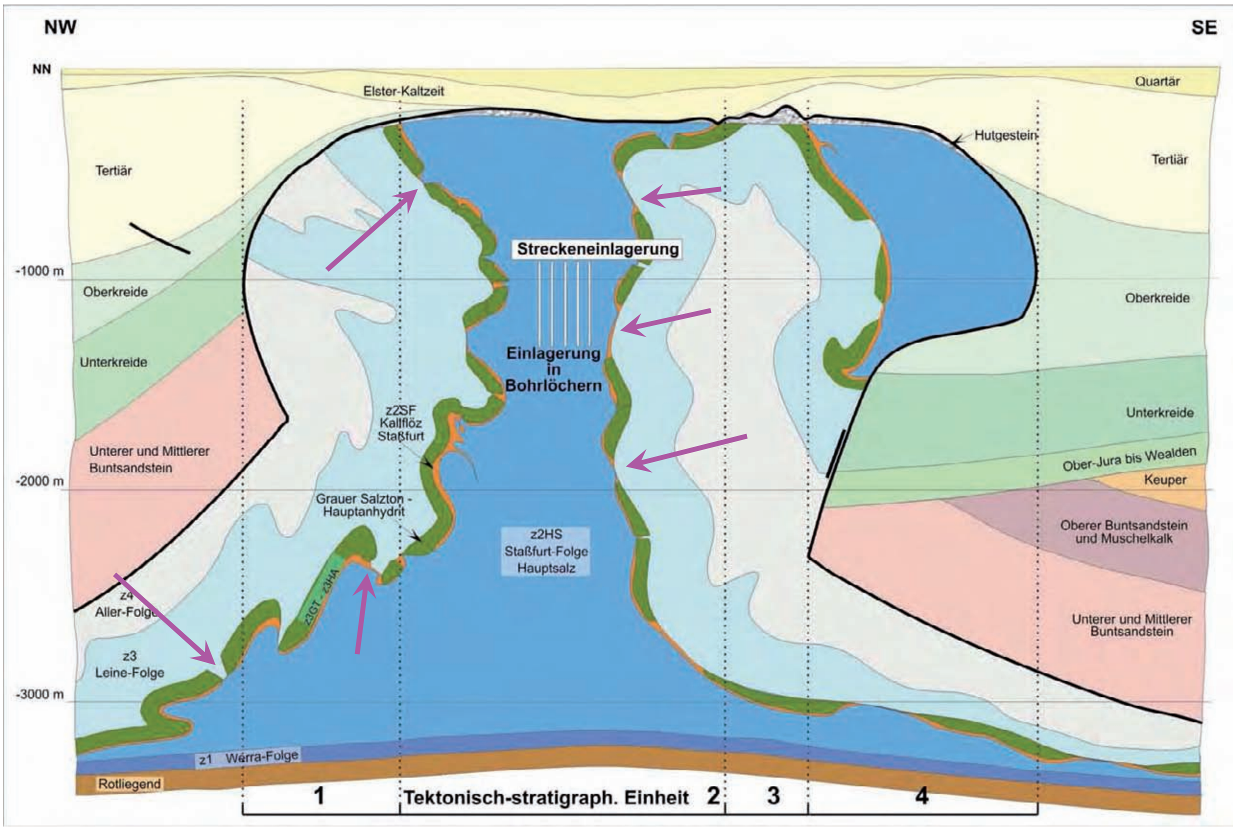

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Developments in Germany: Site selection (AKEnd) and the concept of a “confining rock zone”

- “Part of the geological barrier which at normal development of the repository and together with the technical and geotechnical barriers has to ensure the confinement of the waste for the isolation period”

- Must consist of rock types to which a field hydraulic conductivity of less than 10^{-10} m/s can be assigned
- At least 100 m thick
- Depth between 300 m and 1500 m
- Sufficient lateral extension
- No risk from rock burst
- No findings or data which give rise to doubts whether the requirements regarding field hydraulic conductivity, thickness and extent can be fulfilled over a period of time in the order of magnitude of one million years

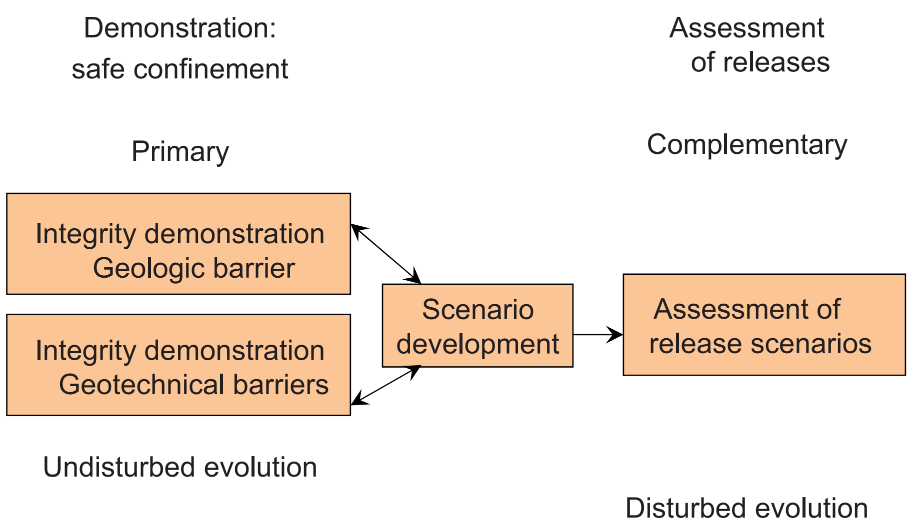
AKEnd and the consequences

- Granite is practically no longer an option (no granite sites in Germany which have potential to fulfill criteria)

- Implications for development of Safety Requirements (BMU 2009)
  - Safety Case concept mirrored in requirements
  - Confining rock zone required
  - 1 million year assessment timeframe
  - Possibility to demonstrate numerical compliance not in the biosphere but at the boundary of isolating rock zone (feasible???)

- Still debated:
  - Confining rock zone concept and associated performance (function) indicators (guideline development)
  - … and some other regulatory issues less relevant for this presentation

The ISIBEL demonstration concept



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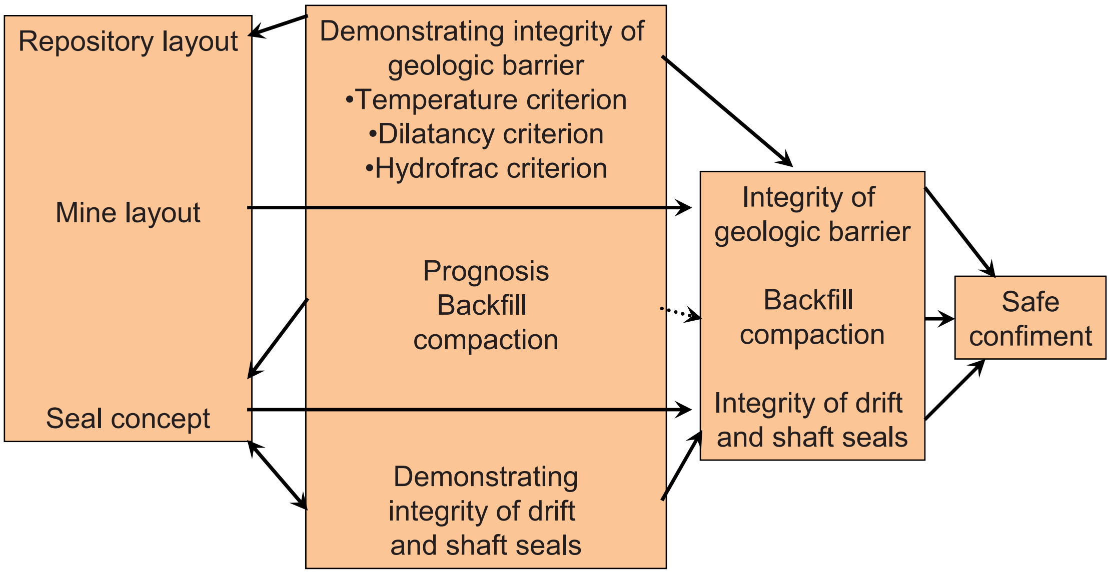
Safe confinement: functions, demonstration and linkage to design



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From Release Scenario to Safe Confinement

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The ISIBEL FEP catalogue as a tool to aid confinement demonstration

- Joint GRS-BGR-DBE TEC development
- Aims:
  - to produce the first FEP catalogue for HLW/SNF disposal in rock salt
  - to establish a product addressing FEP interactions
  - to link FEPs to function “safe confinement”
  - to establish a reviewable product
- Independent review (TUC, FZJ, FZK, PANGEO)
  - QA – independent views
  - Involve additional disciplines
  - Methodology similar to NEA reviews, but adapted to subject

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From Release Scenario to Safe Confinement

The ISIBEL FEP cataloge: selected entries

- General: Name, number, definition, link to NEA FEP, …
- Conditional probability
- Influencing and influenced FEPs (linkage to interaction matrix)
- Influence on confining barriers

The ISIBEL FEP catalogue: selected review findings

- Catalogue as important achievement (methodology, confidence building)
- Review itself as contributor to future improvement acknowledged
- Planned implementation into NEA FEP database strongly encouraged
- Potential misunderstandings concerning site-specific character (or otherwise) – need to clarify to what extent catalogue is applicable to Gorleben (some FEP-specific comments on this issue)
- Review team acknowledges orientation on confinement, encourages further focus on confining rock zone
- Recommendations concerning documentation
- Comments on lack of balance re. several entries – some important literature not accounted for, some statements too apodictic
- Choosing NEA “IFEPs” as starting point is not helpful
- …
- And of course: Many comments concerning single FEPs

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Conclusions & outlook

- Considerable evolution over the last decade concerning development and demonstration of safe confinement in rock salt:
  - Site investigation results
  - Concept development
  - Safety assessment
- This evolution occurred parallel to, and consistent with, the development of the safety case concept.
- It has the potential to make the strengths of the rock salt option visible.

- Future R&D:
  - Compaction behavior of salt grit (backfill)
  - Demonstration of long-term integrity of seals

    … (Relationship between the two – scenarios & assessment)

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DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE IN BEDDED SALT IN THE UNITED STATES

Tom Pfeifle and Frank Hansen
Sandia National Laboratories

Abstract

The performance of heat-generating high-level radioactive waste disposed in bedded salt within the United States is evaluated. Models based on applicable features, events, and processes are used to develop a post-closure performance assessment. Experience of Sandia National Laboratories at the Waste Isolation Pilot Plant repository was used to develop a disposal strategy that shows promise should a salt repository be considered as a disposal alternative in the United States. Disposal of high-level radioactive waste in salt is attractive because the material is essentially impermeable and self-sealing, chemical conditions are reducing, and the United States has many salt deposits throughout the continent. Over a relatively short time, closure of the disposal rooms encapsulates the waste. Summarized advanced multiphysics modeling illustrate this basic behavior. Hence, a salt repository can readily achieve required containment with ample margin of safety. The studies summarized in this paper demonstrate that heat generation within the salt disposal horizon is likely to improve long-term performance beyond the excellent performance exhibited at the Waste Isolation Pilot Plant under ambient conditions. Although the analysis uses key aspects of long-term performance standards prescribed for existing repositories, likely changes to the standards would not detract from the ability of salt to isolate high-level radioactive waste.

Disposal of High-Level Radioactive Waste in Bedded Salt in the United States

Tom Pfeifle, Manager, Geomechanics
Frank Hansen, PhD.
Sandia National Laboratories
May 25, 2010

Objective of Current Study

To evaluate the performance of heat-generating high-level radioactive waste disposed in a hypothetical repository constructed in a bedded salt within the United States and compare results with the regulatory standards for the Waste Isolation Pilot Plant (Hansen et al, 2010).*

*** Hansen, et al., 2010, "Disposal of High-Level Radioactive Waste in Bedded Salt in the United States," SAND2010-XXXX, prepared by Sandia National Laboratories, Albuquerque, NM.**

Outline

- Motivation
- Background on Radioactive Waste Disposal in Salt
- Laws, Agency Responsibilities, and Regulatory Environment
- Performance Evaluation Methodology
- Features, Events & Processes (FEPs)
- Concept of Operations for a Repository in Bedded Salt
- Performance Assessment
- Path Forward/Future Program Needs

Motivation

- A License Application (LA) for construction of a repository at Yucca Mountain (YM) has been submitted by the US Department of Energy (DOE) and docketed by the US Nuclear Regulatory Commission (NRC).
- In March 2010, DOE filed a motion to withdraw the LA and the Obama administration recommended eliminating further funding of YM.

Consequence of YM LA Decision

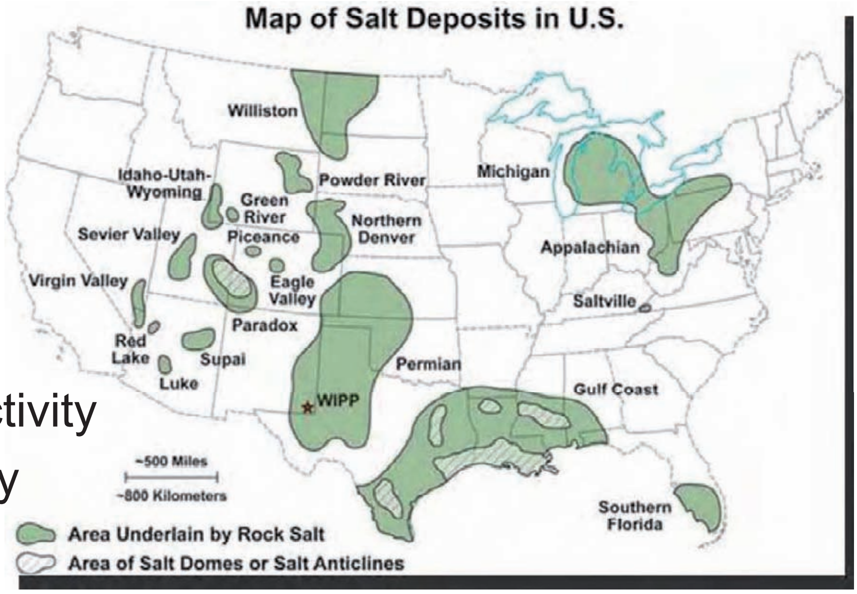
- **Blue Ribbon Commission (BRC) was formed by DOE in January 2010. It will**
  - Provide recommendations for managing the back-end of nuclear fuel cycle
  - Issue an interim report due in 18 months and a final report due in 24 months
- **US Nuclear Waste Policy Act (NWPA) of 1982, as amended in 1987 (designating Yucca Mountain), would need to be changed to accommodate BRC recommendations.**
- **Sandia is conducting R&D activities to inform anticipated discussions of future geologic repositories.**

Why Salt?

- **Salt was recommended by the US National Academies of Science & Engineering in 1957**
- **Salt has positive attributes for waste disposal**
- **Salt formations are plentiful and are widely distributed around the US**
- **Salt has been well characterized both within the US and Internationally (i.e., for waste disposal & for underground storage)**
- **Waste Isolation Pilot Plant (WIPP), a geologic repository for the disposal of US defense transuranic (TRU) waste in bedded salt, has been certified and has been operating for 10 years**

Attributes and Distribution

SALT ATTRIBUTES



- Easily mined
- Deforms plastically
- Fractures self-heal
- High thermal conductivity
- Very low permeability and porosity
- Has existed underground for millions of years
- Deposits are often in stable tectonic regions and exist in many locations with geographic distribution in the U.S.

Applicable Laws/Responsibilities

- **NWPA of 1982, as amended in 1987 – assigned responsibilities for radioactive waste disposal.**
  - **DOE** is to site, construct, operate & close a repository for used nuclear fuel* (UNF) and high-level waste (HLW)
  - **Environmental Protection Agency (EPA)** is to set public health and safety standards for releases of radioactive materials from a repository
  - **NRC** is to promulgate regulations governing construction, operation, and closure of a repository and license a facility
- **WIPP Land Withdrawal Act of 1992**
  - **DOE** is to take ownership of a 4-mile square site from the Department of Interior for purposes of construction, operation & closure of a TRU and hazardous waste repository
  - **EPA** is to promulgate regulations and issue criteria for the initial certification and 5-yr re-certification of WIPP compliance

*** Used nuclear fuel has supplanted spent nuclear fuel as the preferred terminology in US**

Regulatory Framework

- **EPA Regulations**
  - **40 CFR Part 191** ***Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes***
  - **40 CFR Part 197** ***Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada***
  - **40 CFR Part 194** ***Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations***
  - **50 Fed Reg 1515** – Authorizes New Mexico Environment Department to enforce EPA RCRA standards for WIPP hazardous waste (not required for UNF/HLW facility)
- **NRC Regulations**
  - **10 CFR Part 60**, ***Disposal of High-Level Radioactive Wastes in Geologic Repositories***
  - **10 CFR Part 63**, ***Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada***

Performance Evaluation Method

- **Identify potentially relevant features, events, & processes (FEP) that affect long-term performance of the disposal system**
- **Screen/Select FEPs to construct scenarios for use in Performance Assurance (PA)**
- **Construct scenarios from retained FEPs for further screening**
- **Select scenarios to include in PA**
- **Implement/analyze scenarios in PA and compare to regulatory standards**

FEPs Evaluation

- Current study started with WIPP FEPs
  - WIPP originally examined ~1500 FEPs based on Internationally-accepted databases
  - ~240 FEPs considered with ~90 retained; others screened out based on Regulatory, Probability or Consequence arguments
- Adjusted WIPP FEPs based on assumptions for a UNF/HLW repository related to:
  - Salt Site
  - Repository Design
  - Waste Characteristics

Salt Site Assumptions

- In contrast to WIPP, very little brine will reach the waste package
  - Disturbed rock zone (DRZ) will be smaller and will heal faster because of higher temperatures, thus releasing less brine
  - Thermal pulse will further dry a halo surrounding waste
- Site is assumed to reside in an area where rate of inadvertent human intrusion would be similar to that at WIPP

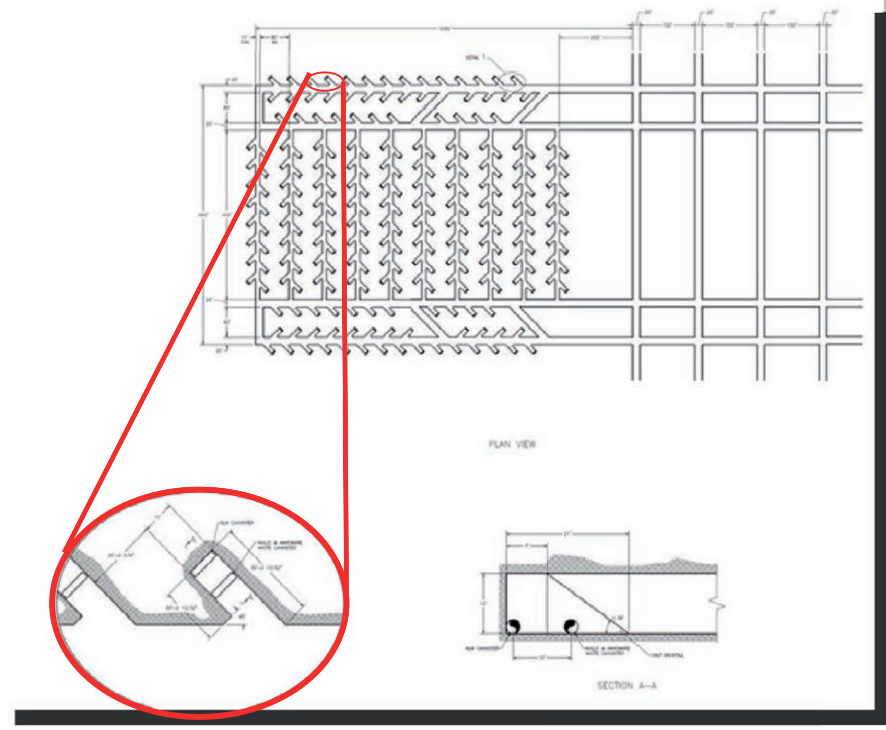
Repository Assumptions

- Size (footprint) is based on quantity of waste and thermal loading considerations
  - For PWR repository, size is set to accommodate 109,300 metric tonne heavy metal
  - For HLW repository, size is set to accommodate 16,423 glass canisters
- No credit is taken for engineered barrier system that would otherwise delay or attenuate releases
  - FEPs related to performance of waste package and waste form as flow and transport barriers are excluded.

Waste Assumptions

- UNF/HLW does not contain any cellulosics CPR
  - Hypothetical gas-generating process of microbial consumption will not occur
- Either UNF from a PWR or HLW in borosilicate glass is disposed in the repository, but not a mixture of both
- Waste does not contain hazardous constituents, BWR fuel, mixed oxide (MOX) or defense spent nuclear fuel
  - Reasonable assumption given UNF consists of more PWR than other waste types

Conceptual Repository Layout*

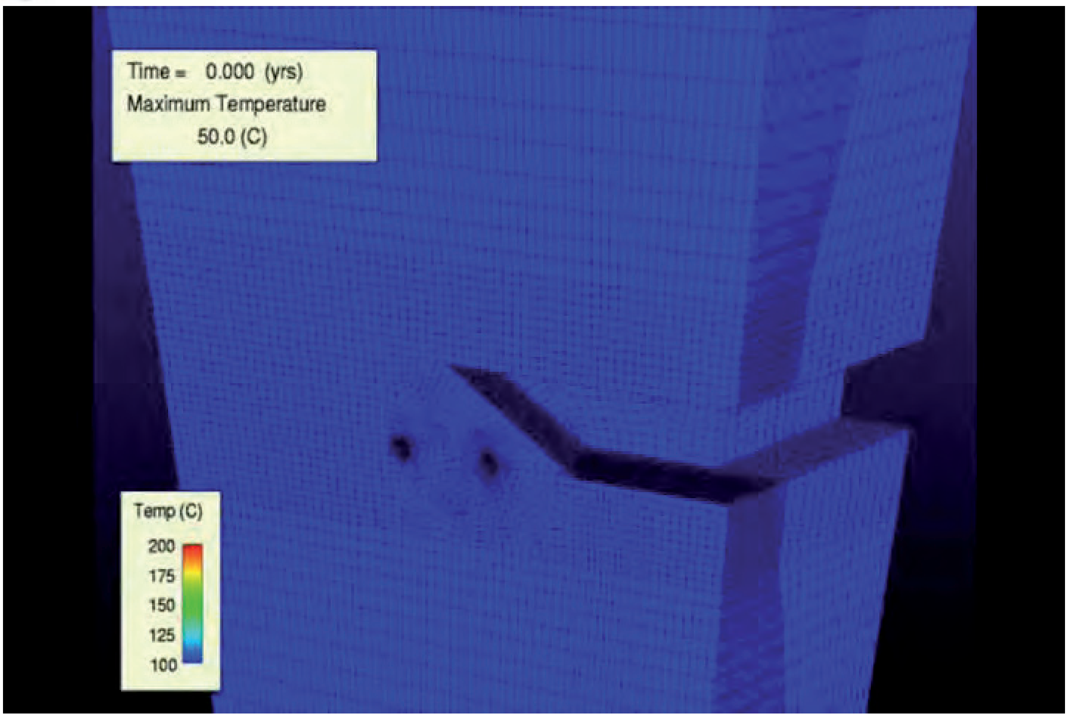


- Waste canisters are placed horizontally
- Canisters covered with mine run salt for shielding
- Placement of waste begins at one edge of a repository and progresses to the other edge staying ahead of the thermal pulse
- Narrow room and alcove widths and low extraction is desirable
- Mining layout is developed on the basis of thermal loading & mining experience

* SRS (Washington Savannah River Company) Washington Safety Management Solutions, Sandia National Laboratory and Los Alamos National Laboratory, September 2008, *A Generic Salt*

Thermomechanical Modeling

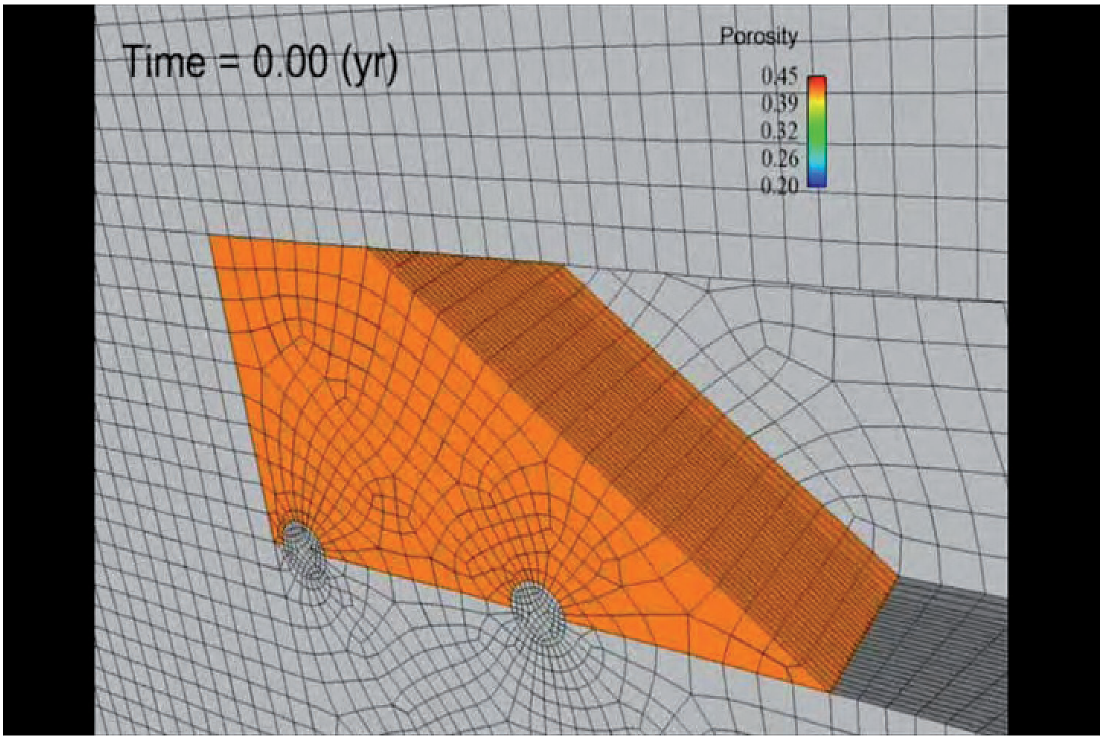
Sandia Sierra Mechanics



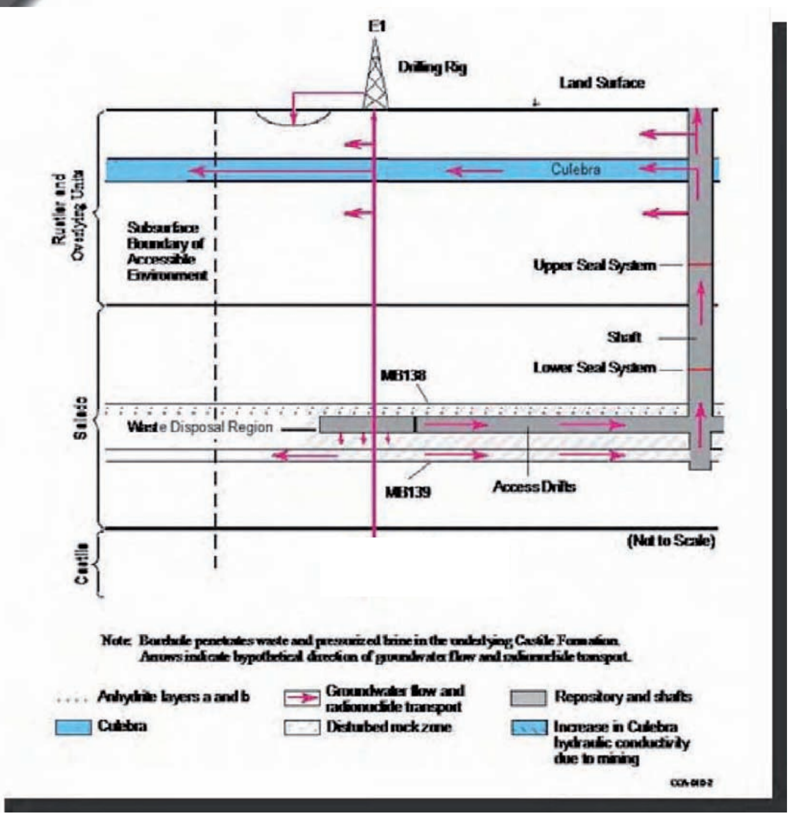
Coupled thermomechanical modeling is used to establish spacing of alcoves to limit maximum salt and waste package temperatures

Crushed Salt Modeling

Sandia Sierra Mechanics



WIPP PA Scenarios



Nominal Case

- Diffusive transport to Accessible Environment (AE)

Intrusion Case

- Releases to AE along interbeds
- Releases to AE through shaft to surface/aquifers
- **Direct releases to surface during drilling**
- Future releases to AE up cemented intrusion borehole after degradation of seals

PA Scenarios – Current Study

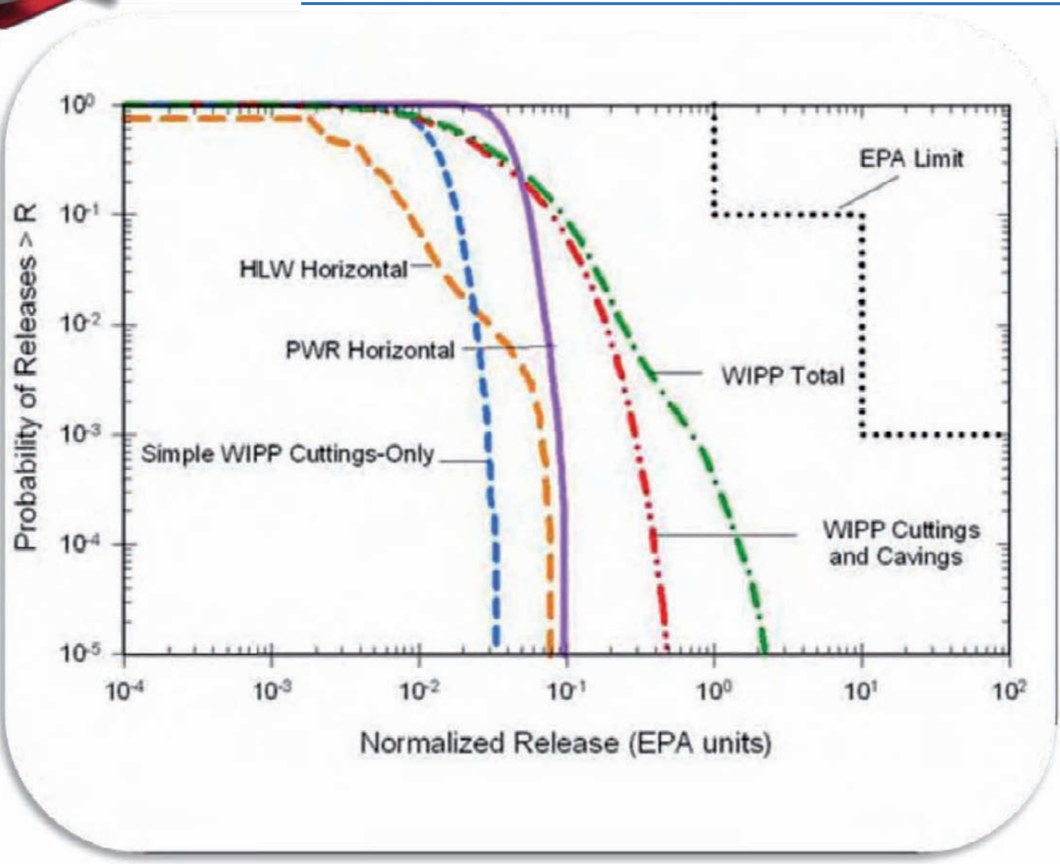
Nominal Case

- Diffusive transport does not contribute to releases based on WIPP PA and is therefore ignored

Intrusion Case

- Emplacement of either UNF HLW or PWR, but no mixture of both
- Canisters are placed horizontally
- Releases occur during surface drilling through cuttings only for horizontal canisters
  - Spallings are not considered because there will be no gas generation
  - Movement of substantial amounts of contaminated brine from the repository into the borehole is not considered because repository is assumed to be dry.
- AE is assumed to be directly above repository

All CCDFs



Conclusions of Study

- Salt could make an excellent medium for hosting a repository for heat-generating HLW/UNL.
- Ability of salt to contain HLW/UNL is similar to or better than the ability of salt to contain transuranic waste under ambient conditions.
- Improvements result from
  - UNF/HLW does not contain biodegradables that can generate gas
  - UNF/HLW produces heat that heals fractures and promotes rapid waste encasement and leads to drier environment.

Path Forward?

1. International Advisory Council on Salt (US, Germany, ?)
   i. Consider **Proof of Principle In Situ Test** to acquire data (temperature, deformation, brine/vapor movement, crushed salt reconsolidation, material corrosion) to verify hot, dry repository assumptions and validate High Performance Computing (HPC) models and calculations
      - **Test Layout? Location (Germany, Other**)?

   ii. Consider **Laboratory Testing at Elevated Temperature**
      - **Crushed salt reconsolidation and thermal properties at different porosities**
      - **Intact salt creep deformation mechanisms and microfracture evolution/devolution (healing under dry conditions)**
      - **Other?**
2. Benchmark HPC models/calculations using US/Sierra Mechanics & German Codes?
   i. Thermomechanical
   ii. Other relevant coupled processes
3. Concurrence on PA & Performance Confirmation Methods

Backup Slides

Sandia National Laboratories

Release Limits for the WIPP (Table 1, Appendix A, 40 CFR part 191)

Radionuclide	Release limit L_i per 1000 MTHM* or other unit of waste (10^6 curies of TRU for WIPP)
Americium-241 or –243	100
Carbon-14	100
Cesium-135 or –137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239,-240, or –242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or –232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-live greater than 20 years that does not emit alpha particles	1,000

* Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

The EPA Normalized Release Unit

- **The "quantity calculated according to Table 1" is the "EPA normalized release," calculated as:**

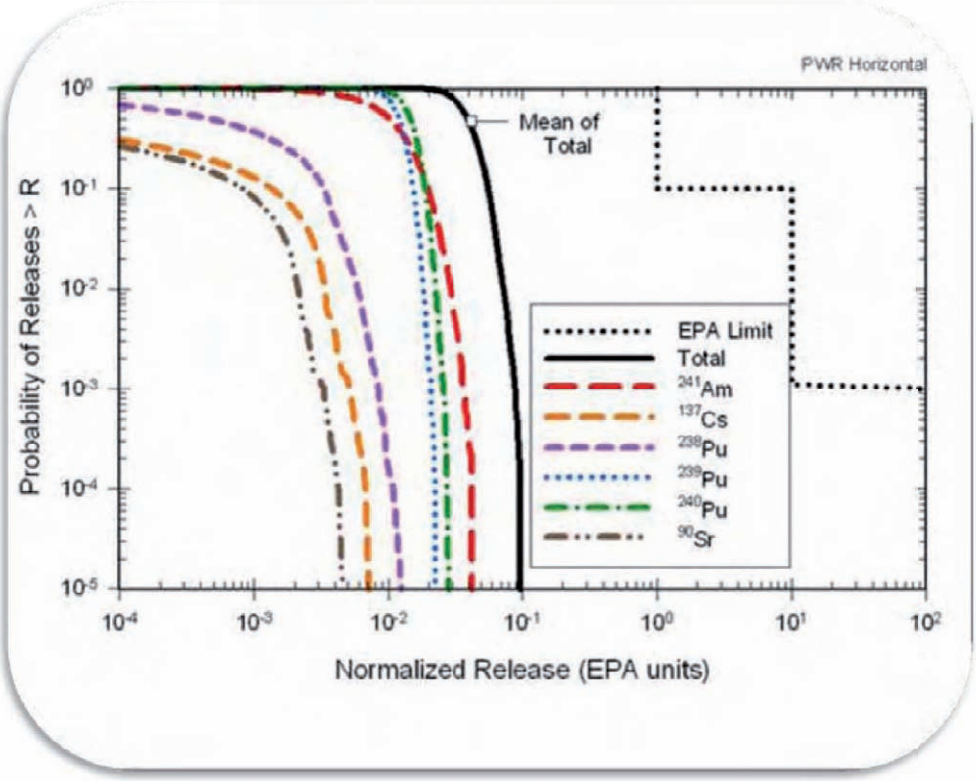
$$nR = \sum \frac{Q_i}{L_i}\left(\frac{1\times10^6\, curies}{C}\right)$$

where

Q_i = 10,000-year cumulative release (in curies) of radionuclide i
L_i = the Table 1 release limit (in curies) for radionuclide i
C = the total transuranic inventory (in curies)

Releases of PWR Radionuclides

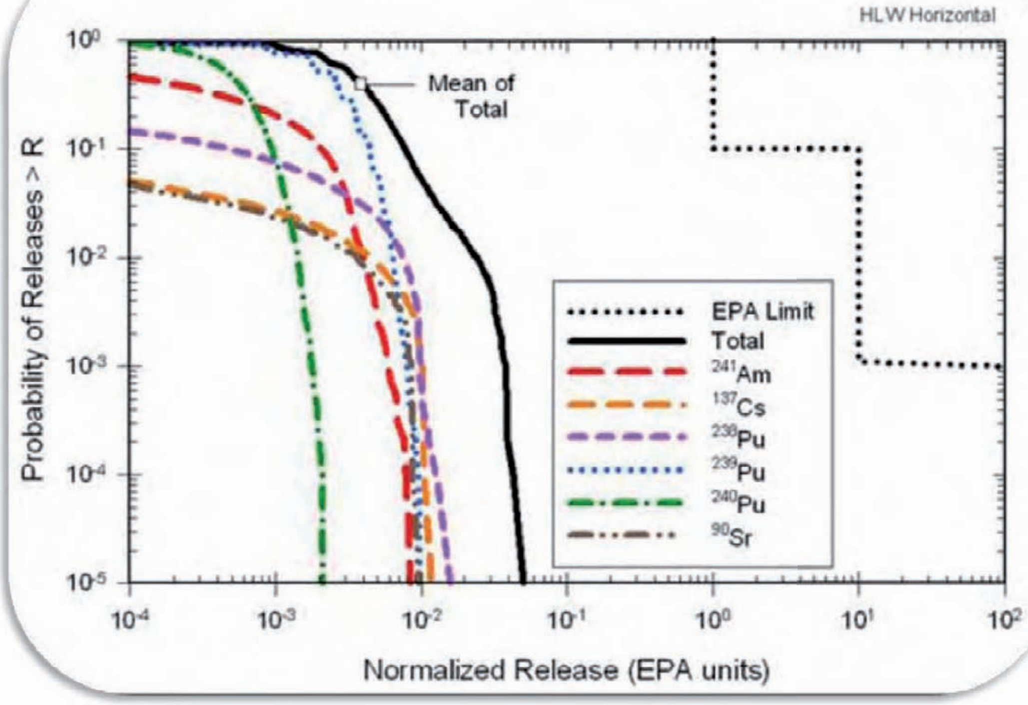
PWR Horizontal



Sandia National Laboratories

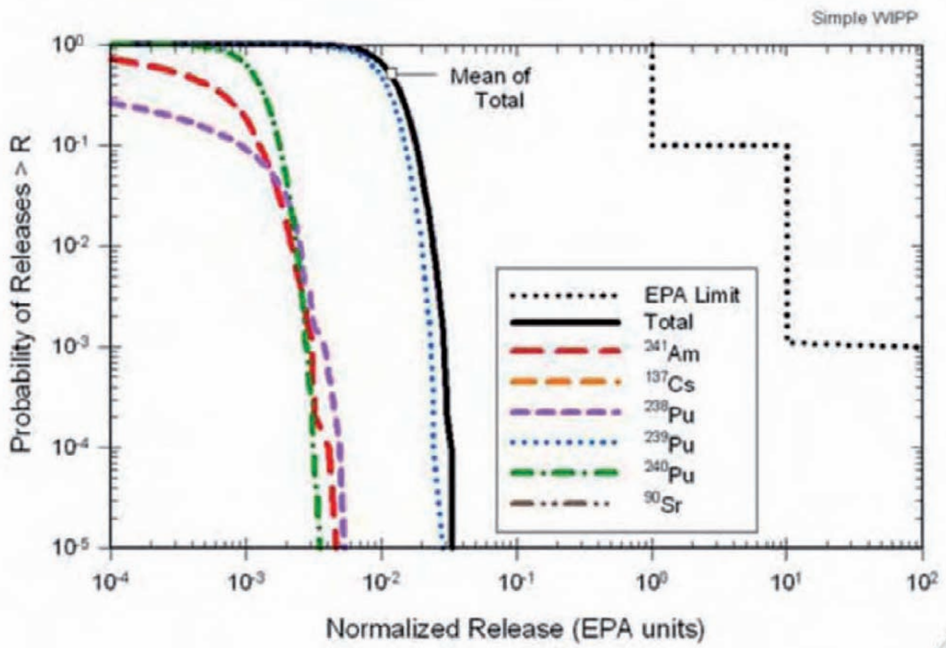
Releases of HLW Radionuclides

HLW Horizontal



Releases of HLW Radionuclides

WIPP



US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

POTENTIAL WASTE INVENTORY FOR DISPOSAL GENERIC SALT REPOSITORY STUDY – INTRODUCTION

Joe T. Carter
Savannah River Site
Process Engineering

Potential Waste Inventory for Disposal Generic Salt Repository Study - Introduction

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Canton, Mississippi

Outline

- U.S. Spent Nuclear Fuel (SNF) Inventory for Disposition
- Inventory for Generic Salt Repository Study
- Decay Heat Impacts on Storage Requirements
- Surface Facilities Concepts

Unique Challenges in the United States

- Highest Nuclear-Generated Electricity Capacity in the World
- Largest Spent Nuclear Fuel Annual Discharge Rate ~2,100 to 2,400 MT/yr
- Largest Inventory of Spent Nuclear Fuel

NUCLEAR-GENERATED ELECTRICITY*

COUNTRY	OPERATING NUCLEAR POWER PLANTS	CURRENT GENERATING CAPACITY (GIGAWATTS)	PERCENTAGE OF TOTAL ELECTRICITY PRODUCTION
United States	104	101.1	19.7
Belgium	7	5.7	53.8
Canada	18	12.7	14.8
China	11	8.6	2.2
Finland	4	2.7	29.7
France	58	63.5	76.2
Germany	17	20.3	28.3
Japan	53	46.2	24.9
Republic of Korea	20	17.7	35.6
Spain	8	7.4	18.3
Sweden	10	9.1	42.0
Switzerland	5	3.2	39.2
United Kingdom	19	11.0	13.5

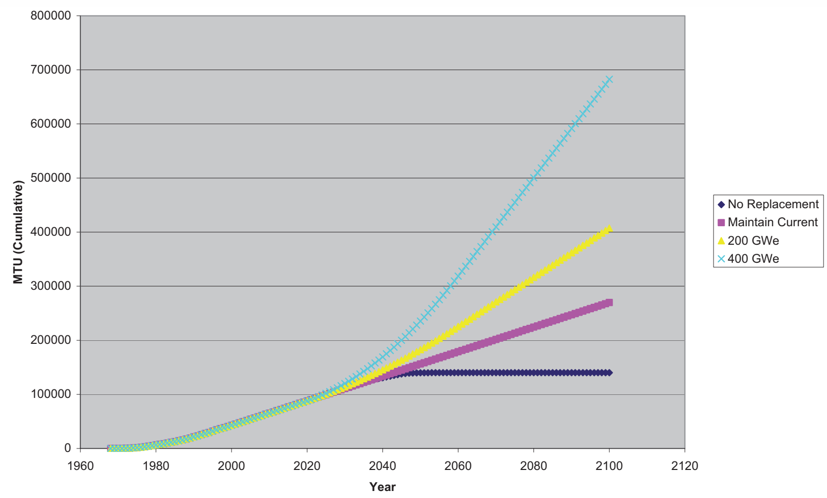
*As of May 31, 2009.

Spent Nuclear Fuel (SNF) Inventory

- SNF Data thru April 2005 Obtained
- Current Inventory Estimated at Dec 2009
  - Nuclear Energy Institute (NEI) estimate method

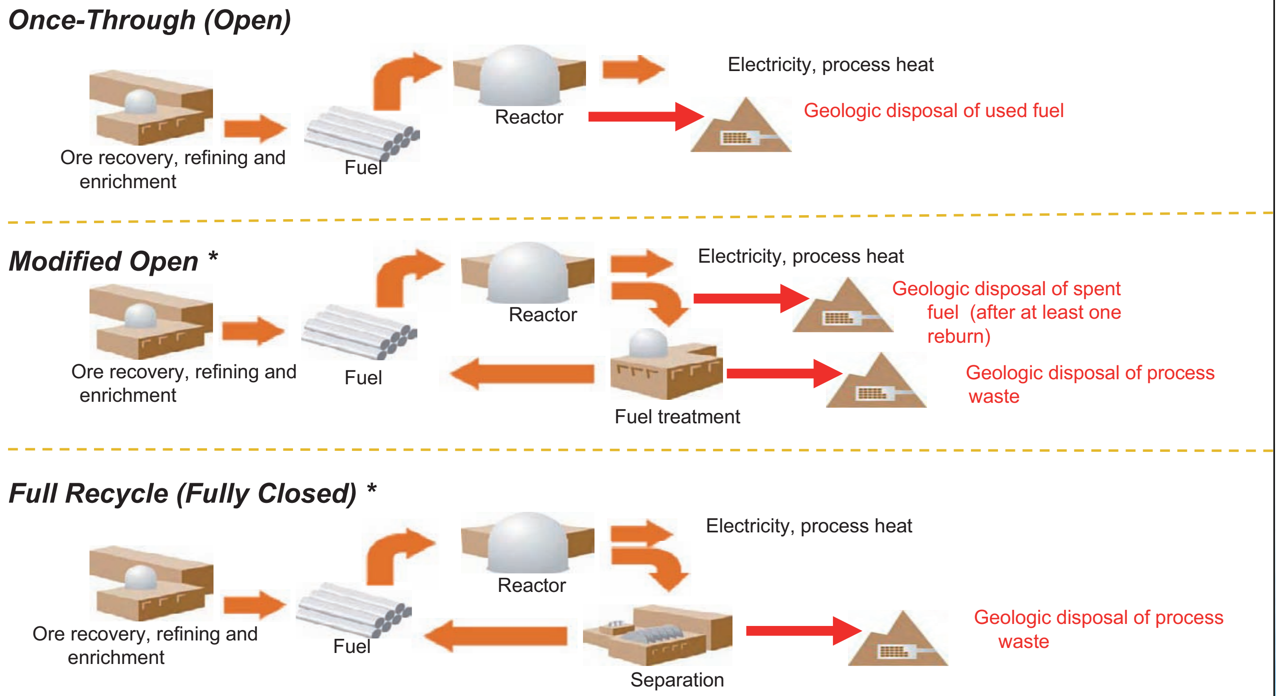
MTU			Average Initial Enrichment		Average Burnup	
PWR	BWR	Totals	PWR	BWR	PWR	BWR
41,067	22,128	63,195	3.72	3.07	39,322	32,698

- Future Inventory Depends Upon:
  - Climate Change Initiatives
  - Fuel Cycle Selection



Alternative Fuel Cycles

US-DOE is Studying Alternative Fuel Cycles in Three Categories



*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

Key Generic Salt Repository Assumptions

Assumes Deployment of Current Reprocessing Technology

- **Waste is generated by recycling LWR SNF**
  - Pu and U recovery for use in single pass MOX fuel (modified open cycle)
  - Single glass HLW form (with Cs, Sr, Np, Am, Cm) from recycling facility
  - Secondary waste from recycling facility and repository operations
  - Direct disposal of SNF was not considered
- **Recycling rates assumed are:**
  - 800MT/yr in years 1-10,
  - 1,500MT/yr in years 11-20, and
  - 3,000MT/yr thereafter
- **Non-site-specific generic salt location**
- **No requirement to retrieve waste**
  - Departure from current U.S. regulations for geologic disposal of HLW

Waste Inventory For the Study

Co-Disposal of HLW, Intermediate (GTCC) and LLW Waste Considered

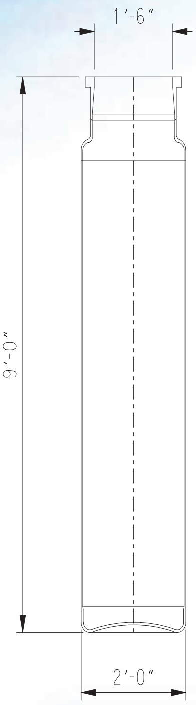
- **40 year Life Cycle Inventory**
  - from 83,000 MT of SNF

Waste Package Type	Waste Package Count		
	Case 1 Vitrified HLW	Case 2 HLW + GTCC	Case 3 HLW + GTCC + LLW
HLW Canisters -RH	20,750	20,750	20,750
GTCC Hulls & Hardware - RH	-	7,990	7,990
Standard Waste Box - CH	80	38,000	38,000
55-gal. drums - CH	-	16,650	22,080
B-25 LLW disposal box - CH	-	-	115,250
High Integrity Containers - CH	-	-	23,650
Engineered Box -RH	-	5,340	5,340
Engineered Box - CH	-	2,080	24,010
B-12 LLW disposal box –CH	-	-	103,750
TOTAL	**20,830**	**90,810**	**360,820**

- **100 year Life Cycle Inventory**
  - from 263,000 MT of SNF

Waste Package Type	Waste Package Count		
	Case 1 Vitrified HLW	Case 2 HLW + GTCC	Case 3 HLW + GTCC + LLW
HLW Canisters -RH	65,750	65,750	65,750
GTCC Hulls & Hardware - RH	-	25,330	25,330
Standard Waste Box - CH	200	108,440	108,440
55-gal. drums - CH	-	52,770	66,600
B-25 LLW disposal box - CH	-	-	314,570
High Integrity Containers - CH	-	-	74,470
Engineered Box -RH	-	16,080	16,080
Engineered Box - CH	-	6,270	70,200
B-12 LLW disposal box –CH	-	-	328,750
TOTAL	**65,950**	**274,640**	**1,070,190**

HLW decay heat limits repository design basis



Isotope	Half-Life (years)	HLW Heat Load per Canister (Watts)							
		Time After Recycling (years)							
		0	2	3	5	15	30	60	100
Sr-90	28.78	2,775	2,645	2,582	2,460	1,933	1,347	654	250
Cs-137	30.07	3,189	3,045	2,976	2,842	2,256	1,597	800	318
Pu-238	87.70	2	2	2	2	2	2	1	1
Am-241	432.70	197	196	196	195	192	188	179	168
Cm-244	18.10	2,215	2,052	1,975	1,829	1,247	702	223	48
< 3yr Half Life		1,348	328	167	47	1	0	0	0
Total (W)		**9,726**	**8,267**	**7,897**	**7,375**	**5,631**	**3,836**	**1,857**	**785**

- 60 GWd/MT spent nuclear fuel, 5-year-cooled, then recycled, shipped 2 years after recycling
- 8.4 kW/canister used in thermal analysis
  - **650,000 Ci Cs-137 per canister**
  - **400,000 Ci Sr-90 per canister**

Preliminary 3-D Thermal Analysis

- **Preliminary 3-D thermal analysis initiated to:**
  - Understand thermal front movement to ensure worker safety
  - Understand near field / neat term thermal profile better
  - Used bounding 60GWd/MT burn-up, 5 year cooled fuel, W/O decay storage
- **Both alcove and panel scale finite element and finite volume model grids were developed**

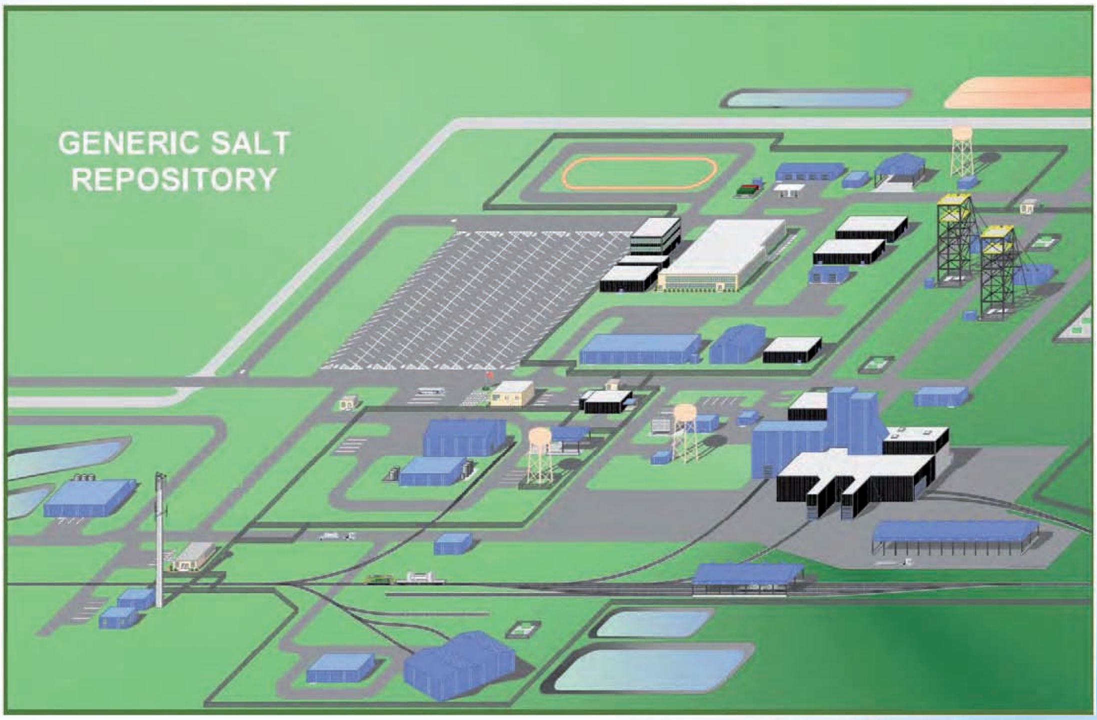
Conclusions

- **Thermal front is slow enough to not significantly impact mining and waste emplacement operations**
- **Near term near field analysis indicates temperature exceeds preliminary criteria**
  - Waste Package centerline temperature and salt maximum allowable

Decay storage for 30 years results in acceptable near term /near field thermal profiles for HLW when recycled by today's commercially available technology

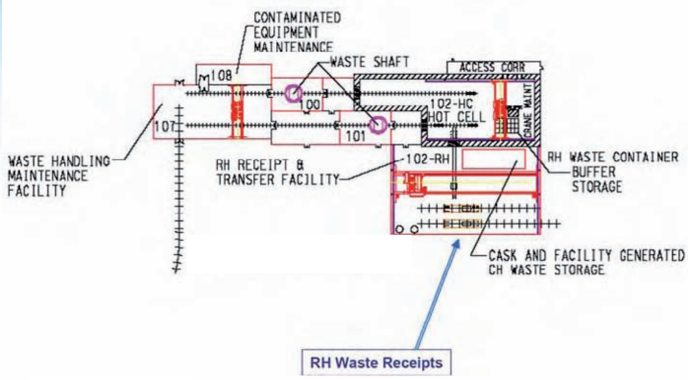
- Decay storage assumed to occur at the reprocessing facility

Surface Facilities

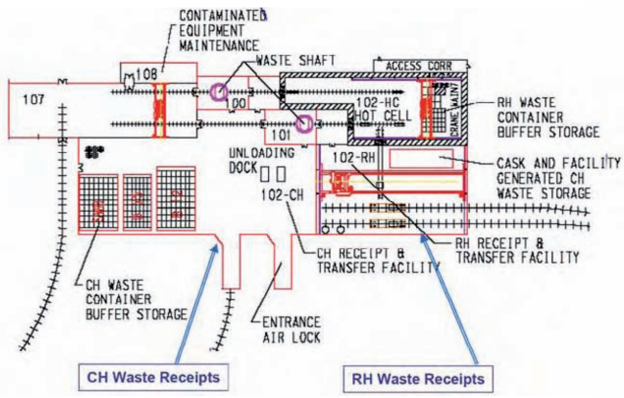


Waste Receipt and Transfer Facility (WRTF)

WRTF for Case 1 (Vitrified HLW)



WRTF for Case 3 (HLW+GTCC +LLW)



- **RH waste processing concept**
  - Both rail and truck receipt of packaged waste
  - Remote Handled (RH) waste transferred to reusable shielded container
  - Transported underground
  - Direct placement on alcove floor
  - Backfill with run-of-mine crushed salt to provide shielding

- **CH waste processing concept**
  - Contact Handled (CH) wastes in addition to RH wastes
  - Both rail and truck receipt of packaged waste
  - Transferred to facility pallet
  - Transported underground
  - Placed in access ways to alcoves

Questions

Underground Operations in Next Presentations

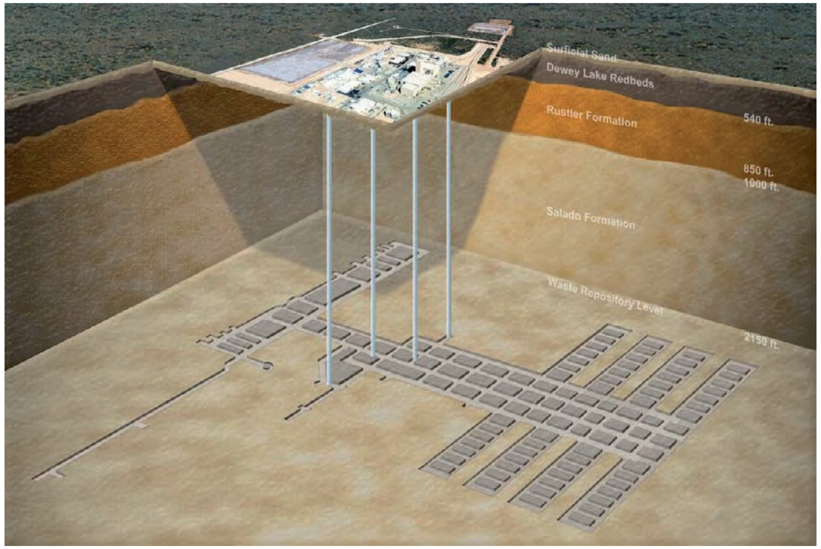
US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

THREE DECADES OF WIPP UNDERGROUND OPERATIONS – SUCCESSES AND LESSONS LEARNED

By John D. VandeKraats, P.E.
Manager, WIPP Repository Operations
URS – Washington TRU Solutions LLC

The U.S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) has been receiving and disposing transuranic (TRU) waste in the bedded salt of the Permian basin for more than eleven years. As of May 2010 over 67,000 m^3 of waste has been disposed in over 130,000 containers. This represents about 8,500 over-the-road truck shipments covering over 10,000,000 loaded miles (16M km).

View of WIPP Surface and Underground Facilities



BACKGROUND AND HISTORY

The WIPP story began in the 1950s when the National Academy of Sciences proposed that burial in salt was a promising method for disposing radioactive wastes. In the 1970s, the U.S. Atomic Energy Commission chose the area in southeast New Mexico for study and exploratory work. Salt deposits in the vicinity of the WIPP are well-known and understood due to the presence of potash mining and petroleum exploration and extraction operations. The salt beds at WIPP are about a half mile (1 km) thick.

By 1979 the U.S. Congress had authorized the WIPP as a research and development project for disposal of defense-generated TRU wastes. The first shaft work began in 1981. Much of the mine development work since that time has been performed by miners who have come from the local potash industry. These personnel have proven to be an available and capable labor pool.

A Site and Preliminary Design Validation (SPDV) program was developed to characterize the site and obtain geotechnical data. The SPDV program was used to confirm that the site was suitable for permanent disposal of the planned wastes against and complied with established design criteria. Geotechnical monitoring has continued from the beginning to confirm repository performance and to ensure operational safety.

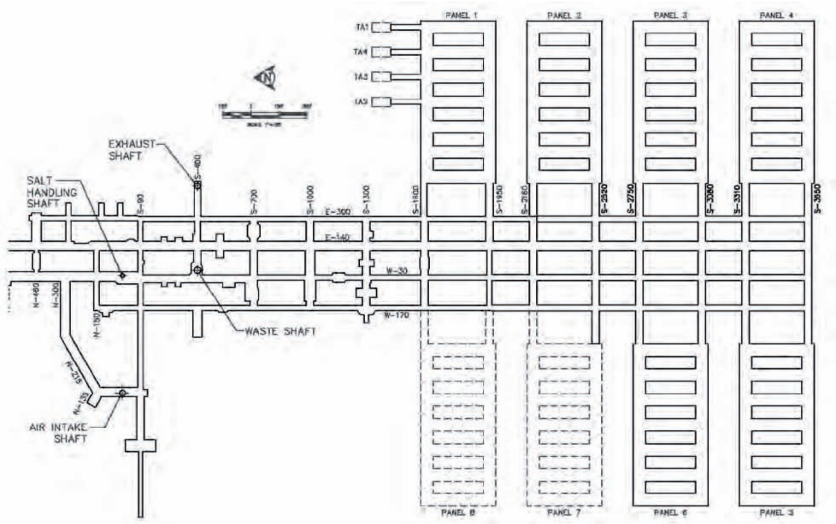
From 1982 through 1986 the underground facility was developed using continuous mining machines and diesel powered haulage equipment. This development included mining of the main drifts and their attendant cross drifts and a simulated disposal panel consisting of four full-sized (13 ft. [4 m] x 33 ft. [10 m] x 300 ft. [91 m]) rooms. In addition, experiments were fielded to investigate the behavior of the site salt deposits including geomechanical response to various excavation geometries and exposure to simulations of heat generating waste. Other experiments studied hydrologic properties and still others investigated the concepts for plugging and sealing the repository.

The results of the validation activities confirmed initial expectations about repository geology and mining operations. It was confirmed that WIPP salt beds are uniform, continuous and relatively level across the facility. It was found that excavation using modern continuous mining equipment could be performed precisely and can be done relatively quickly, easily and economically. The finished openings are clean and dry and any salt dust generated can be controlled with water. The natural reflectivity of the salt also helped provide well lit areas.

Geomechanical data collected validated the expectation that the openings creep and close over time, with the highest response rates observed immediately after excavation (feet per year) and decaying down to a steady state creep rate over time (inches per year). These geomechanical data were found to be useful in understanding ground conditions and in determining when and where to install any ground support needed to preserve opening integrity and ensure operational safety.

By 1986 studies were sufficiently complete to conclude that the underground facility could be developed as planned. That same year work commenced on mining the first of eight planned waste panels (Panel 1). Each was designed to consist of seven rooms where remote handled (RH) waste canisters could be emplaced in boreholes in the ribs and drums and other contact handled (CH) containers could subsequently be stacked in the rooms. This first panel, termed Panel 1, was completed in 1988. However, the regulatory environment delayed WIPP opening. Panel 1 stood open and ready from that time until all required permits were acquired and first CH waste emplacements began in 1999.

WIPP Disposal Area Layout



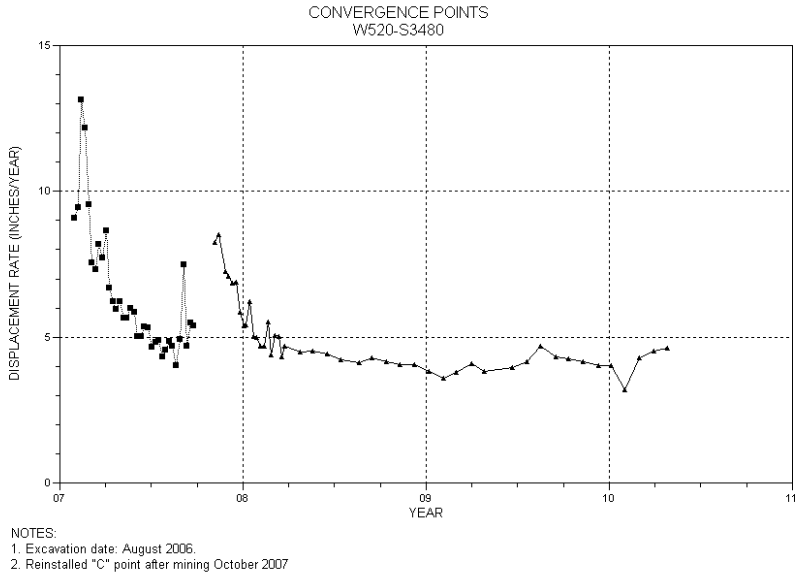
<u>UNDERGROUND OPERATIONS – EXPERIENCE TO DATE</u>

After almost 30 years since the initial excavation began, the WIPP underground repository continues to be stable and to comply with the original objectives and requirements. The repository continues to be mined and developed as disposal space is needed. The underground footprint is essentially unchanged from its original eight-panel design. Excavation performance has met, and continues to meet, design requirements. Although the original life of the facility was expected to be only 25 years, start-up delays and modified project priorities have pushed its expected life well beyond that. Even with these challenges there is confidence that with continued maintenance the repository will continue to perform adequately and meet desired extensions.

Geotechnical monitoring continues in all areas accessible to personnel, not only to confirm long-term performance, but also to ensure operational safety. This monitoring includes surface subsidence monitoring and underground geomechanical monitoring (e.g. convergence monitoring and roof dilation) at literally hundreds of locations, visual observations including mapping and tracking fractures that develop, and investigations in observation holes. Particular attention is paid to those areas where local geology (e.g. localized bedding features) may impact ground conditions.

Where openings are comparatively large (tall or wide), convergence rates are typically higher than in smaller cross sectional openings. Since waste disposal rooms are among the largest and widest at 13 feet (4 m) high, 33 feet (10 m) wide, and 300 feet (91 m) long, it is not unusual to have as much as a foot (0.3 m) of convergence in the first year after excavation when the ground response is highest and three to five inches (8-13 cm) per year thereafter. Although this convergence is desirable for entombing waste, it is a factor that must be taken into account during the operational phase. If the rooms are not used in a timely manner, this convergence would progress to the point that the disposal room clearance is not sufficient to perform waste handling operations. This lesson was learned early when delays in permitting left Panel 1 ready, waiting for a decade. Before emplacement operations could begin in these areas, it was necessary to renovate them by re-excavating the floor and ribs to reestablish the necessary operational clearances and flat working surfaces.

Example of a Typical Convergence Rate over Time



The first years of WIPP disposal operations were limited to emplacing CH waste drums and other containers. In 2006 regulatory approval was granted to begin disposal of RH waste canisters. Beginning in Panel 4 these canisters have been emplaced in 30 in. (76 cm) diameter holes drilled 17 ft. (5 m) deep typically every 8 ft. (2.4 m) along the ribs of the disposal rooms. Computer modeling of this layout was used to predict expected geomechanical response of drilling these holes. Again, geomechanical monitoring was used to validate the concept and plan.

Typical Waste Disposal Room

Today, with the repository now receiving both CH and RH waste on a regular basis, disposal panels are prepared just-in-time, that is, the panel excavation, outfitting, and regulatory certification are completed a few months before the waste disposal schedule requires them to be available. Panels are fully mined and outfitted with ventilation controls, lighting and communications systems while the previously completed panel is being filled with waste. Panel rooms and drifts are mined to a height and width that takes into account the convergence projected to occur prior to and during waste emplacement. Similar to the rooms, RH boreholes are only drilled as needed and these are, likewise, drilled just in time. Just-in-time mining levels the work-load of both personnel and equipment making it an efficient work method. In addition, this timing provides younger openings which are more stable and hence require less maintenance during the disposal cycle. This minimizes the potential for conflicts during waste disposal operations.

Some of the main access entries are now nearing 30 years of age. These are openings that must remain used and useful for the life of the facility. These openings receive regular maintenance and renovation when necessary. Renovation is relatively easy and has been done in a variety of ways. Most commonly the floor is re-leveled by watering and dragging mined salt on the roadway and occasionally the walls are trimmed. As the roof creeps and expands roof bolts are put into material yield and may fail. They are replaced as necessary to maintain the integrity of the ground support. In some cases a continuous miner may be used to excavate the floor or roof to re-establish operating clearances or remove loose fractured ground.

LESSONS LEARNED

Although safety is emphasized in the mining industry, by necessity WIPP extends this emphasis to the underground repository at the levels expected of a DOE nuclear facility. Safety is emphasized for personnel and extends to the facility and the public through both occupational and nuclear process rules. WIPP has been awarded "Mine Operator of the Year" honors for 22 of the past 23 years by the New Mexico Mining Association. This is based on the fact that WIPP incident and injury rates (0.17 injuries per 200,000 work-hr. in 2008) rank far below the national averages for operating mines (3.13 in U.S. non-metal mines in 2008 – Source: U.S. Mine Safety and Health Administration web site). The lesson to be learned is to set clear safe work expectations and to train operators on the best methods to achieve them. The WIPP safety culture emphasizes clear expectations, good communications, operator feedback, recognition of good performance, and continuous improvement. These concepts are institutionalized and taught to all employees and contractors beginning with the first classroom training and flow through procedures and work instructions.

Another lesson learned is the need to consider and, whenever possible, plan for additional requirements and changing priorities. The original throughput capacity for the facility was to handle 17 CH and two RH shipments per week. Current throughput rates are about 30 CH and five RH shipments each week. To accommodate the increase, surface waste handling facilities were modified and augmented. The increase also impacted the rate that panels were required to be mined and prepared. The panel completion rate could be increased fairly simply by hiring more employees and running additional equipment. However, a challenge developed due to the limits of hoist availability and capacity.

The problem was solved by adding an additional work shift to mine and hoist salt and by stockpiling or surging excess mined salt underground, and then hoisting it to the surface during a subsequent late shift. Hoisting on the late shift was found to more efficient due to the ability to dedicate hoist time to mucking operations. This stockpiling process involves double handling of a portion of the mined salt and incurs some additional handling cost, but this additional cost was justified by faster removal of waste from generator sites. The lesson to be drawn from this experience is to design a repository to be very robust and capable of adaptation should priorities change.

Given that convergence rates and associated deterioration are somewhat higher for larger openings at WIPP it would have been advantageous if opening sizes would have been minimized. Although the size of equipment may have little impact if used on the surface it will require a large opening in which to operate in the underground if the operating envelope is large. This has been found to be especially true for large pieces of RH waste handling equipment such as the Remote-Handled Facility Cask Transfer Car and the large (up to 40 ton) forklifts used at WIPP. The lesson learned is to design large pieces of waste handling equipment, as possible, so as to minimize their operating envelope and, therefore, their potential impact on long-term underground opening performance.

RH Waste Handling Equipment

Another lesson learned is the need to identify and avoid potential single point failures and, as possible, to mitigate them in the design stage. Additional equipment and spare parts have been procured and added to inventories to address identified single point failure situations. However, the facility itself presents that possibility since waste transportation from surface to the disposal panels is currently only possible via the Waste Shaft and the East 140 drift. To date this has not been a problem, but as the facility has aged ground control maintenance requirements in the underground have increased. If unplanned or major maintenance becomes necessary no alternative currently exists, but to suspend waste disposal operations in the underground while performing the maintenance work. WIPP is currently pursuing the possibility of modifying another main drift to serve as an alternative waste transport route, so openings maintenance can be performed in the East 140 drift while continuing to transport and emplace waste.

Three Decades of WIPP Underground Operations – Successes and Lessons-Learned

The mining industry lends another lesson to be considered. In many underground mining operations a retreat sequence is used to extract the ore. That is, access drifts, mains and any "first mining" areas are typically excavated in a sequence that progresses from the shafts to the ore body edge, end of a panel, or to the lease boundary. Then the maximum amount of ore is mined or "second mining" commences at the extremity and progresses by "retreating" back toward the main access and shafts. This is advantageous for several reasons. Typically, the mining face, where the mining is taking place, is immediately adjacent to a solid barrier or pillar where stability is best. Also, this better ensures pillar stability near the shafts. The ore can be transported back safely through mains in the relatively solid pillars to the shafts where it can be hoisted out of the mine. The ground that has been mined need not be re-entered, accessed, or maintained further. This ensures safety of personnel and minimizes maintenance requirements.

This retreat process has been employed at the WIPP in the waste disposal process. By design, in each disposal panel, waste is emplaced in the room furthest from the mains first and when it is filled it is closed to access and removed from the ventilation system. Then the process is repeated in the adjacent room. This sequence of retreating out of a panel continues until the panel is filled and closed. Although the retreat process is used in panels, the WIPP long-term plan requires the panels to be filled in a rotational sequence around the main entries, which are then filled on retreat. This has some theoretical advantages, but these are far outweighed by challenging operational ventilation configurations and the additional maintenance and renovation work required by the existing sequence. A lesson learned might be that if the original design had allowed for the panels located furthest from the shafts to be filled first and their mains to be subsequently filled and closed, costs associated with long term maintenance of the aging mains may have been substantially reduced over the life of the project.

A final lesson is to simply conclude that the WIPP repository continues to be stable and to comply with the original objectives and requirements despite the challenges encountered in mining as well as those associated with operations and changing project direction. Salt has proven itself an excellent medium for permanent disposal of radioactive waste. The WIPP continues its mission today and will continue to operate safely and compliantly to dispose of the nation's waste.

Washington TRU Solutions LLC

Three Decades of WIPP Underground Operations

Successes and Lessons Learned

John VandeKraats
URS Washington TRU Solutions

Waste Isolation Pilot Plant – Carlsbad, NM

Washington TRU Solutions LLC

WIPP Successes - Statistics

- 67,000 m3 of TRU waste disposed
- 130,000 Contact-Handled (CH) and Remote-Handled (RH) containers
- 8,500 over-the-road shipments
- 10,000,000 loaded miles (16M km)
- 11 years of safe disposal operation

WIPP Layout

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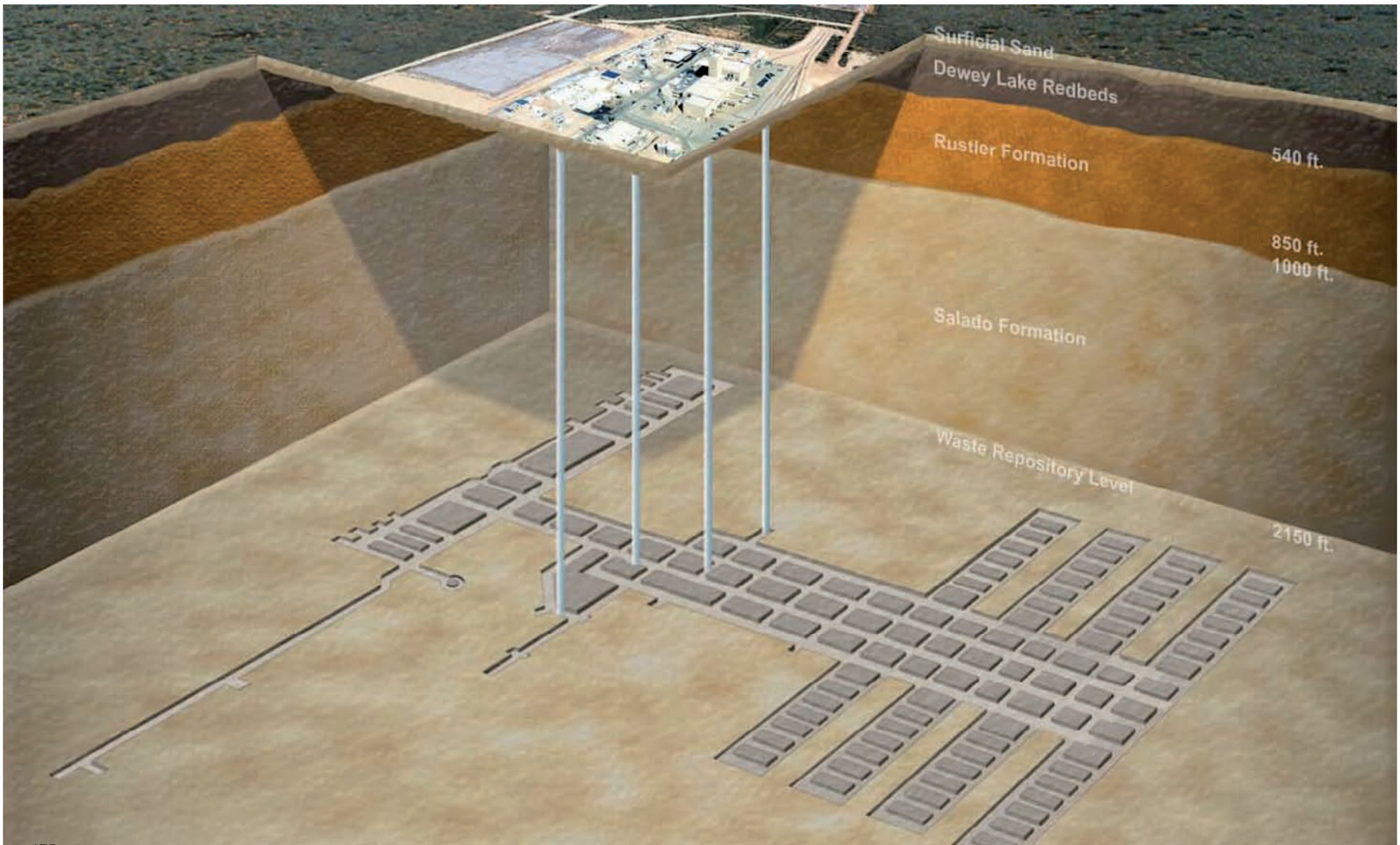

Underground Operations Timeline

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- **1950s** – Salt a promising method for disposal
- **1970s** – Southeast NM considered for site
- **1979** – Congress authorizes WIPP
- **1981** – First shaft work begun
- **1982-86** – Development and validation
- **1988** – Facility ready for waste
- **1999** – Permits in place, 1st CH waste receipt
- **2006** – 1st RH waste receipt

Underground Ops – Experience to Date

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- 30 years underground
  - Underground continues to comply with objectives
  - Life extensions due to delays and modified priorities
- Eight panel footprint remains unchanged
- Geotechnical monitoring essential
- Vigilant ground control maintenance
- Just-in-time mining principle followed

WIPP Underground Footprint

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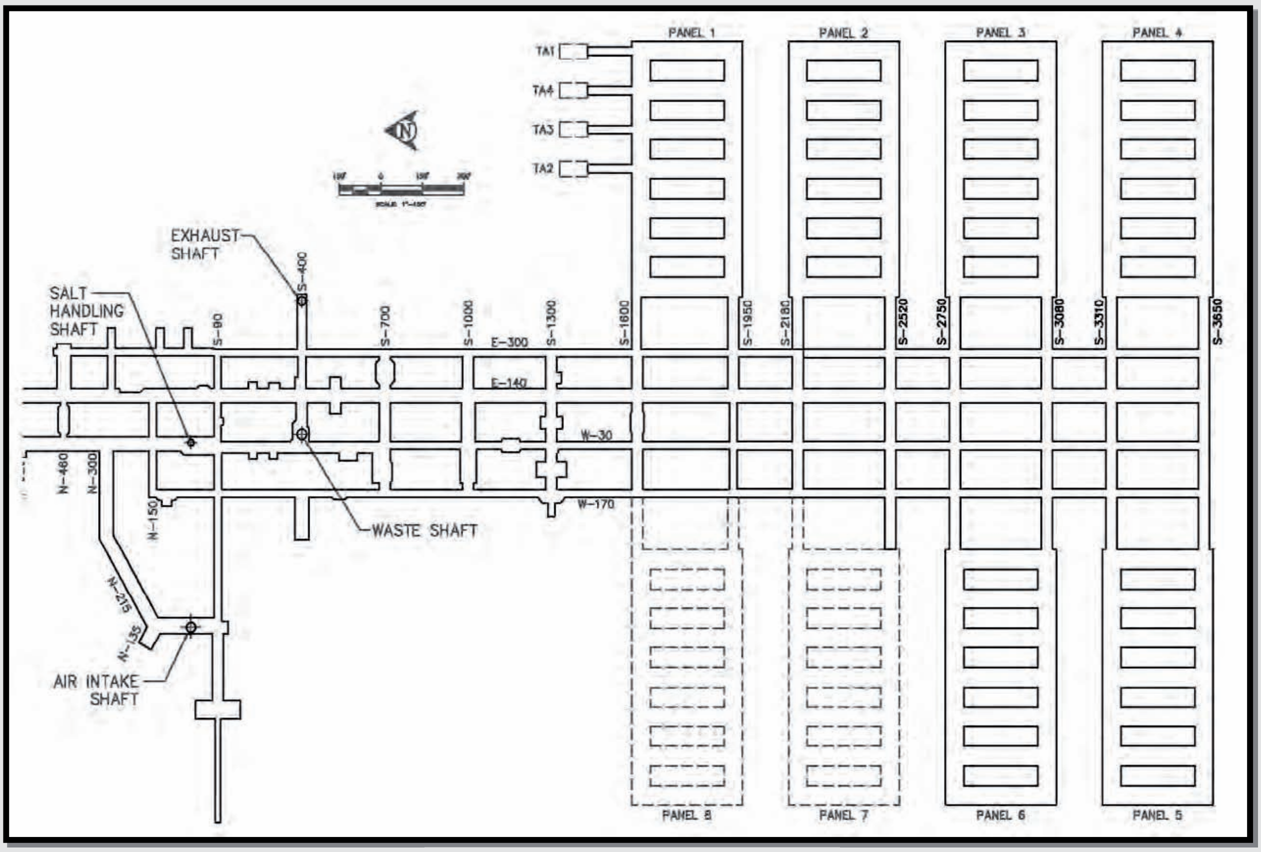

Typical Waste Disposal Room

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RH Waste Handling Equipment

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Lessons Learned

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- Safety, safety, safety
  - 22 Mine Operator of the Year awards
  - Continuous improvement
- Plan for additional requirements
  - Throughput from 17CH/2RH to 30CH/5RH a week
- Expect changing priorities
  - Budget
  - Facility modifications
  - Life extension
- Minimize equipment design envelope

Lessons Learned

URS
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- Mitigate potential single point failures
  - Spare parts
  - Transport path
- Retreat processes for emplacement
- Stay on target with objectives
  - Compliance
  - Safety
  - Maintenance

WIPP Continues its Mission . . .

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May 25-27, 2010
Canton, Mississippi, USA

LESSON FROM WIPP OPERATIONS APPLIED TO A CONCEPTUAL HLW REPOSITORY IN SALT

Roger Nelson
Carlsbad Field Office
US DOE

Lessons from WIPP Operations Applied to a Conceptual HLW Repository in Salt

Roger Nelson
Carlsbad Field Office
US DOE

US-German Workshop on Salt Repository Research, Design and Operation — May 25, 2010

Canton, Mississippi

Emplacement Experience at WIPP

Large, complex, heavy and hard to maintain equipment

Remote Handled waste shipping casks are received in a horizontal position at WIPP

Rotation

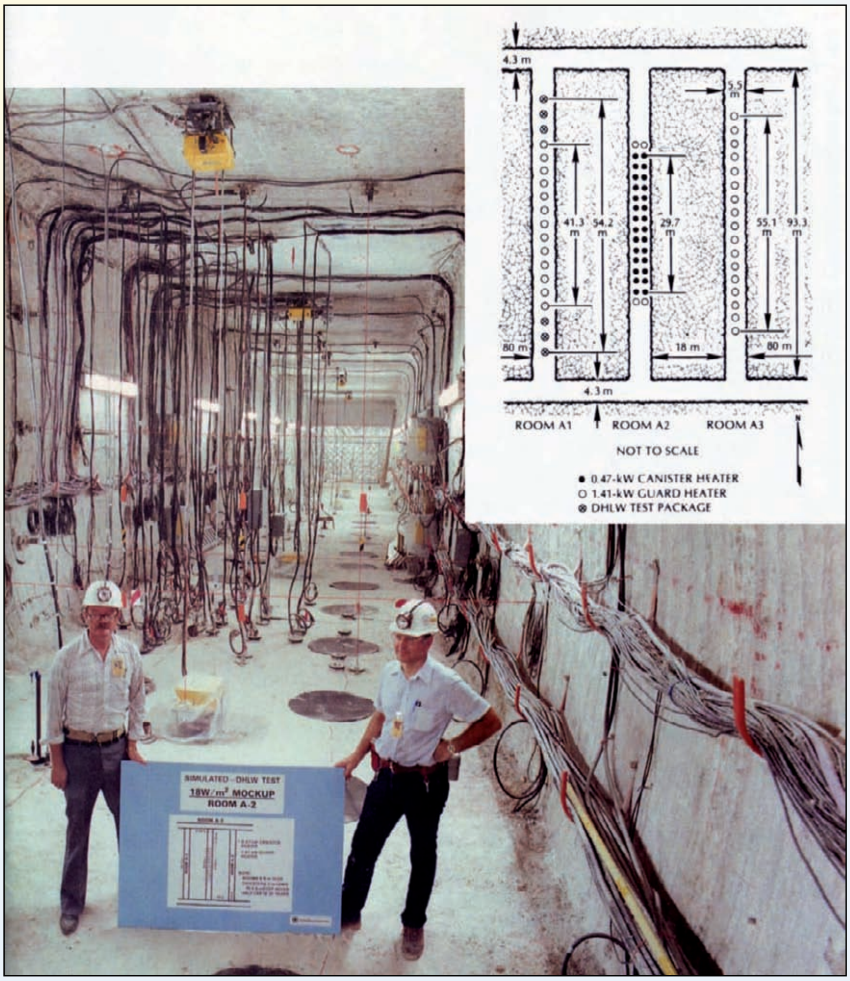
Waste canisters are pulled from the shipping cask behind shield doors and placed into a shielded facility cask for handling

Rotation

In the underground, the facility cask is removed from the hoist and transported to a disposal room by a 41-ton fork lift

RH waste in the canister is emplaced in boreholes pre-drilled into the walls of disposal rooms, and a concrete shield plug is inserted afterwards

RH & CH Waste Compete for Disposal Resources



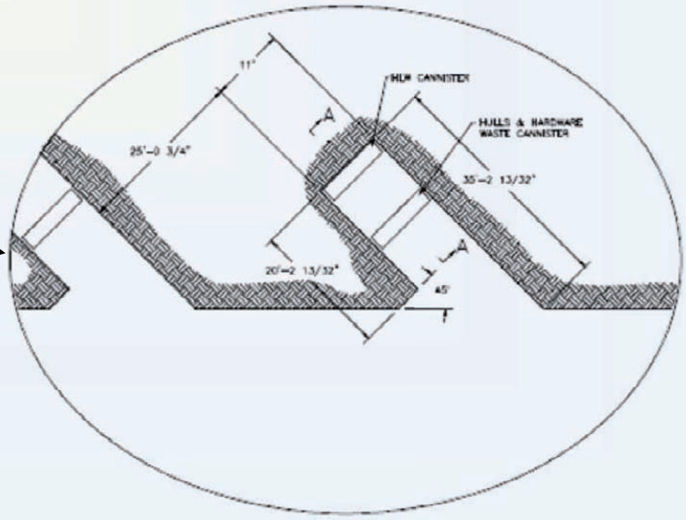
Early concepts at WIPP included thermally hot canisters placed vertically in the floor

- 18 W/m^2
- Coupons, brine, temperature monitored
- Peak temperatures never reached

If WIPP could "do it over"

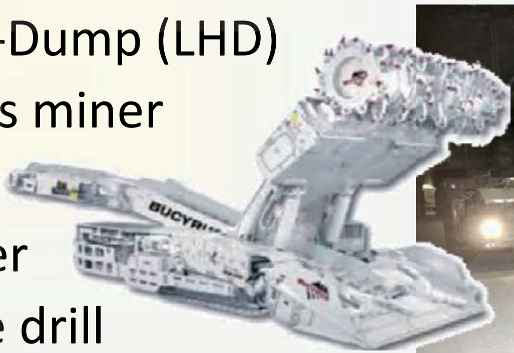
- Basic waste handling concept
  - Unload/transport shielded waste in single horizontal orientation
  - Eliminate RH placement in walls or vertically in floor
  - Emplace RH on floor, unshielded, and backfill with run-of-mine salt to provide shielding (reduce handling and mechanical complexity)
  - Accept that "retrieval" of thermally hot and highly radioactive waste will be the same next month or 100 years in the future

- Basic mining approach
  - Minimal mining
    - Single pass when possible
    - Angled entries
    - Narrow entries
  - Minimum roof support
    - Just-in-time mining
    - Maintain Mains
  - Mine and emplace in same region of repository

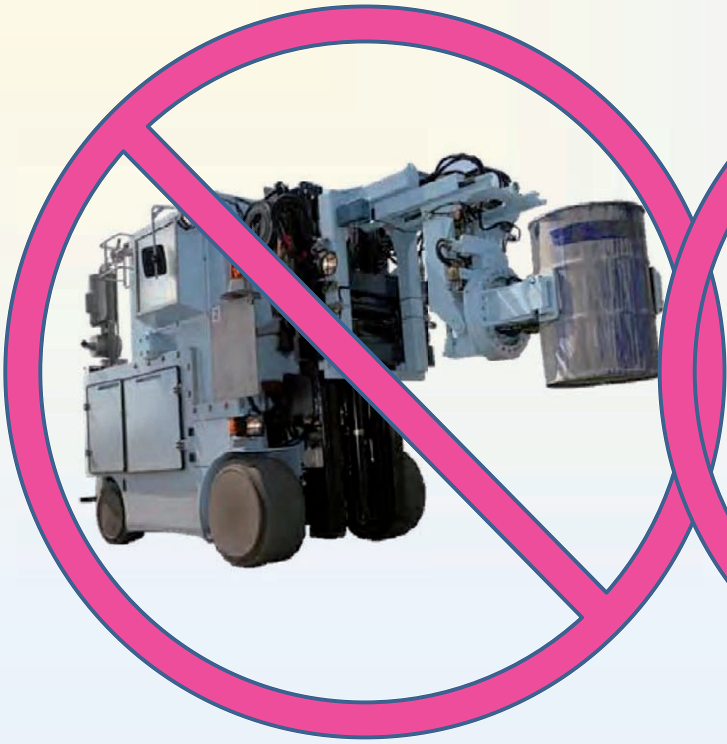


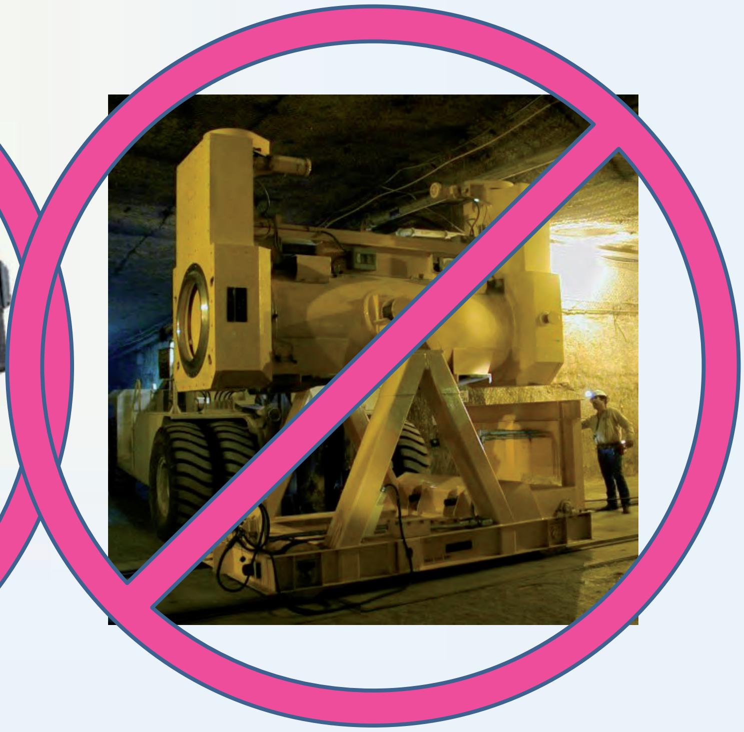
Use Standard Mining Industry Equipment

- Load-Haul-Dump (LHD)
- Continuous miner
- Bolter
- Transporter
- Probe hole drill
- Hoists and conveyances
- Single model fleet minimize spares inventory
- Ventilation separation with standardized bulkhead, airlock, and overcast



Minimize Custom Equipment





Minimize "specialty" one-of-a-kind equipment

Minimize vertical reach requirements

Underground Openings

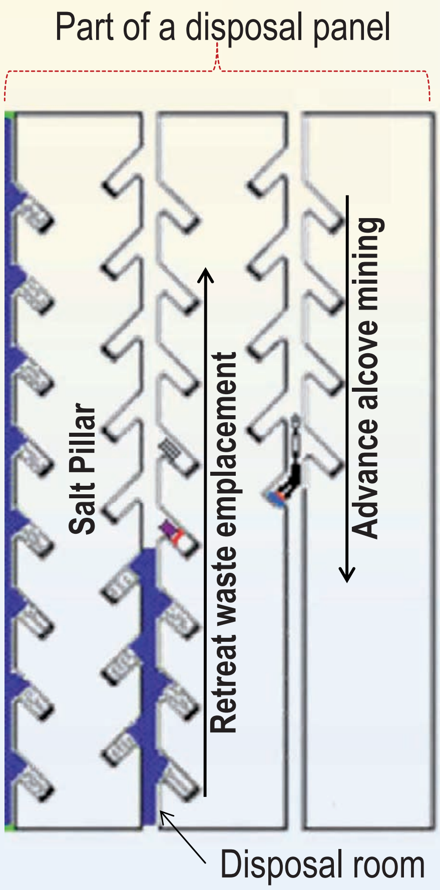
- Disposal alcoves, rooms and panels: 3.5 m wide X 3 m high
  - Single pass mining
  - Good standup time without supplementary support
  - Provides headroom for ventilation after secondary waste is emplaced
- Mains (common access drifts): 7 m wide by 3 m high
  - Minimize excavation fraction
  - Wide enough to accommodate traffic
  - Mining occurs on 2 shifts per day
- Shafts (6)
  - Salt removal (+ personnel access)
  - Air intake (+ personnel access)
  - 2 Exhaust Shafts (no access)
    - Repository size → very large fans
    - HEPA filtration at surface capable
    - 2 ventilation circuits (construction + disposal)
  - 2 Waste Shafts
    - Eliminate single-point failure (heavy loads → frequent maintenance)

MULTIPLE CONTAINER SIZES

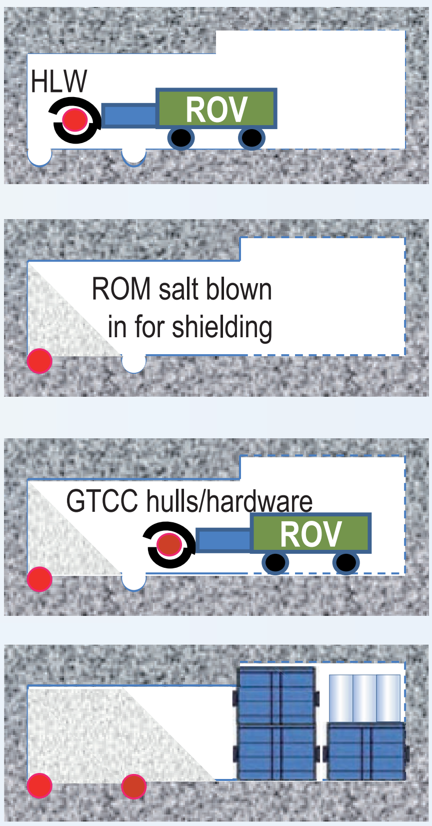
	Container Description	40-year* life cycle	100-year life cycle
Canisters	High-Level-Waste canister	20,750	65,750
	Hulls & hardware - RH	7,990	25,330
Boxes	Standard waste box - CH	38,000	108,440
	Engineered waste box - CH	24,010	70,200
	Engineered waste box - RH	5,340	16,080
	B-25 Box (LLW)	115,250	314,570
	B-12 Box (LLW)	103,750	328,750
Drums	55-gallon drums - CH	22,080	66,600
	55-gallon shielded drums (HIP)	23,650	74,470

*** All waste from reprocessing entire US commercial power plant fleet (2010)**

RH and CH Emplacement Concept

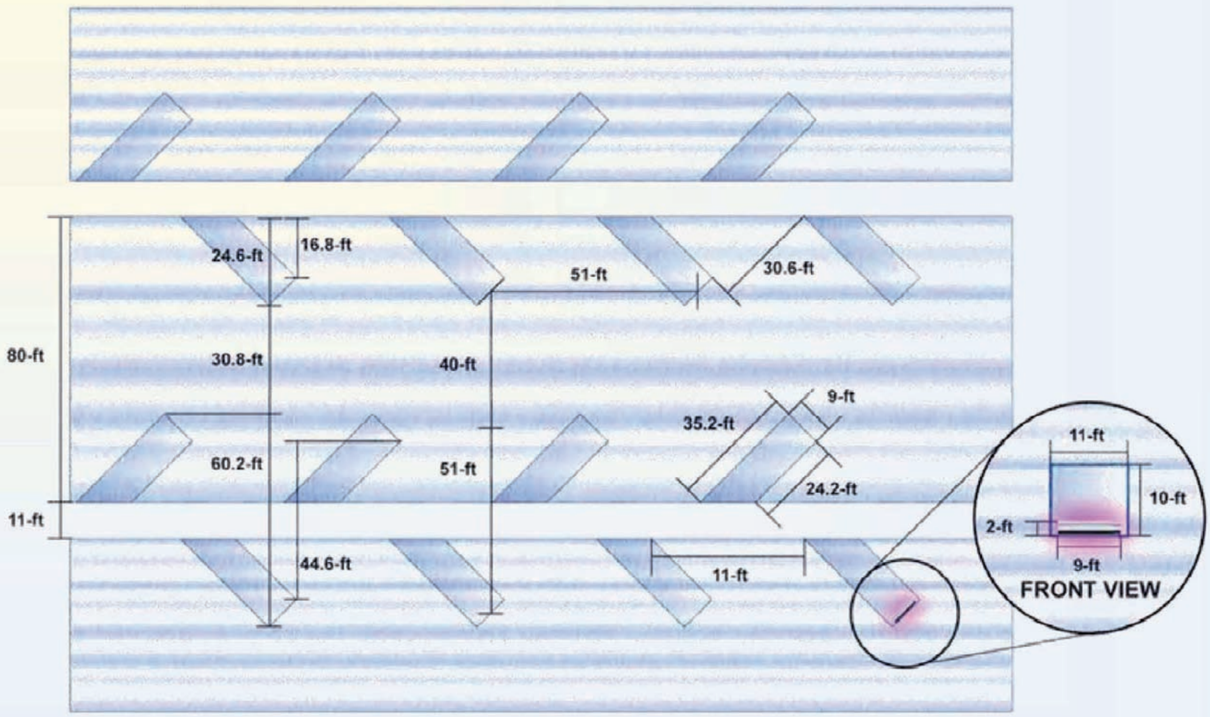


- m deep alcoves
- ngled entries
- ining and waste emplacement in adjoining rooms



Thermal Calculation Spacing

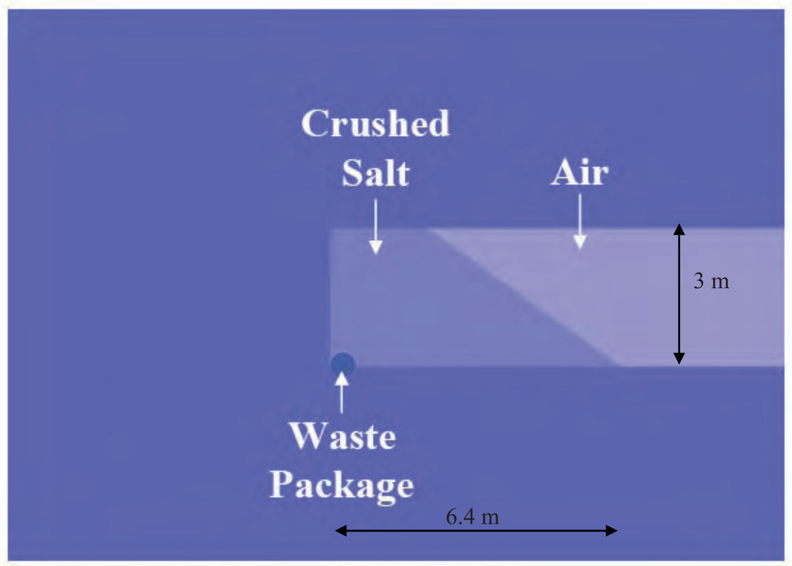
but how far apart should canisters be?



cknowledgement:

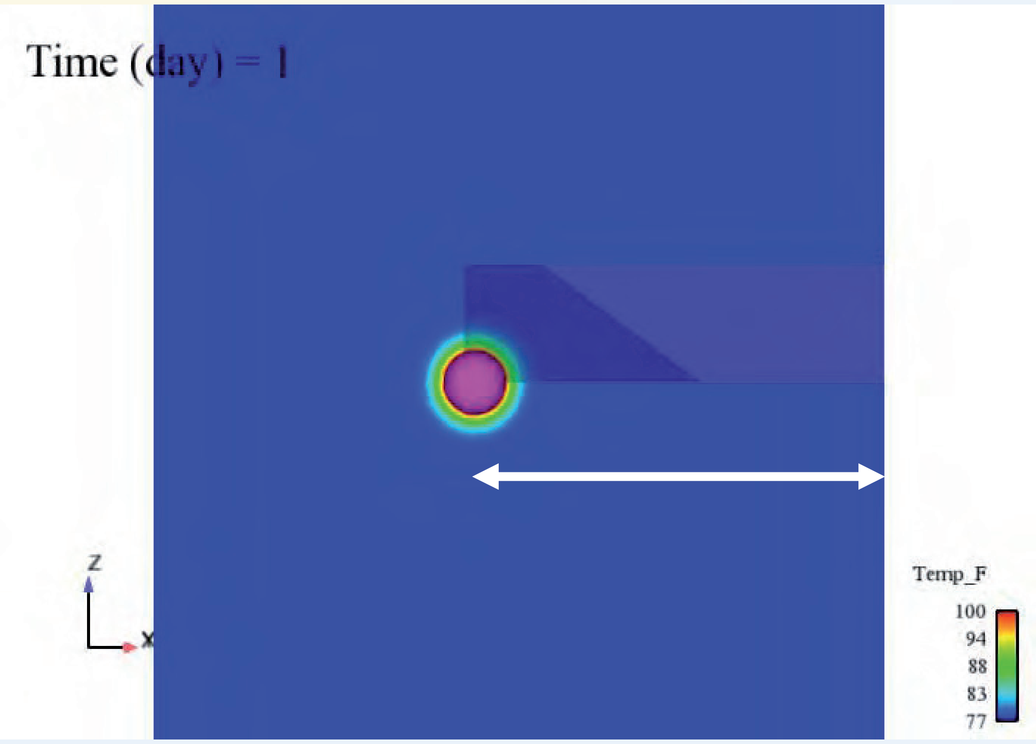
aniel J. Clayton

Thermal modeling concept (alcove scale)



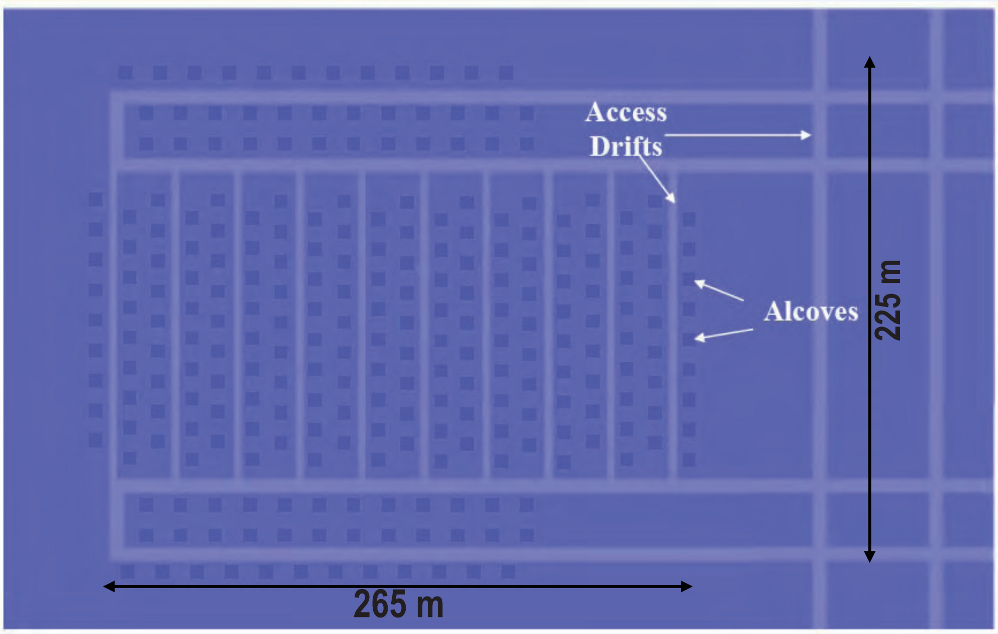
- Waste configuration
  - 8.4 kW
  - 0.6 m diameter
  - 2.7 m length
- Properties of intact salt used for both crushed salt backfill and drift
  (Assumes instant reconsolidation)

Side View Alcove 1st Year 100°F Isotherm (purple)

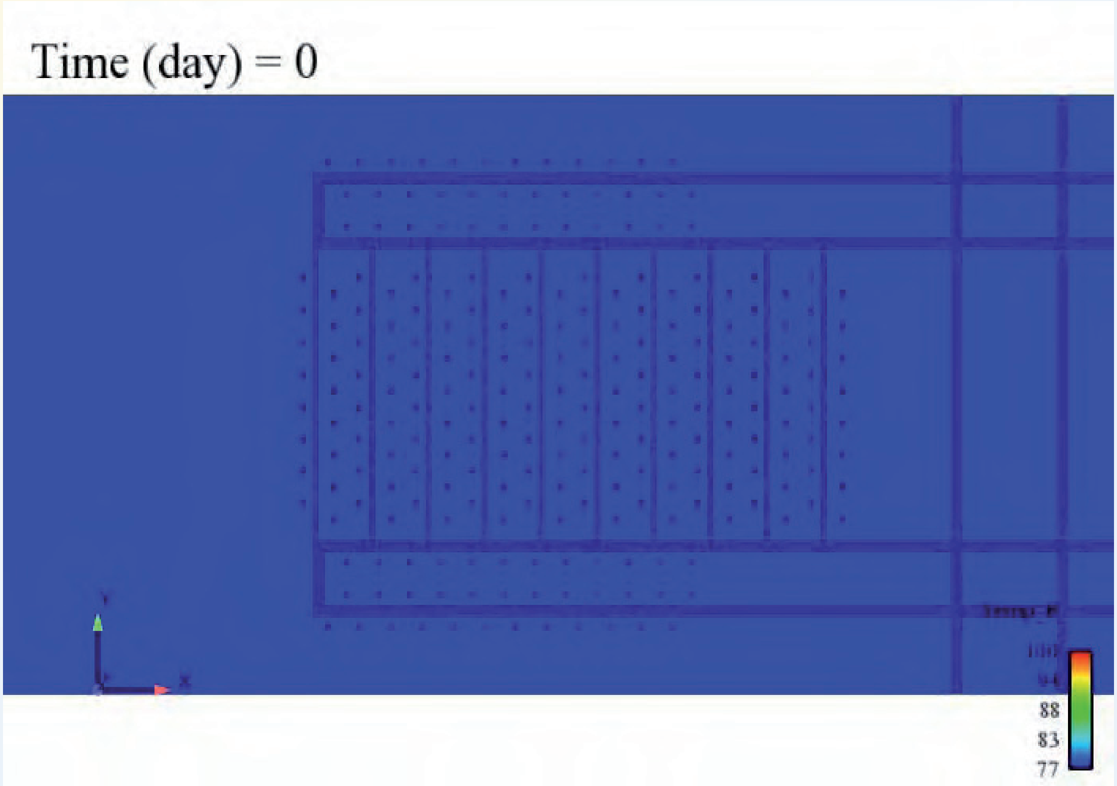


Thermal modeling framework (panel scale)

- Canisters on 12 m centers
- Same thermal properties as in alcove model
- Assumed placement: 1 canister per day



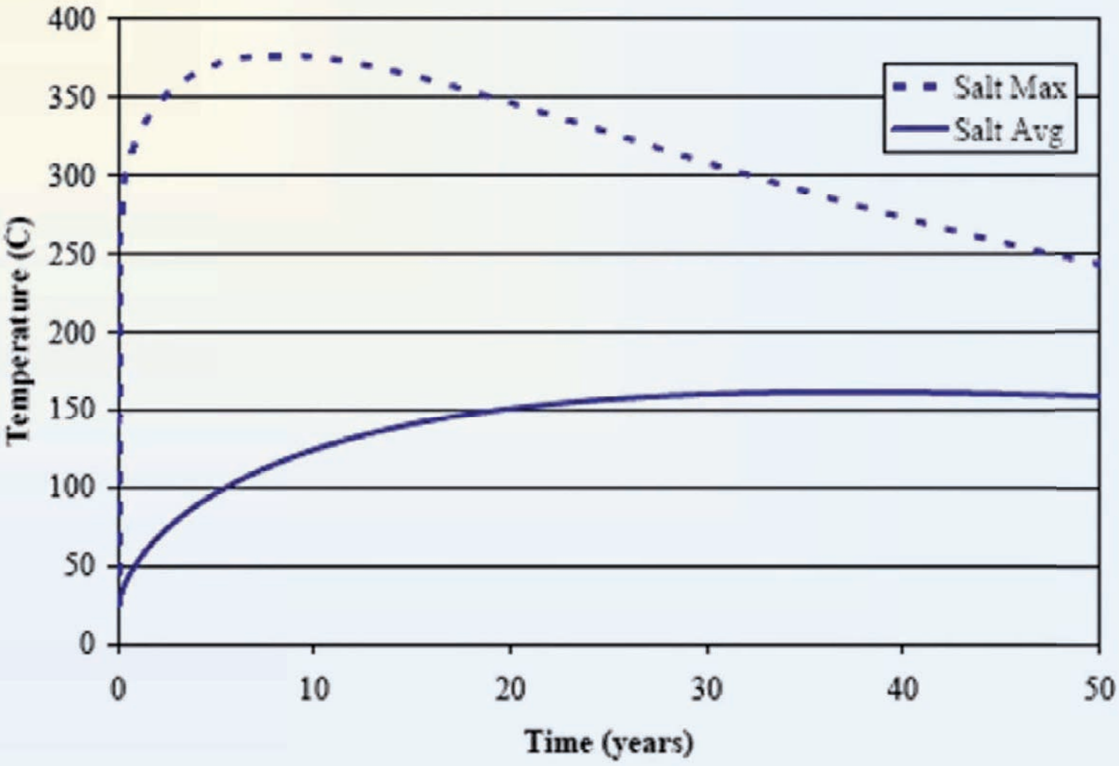
Plan View Panel 5 Years 100°F Isotherm (purple)



Salt Temperatures (high thermal loading)

Waste Package 8.4 kW

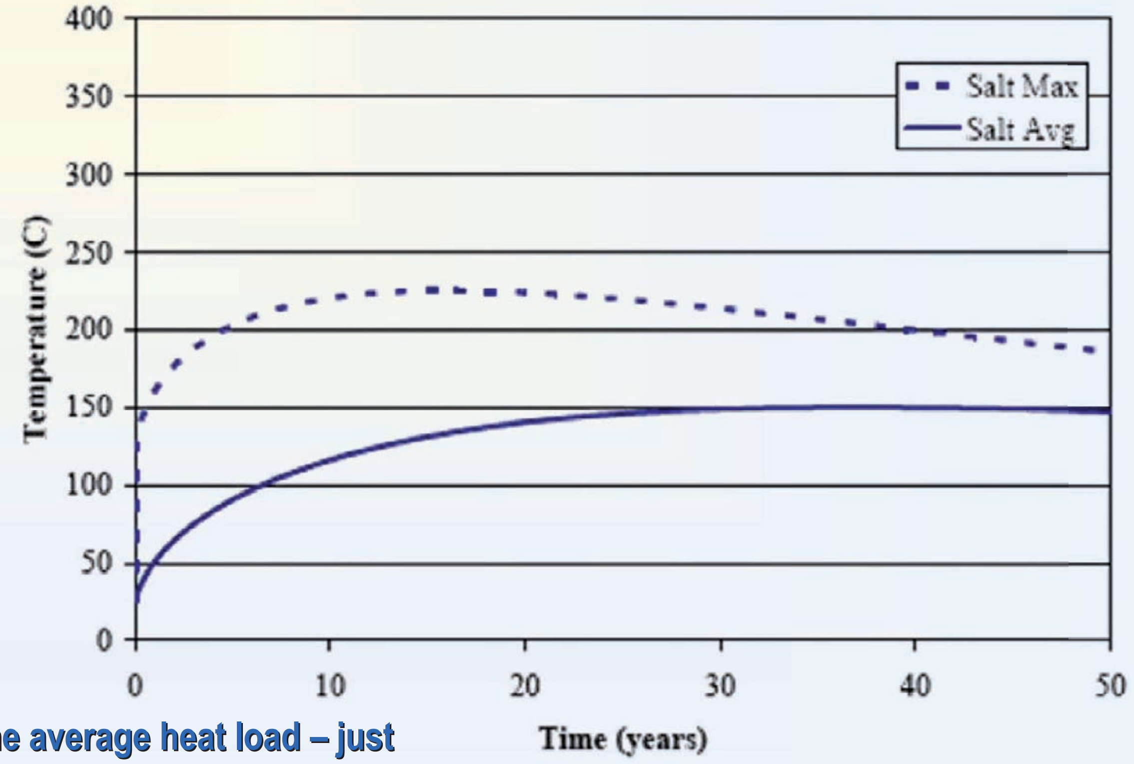
Areal Thermal Loading 39 W/m²



Salt Temperatures (medium thermal loading)

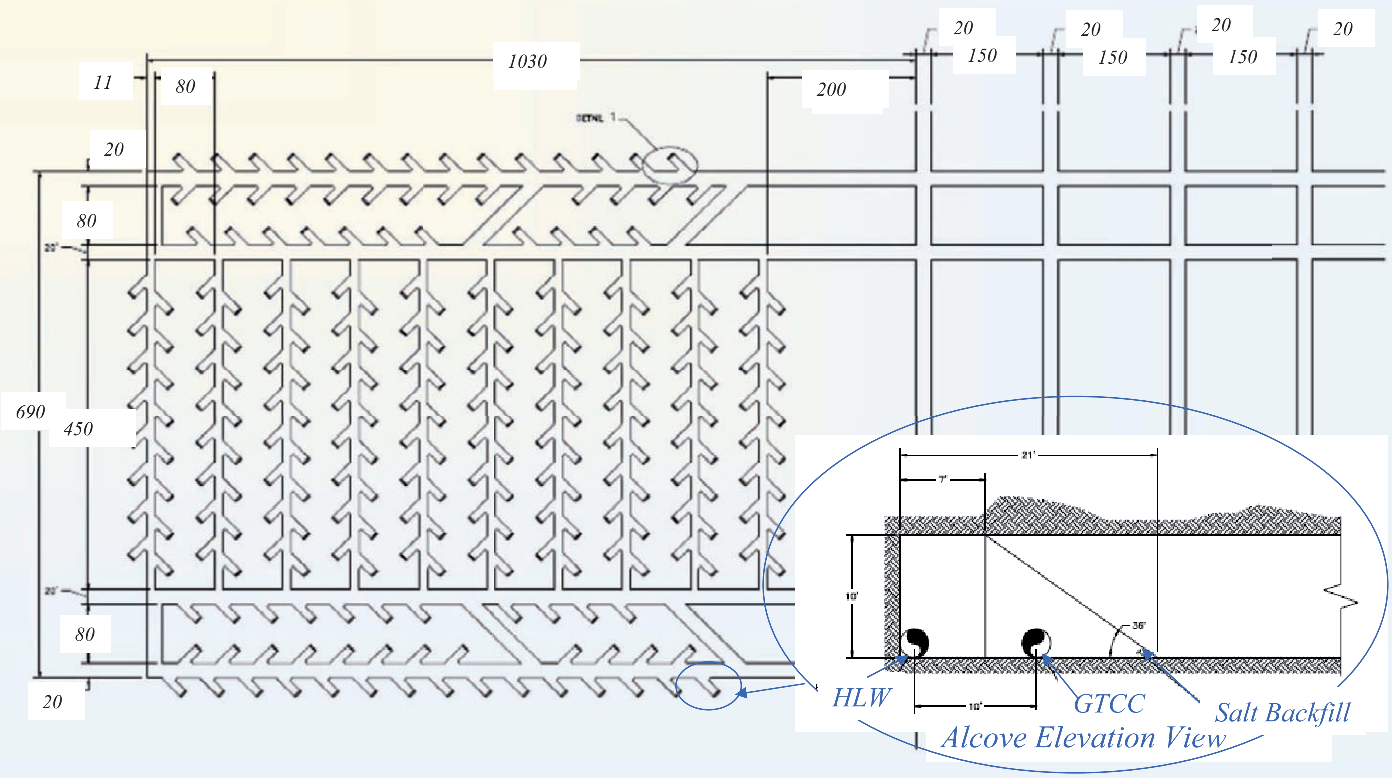
Waste Package 4.2 kW

Areal Thermal Loading 39 W/m²

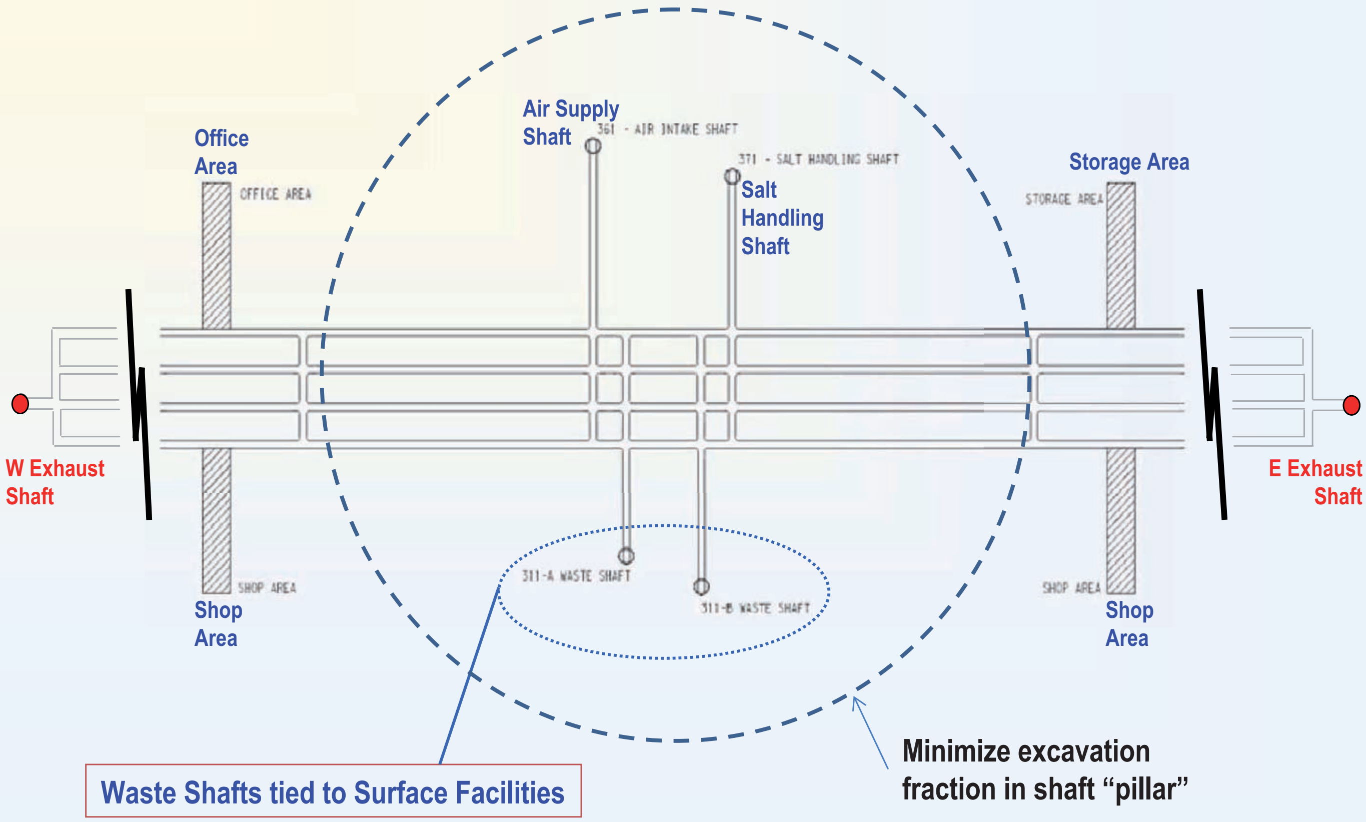


Same average heat load – just spread out more smoothly

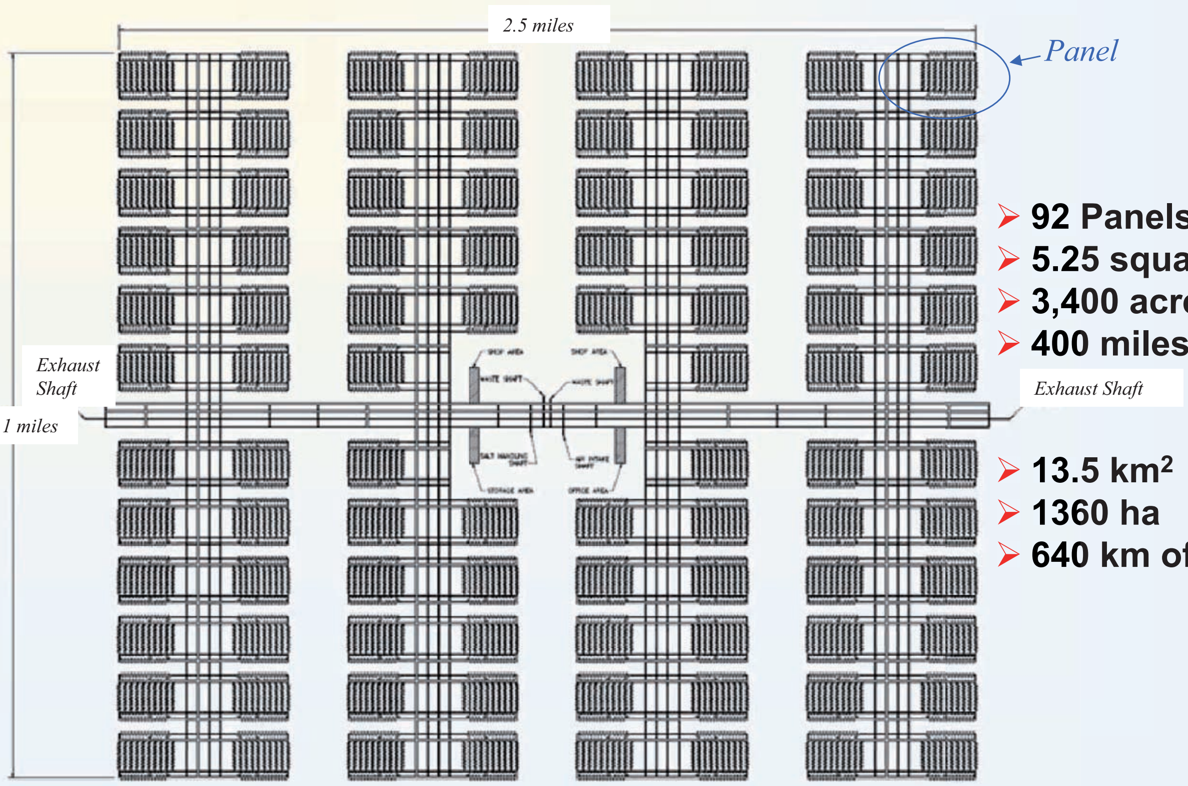
Recommended Disposal Panel Layout



Recommended Shaft Layout



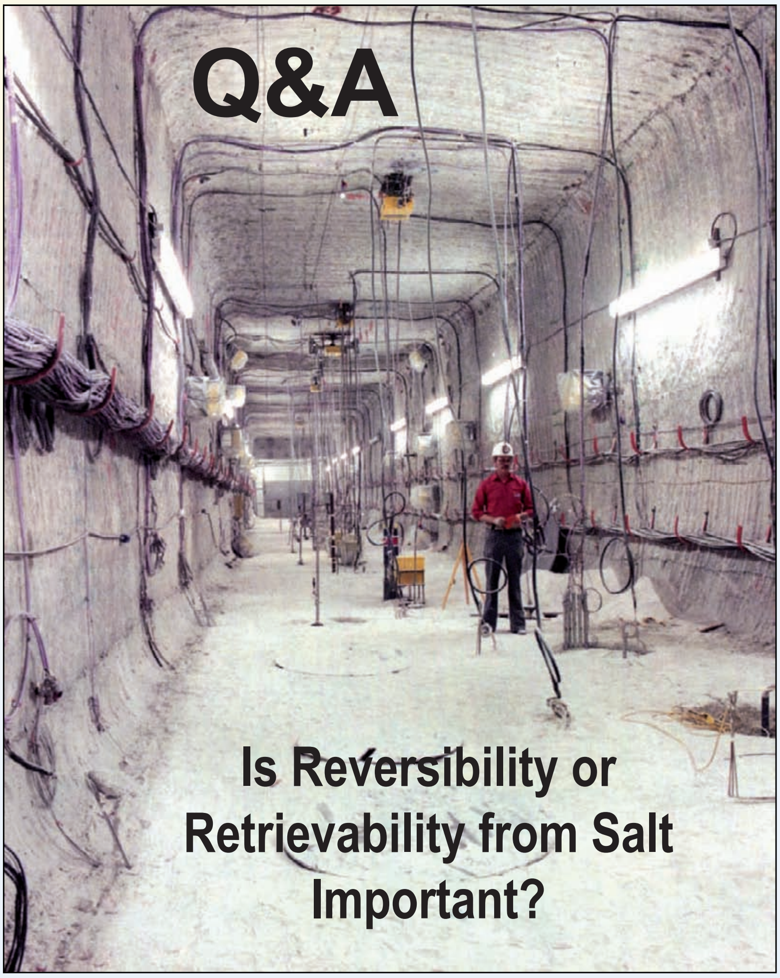
Recommended Repository Layout



- 92 Panels required
- 5.25 square miles
- 3,400 acres
- 400 miles of drifts

- 13.5 km²
- 1360 ha
- 640 km of drifts

236 canisters/panel over 40 years → ~540 per year (~2/day)


Q&A
Is Reversibility or Retrievability from Salt Important?

207

GERMAN CONCEPTS TO DISPOSE OF NUCLEAR WASTE THE WAY AHEAD

E. Biurrun*, W. Steininger**
* DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany
** Projektträger Karlsruhe, Wassertechnologie und Entsorgung
76344 Eggenstein-Leopoldshafen, Germany

INTRODUCTION

In the early seventies of the 20th century, in view of the rapid expansion of nuclear power for electricity generation in Germany, the selection of a site for an integrated nuclear waste management center (NEZ in the German acronym) was a major issue for the Federal Government there. In line with the ambitious energy policy at that time, which anticipated among others a large number of nuclear power plants and a closed fuel cycle, the NEZ was to centralize all the facilities of the back-end of the nuclear fuel cycle at a single location.

The site should on the one hand be capable to host an industrial-size reprocessing plant and its ancillary facilities, which implied requirements in regard to infrastructure, distance to the power plants, availability of qualified personnel, etc. On the other hand the location had to be above or in the immediate vicinity of a suitable site, which then would host the repository for all kinds of radioactive waste, but especially for the heat-generating HLW which resulted from the spent fuel reprocessing. Correspondingly, the site suitability studies were to pay special attention to the site's capability to host a repository.

At a previous time the decision had been made that disposal of all kinds of waste was to be carried out in deep geological repositories, and that in particular heat generating waste was to be disposed of in a salt formation, because there are a large number of such formations, potentially suitable to host a repository, under the Northern German plains. Because salt and potash mining has been carried out in Germany for longer than a century, plenty of knowledge on the geology of the salt formations exists, and long experience in constructing and operating mines was available. However, the preference of this host rock limited geographically possible repository locations basically to the two northernmost states, namely Lower Saxony and the much smaller Schleswig-Holstein.

THE GORLEBEN SITE SELECTION

The German Federal Government, represented by the then Ministry for Research and Technology contracted in 1973 the company *"Kernbrennstoff-Wiederaufbereitungs-Gesellschaft"* (KEWA) to carry out a site selection for the NEZ. In the framework of this KEWA-Study /1/ a site selection process in three phases was carried out, considering all the territory of the then Federal Republic of Germany (West Germany only at that time).

In the first phase an outline review with regional studies and preliminary evaluations of candidate areas was carried out, the *"Landkreise"* (Rural Districts) being the smallest considered unit. In the second phase regional studies were conducted, aimed a identifying and setting up a ranking of most promising site areas. The Gorleben site was excluded at this early stage from further consideration because the rural district of Lüchow-Dannenberg, to which Gorleben belongs, was at that time a remote, pristine area. Correspondingly, it was included in a map of recreation areas as important for local tourism and this was one of the exclusion criteria used.

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The second phase rendered a total of 10 candidate areas where the NEZ could be sited. The geological, hydrological, and meteorological data and information used in these two phases were taken from existing sources, i.e. no dedicated site survey was carried out. Finally, in a third phase a specialist evaluation by expert organizations and specialized companies was carried out, taking into account existing planning information. An important source was a geological study /2/ conducted by the company KBB GmbH (Hanover) with an inventory and evaluation of salt domes in Northern Germany.

At the end of phase 3 a ranking of four candidate sites was presented, all of them in Northern Germany since sites there were deemed in principle better suited than those in the south. They were: 1 Börger (salt dome Wahn); 2 Ahlden (salt dome Lichtenhorst); 3 Faßberg (salt dome Weesen-Luterloh) in Lower Saxony and 4 Lütau (salt dome Juliusburg) in the federal state Schleswig Holstein. This later one was not considered any further due to its location too close to the border of what then was the German Democratic Republic (East Germany). In later phases the work of KEWA focused on detailed studies of the candidate sites. Additionally, the Gorleben site was included in such studies in 1976, as meanwhile the exclusion criteria "recreation area" had been discarded. In its interim report /3/ KEWA clearly stated that the Gorleben site was the most favorable one from all considered sites.

The Government of Lower Saxony in its role as the host state for the integrated waste management center carried out in the following time a site selection of its own based on the previous work of KEWA for the federal government. A project team with members of all concerned ministries in Lower Saxony, the IMAK (in German the acronym for Joint Ministries Committee), was assigned this task in 1976 and carried out a site selection process in three phases. An important condition was that the NEZ should be built at a site determined by the deep geological repository. The selection criteria, published in the minutes of a meeting of the Environment Committee of State Parliament /4/, correspond to criteria still used at present.

In the first phase 140 sites were considered and a first set of 23 selected for further analysis. Exclusion criteria were then applied and 13 sites chosen for continued consideration. The selection process then focused in aspects as safety and environment, site geology, site location and infrastructure and economical aspects. At the end of phase 3 four site remained; the mentioned salt domes of Wahn, and Lichtenhorst, Gorleben and a further site Mariaglück (salt dome Höfer). The IMAK submitted the result to the cabinet of ministers in Lower Saxony for its consideration in December 1976. In a fourth phase finally Gorleben was selected.

- The salt dome Wahn was discarded because it is partially located under a training ground of the federal army,
- The salt dome Lichtenhorst because it is in a priority and reserve area for water supply to Lower Saxony's capital city of Hanover
- The salt dome Höfer because it had already been used for mining.

On February 22, 1977, finally, the German Federal Government confirmed the selection of Gorleben by the Government of Lower Saxony as the site for the NEZ and thus for the deep geological repository. This decision was later confirmed by the Heads of Governments of the federal states and of the Federal Republic of Germany.

Fig. 1. Gorleben site

DEVELOPMENT OF THE GORLEBEN SITE AND REPOSITORY TECHNOLOGY

The council of the heads of government of the Federal Republic of Germany and of the Federal States in a ground-breaking decision of September 28, 1979 /5/ established the basis for the German waste management concept. The council welcomed the decision by Lower Saxony, to permit the construction of a repository at Gorleben in case the site exploration and the exploration mine development prove the suitability of the site for waste disposal. Therefore, the site exploration and exploration mine development was to be swiftly carried out.

Site survey from the surface started shortly thereafter, and led to drilling of a large number of exploration boreholes down to a depth of about 270 m, aimed at obtaining information on the overburden and on the layers immediately above the salt. Furthermore, a large number of hydrogeological wells were drilled in the surroundings of the dome to study the hydrogeological conditions in the area. Exploration from the surface included detailed, precision leveling of the area on top and around the salt dome, seismic survey, and an extensive program of evidence collection and preservation to determine the environmental situation of the area prior to the development of the repository facility. Finally, four deep drilling well were sank into the flank area of the repository down to more than 2000 meter, and provided valuable information on the salt structure necessary for the planning of the exploration mine. Two further shaft exploration boreholes were sank at the selected positions for the two access shafts that were later sunk there.

In 1983 all the data from the surface exploration required for a preliminary site suitability evaluation was available. In an extensive interim report by the responsible governmental bodies, the German Geologic Survey BGR and the then Federal Institute for Physics and Metrology, paved the way for the underground survey by stating the presumed suitability of the site to host a repository. In view of the excellent surface survey results, which strongly supported the presumed site suitability, the exploration mine was designed and constructed so that important and costly elements as the access

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shafts and the surface and underground infrastructure could later be used as part of the repository without major alterations and refurbishment. By that means, transformation of the exploration mine into a repository after licensing could be rapidly carried out optimizing the use of economic resources.

After some preparatory work, construction of the exploration mine by DBE started in 1986 with the excavation of two shafts in the central part of the salt dome. After 1996 the infrastructure rooms at the exploration mine level of 840 m were swiftly excavated and equipped. Thereafter, the excavation of drifts and galleries around the "*Erkundungsbereich 1"* (EB1 Exploration area 1) was started. After a change in the Federal Government in 1998 there was a change in the waste management policy that lead finally to the nuclear phase-out decision and the moratorium of the site exploration since November 2000. Until this time, some 400,000 m³ of void space had been excavated in the framework of the exploration mine construction. Figure 2 displays the current status of underground mine construction.

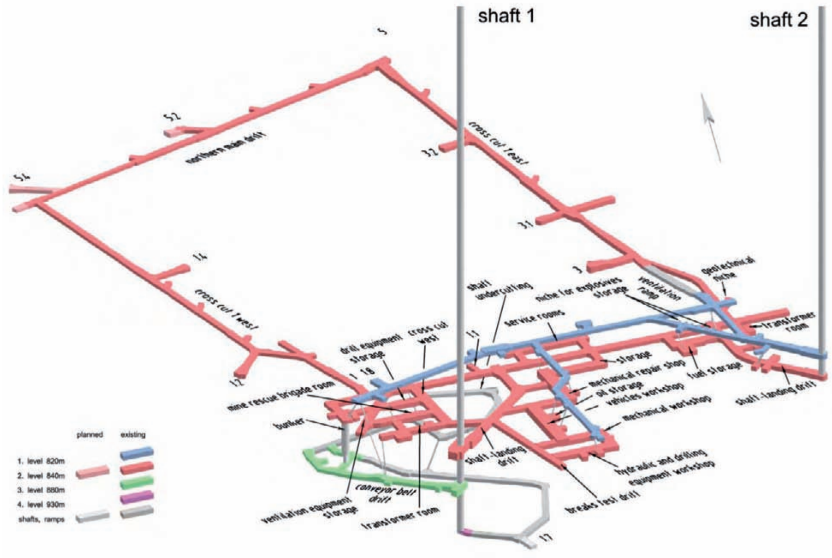

Figure 2: Gorleben site underground facilities

The Moratorium that was to last as a minimum for three years and as a maximum for 10 years was adduced to provide time for studying issues the new Federal Government wanted to have resolved before continuing site development. In spite that the issued had been resolved by 2005 and the results published in a report, the Moratorium was not lifted and the exploration was not continued.

In spite that the Gorleben site had been selected by elected government bodies fully in line with democratic legitimacy principles, and after investing 1.3 billion Euros over 20 years in the site development, the Ministry of the Environment designated in 1999 a commission to develop a set of criteria and a procedure for selecting a new repository site starting from scratch. The results of the so-called AkEnd commission were published in 2002, but implementation failed since there was no agreement inside the Federal Government and with the Federal States about conducting a new repository site selection, and therefore the necessary legal basis was not passed by parliament. In 2005 a new coalition government was inaugurated, but the parties in the coalition failed to reach an agreement on the future development of the Gorleben repository project. A new policy is only currently becoming possible after the inauguration of a new administration in October 2009.

Concurrent with the site development, the technology for waste disposal has been developed to technical maturity and demonstrated in 1:1 scale. Among others a pilot conditioning plant in which the spent fuel and the vitrified HLW will be discharged from the interim storage casks and loaded into the final disposal cask or container was designed and built at Gorleben, adjacent to the repository site (see Fig 1, on the upper left corner). The facility is currently fully operational but has not been yet hot commissioned since the repository development has suffered substantial delay. At the same site also an interim storage facility for HLW and spent fuel with a capacity of up to about 4000 tons of heavy metal was build and is currently in operation to provide time for the decay heat of the waste to decrease before disposal. The facility currently contains some 1200 tons of HLW in the process of aging.

The technology for the shaft transportation of heavy casks containing spent fuel or vitrified HLW down to the disposal level was also developed and demonstrated, as it was not state-of-the-art before. Furthermore, a rail bound waste handling and transportation system was developed and tested, including all ways and means needed underground for the drift disposal operations (the reference concept for direct disposal of sf), including the waste emplacement machine. In more recent times, in a further series of equipment design and demonstration projects, an optimized concept for the borehole disposal of spent fuel and vitrified HLW has been developed. The equipment was intensively tested in a series of demonstration tests, so that currently two alternative emplacement technologies exist that can principally be used for a repository in a salt formation. In a separate paper presented to this conference the equipment development program is comprehensively dealt with /6/ and therefore these matters are not repeated here. An example of the machinery developed for sf direct disposal in drifts is shown in Figure 3.

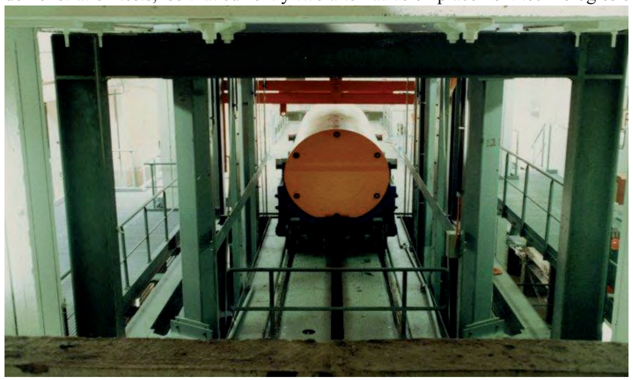

Figure 3: Equipment testing and demonstration facility

In addition significant attention has been given within the RD&D program to issues like repository performance assessment and safety case. Among others it is worthwhile to specially mention the ISIBEL Project. In this project with participation of scientist and experts from the German Geologic Survey BGR, the German Gesellschaft für Anlagen- und Reaktorsicherheit GRS, the Institute of Nuclear Waste Management INE of the Karlsruhe Institute of Technology, from DBE TECHNOLOGY as well as from university researchers, a comprehensive, novel safety case concept for a repository in a salt formation has been developed /7/. With this, in principle also state-of-the-art scientific instruments for demonstrating the long-term safety of a repository in salt are available.

THE WAY AHEAD

In view of the above, and in spite of the politically motivated stop of site exploration in the past ten years, it is clear that with the Gorleben repository project Germany still has in place one of the most advanced

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repository programs. Currently, with the construction of the Konrad deep geological repository for non heat generating waste valuable experience is being obtained in the country on the industrial aspects of geological repository construction. Already in the year 2000-agreement achieved between the Government and the electricity utilities to phase out nuclear power use past there are some important statements dealing with Gorleben

- The Government confirmed that up to that time there are no scientific findings pointing at the non-suitability of the Gorleben dome to host a repository for heat generating waste.
- Data acquisition from the installed monitoring devices and some needed work were continued as necessary to secure the site later use as a repository.

In addition, the agreement implies that after clarifying the open questions, which happened before 2005, survey at Gorleben will continue and that at the latest in 2010. Correspondingly, and irrespectively of what the future of nuclear power use in Germany might be the way forward is now finally open.

The German administrative procedures prescribed by the Nuclear Energy Act to license a deep repository, the *"Planfesstellungsverfahren"* (Plan approval procedure), does not anticipate active public participation until near the end of the process. In spite of the very proactive support of the village of Gorleben to the repository project, public acceptance needs to be improved to the extent possible. Obviously, ways and means need to be implemented to ensure that at least the population without a completely rejecting attitude has a stake in the future work. In spite that a formal framework for such public involvement is not part of German law, strong efforts need to be made to achieve the widest possible degree of consensus within the local population. At the same time it is necessary to remain aware that a certain minority will keep strongly opposing the repository project, regardless of the actions taken.

After the 2009 elections the new Federal Government, communicated in the coalition agreement to lift the moratorium on exploration and to continue with exploration, accompanied and supported by several activities:

- A preliminary safety case is intended to be performed,
- A peer-reviewed by independent, international experts to ensure the program is steadily conducted according to the best international practices and in line with the most advanced state-of-the-art.
- A public review commission is established with the widest possible participation of all stakeholders in the Gorleben region and beyond, to serve as vehicle to inform the public on comprehensive and timely basis. Furthermore, the needs and interests of the stakeholders shall be accounted for as far as possible in the review work.
- An actualization of the Gorleben repository conceptual design shall be carried out in the near future, in order to serve as guide for the underground exploration work.

With this, it appears now possible that a statement either confirming or rejecting the suitability of Gorleben to host the German repository for heat generating was can be achieved within a few years: This development is very promising after years of standstill.

Acknowledgment

The R&D work referred to in this paper was made possible through the generous financial support of the Federal Ministry of Economics and Technology, of the German nuclear industry, represented by GNS, and of the European Commission.

References

/1/ KEWA GmbH (1974): Ermittlung mehrerer alternativer Standorte in der Bundesrepublik Deutschland für eine industrielle Kernbrennstoff-Wiederaufarbeitungsanlage (vom BMFT gefördert), Frankfurt/M.-Höchst (Identification of several siting alternatives in the Federal Republic of Germany for an industrial spent nuclear fuel reprocessing plant (Supported by the Ministry of Reseach and Technology))

/2/ KBB GmbH (1974): Zusammenstellung und Bewertung geologischer und topographischer Daten von Salzstöcken in Norddeutschland für den Bau von Kavernen, Hannover. (Compilation and evaluation of geological and topographic data on salt domes in Northern Germany for the construction of caverns.)

/3/ KEWA-Zwischenbericht über den Berichtszeitraum vom 1.1. – 31.12.1976 KEWA-Kernbrennstoff-Wiederaufarbeitungsgesellschaft (Hg.) (Oktober 1977): Untersuchung eines Standortes zur Errichtung einer Anlage für die Entsorgung von Kernkraftwerken, Teiluntersuchungen zu zwei Alternativstandorten, Kennzeichen KWA 1225. Zwischenbericht.

/4/ Protokoll aus der 6. Sitzung des Umweltausschusses des Niedersächsischen Landtages in der 8. Wahlperiode vom 17.10.1977 (Minutes of a meeting of the environmental committee of the Parliament of Lower Saxony in the 8th sessions period of October 17, 1977)

/5/ Beschluß der Regierungschefs von Bund und Ländern zur Entsorgung der Kernkraftwerke vom 28. September 1979 (Decision by the council of the heads of government of the Federation and of the Federal States on the management of waste from nuclear power plants of September 28, 1979)

/6/ Haverkamp, Biurrun et.al. “Optimization of spent fuel direct disposal technology for a geological repository in rock salt in Germany”. Proceedings of WM2010, Phoenix, AZ, 2010

/7/ Review and Appraisal of the Tools available for Safety Assessment of Final Repositories for HLW (ISIBEL , Status of the Total Performance Assessment for a Repository for HLW in Rock Salt) GRS, BGR, DBE TEC.

GERMAN CONCEPTS TO DISPOSE OF NUCLEAR WASTE

THE WAY AHEAD

Contents

In the early 70' Germany developed a concept for an Integrated Waste Management Center (NEZ):

- A SF reprocessing plant co-located with
- An HLW repository

In 1973/1974 NEZ site selection was a major issue

Before it had been decided that all radioactive waste was to go to deep geological repositories

And *heat generating waste was to be disposed of in a salt formation*

In *1973* the Federal Government contracted the

"Kernbrennstoff-Wiederaufbereitungs-Ges." (KEWA)

to carry out a site selection for the NEZ,

- In three phases
- Considering all the territory of West Germany

→10 candidate areas were identified

→Gorleben was excluded because it is in Lüchow-Dannenberg, a recreation area

The Government of Lower Saxony, the NEZ host state, in carried out thereafter a site selection of its own

- **By a project team set up to this aim in 1976**
- **In tree phases**
- **The selection criteria, published in 1977, correspond to criteria still used today**
- **Leading to four sites being identified for a final selection**

  - ***Wahn***
  - ***Lichtenhorst***
  - ***Gorleben*, and**
  - ***Höfer* (Mariaglück)**

Lower Saxony's Government finally selected Gorleben (December 1976)

- **The Wahn salt dome was discarded because it is partially located under an army training ground**
- **The Lichtenhorst dome because it is in a priority and reserve area for water supply to Hanover**
- **The Höfer salt dome because it had already been used for mining**

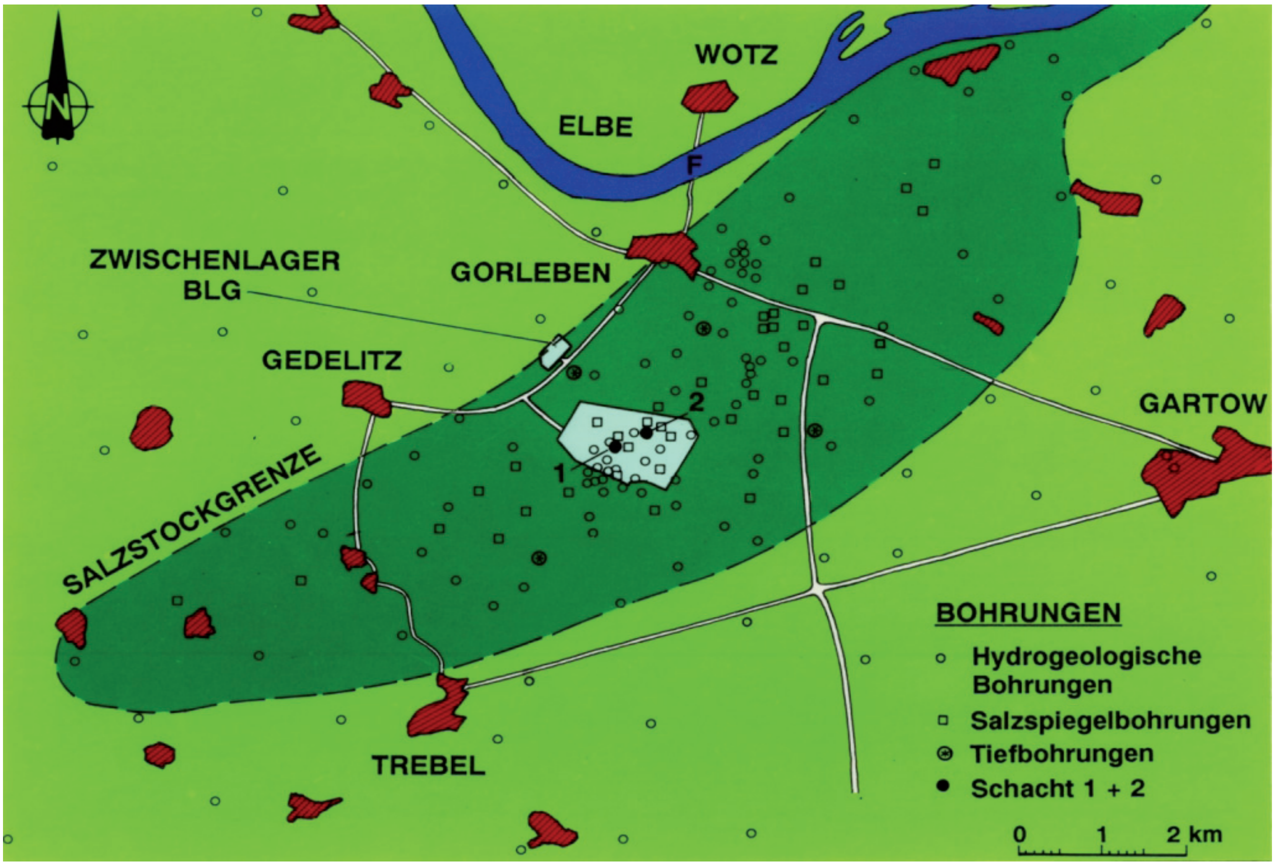
On February 22, 1977, the German Federal Government confirmed Gorleben as the site for the NEZ and for the repository.

Site and Technology Development - Milestones

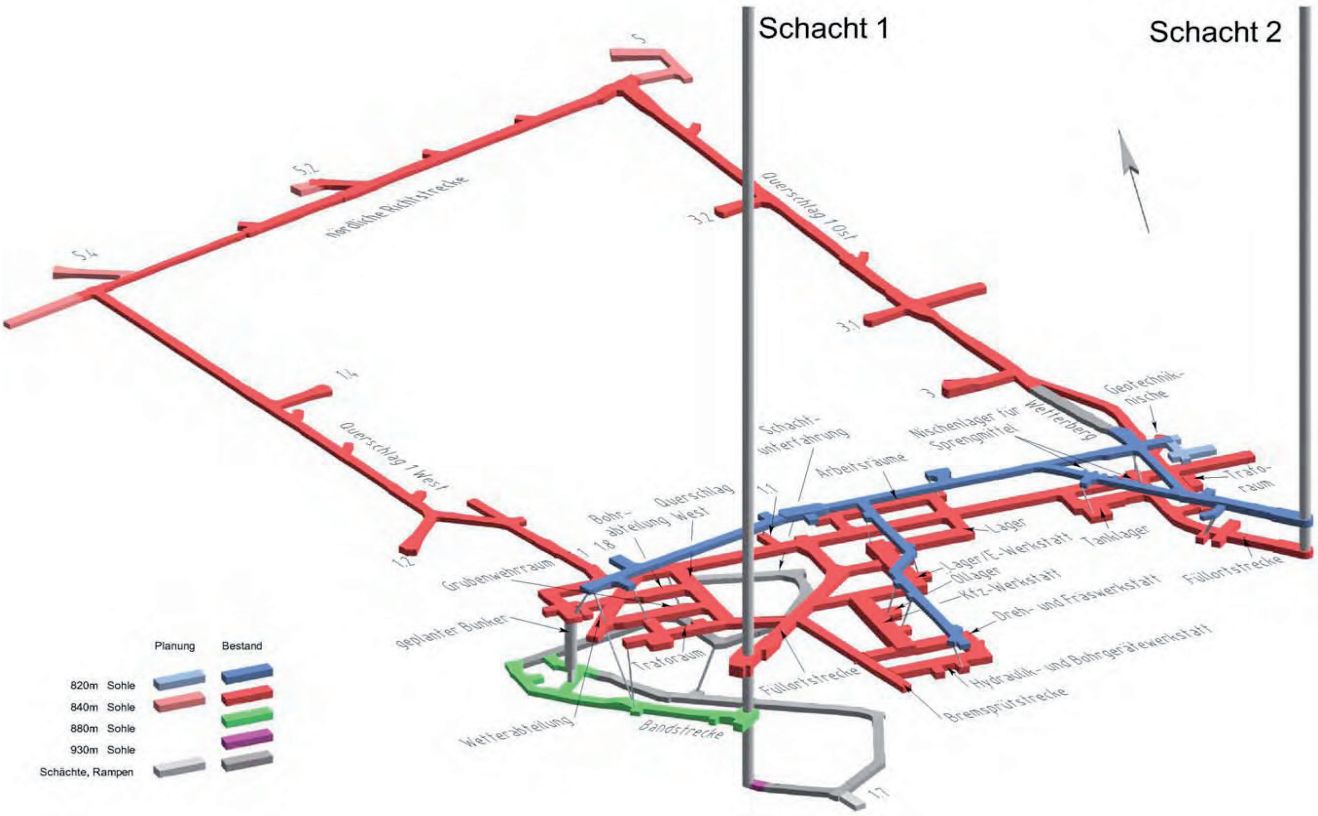
22.02.1977	Site designation Gorleben (Nukleares Entsorgungszentrum/NEZ)
April 1979	Start of surface site characterization
1980/1981	Four deep boreholes (1002 / 1003 / 1004 / 1005)
Mai 1983	Comprehensive suitability statement by PTB
Sept. 1986	Ground-breaking Shaft 1
Oct. 1996	Communication between Shaft Gorleben 1 and Gorleben 2 (840-m-Sohle) established: Thereafter excavation of infrastructure area and characterization of Exploration Area 1
01.10.2000	Site characterization interrupted. Thereafter stand-by operation only
03.03.2010	Germany announces to the IAEA Board of Governors that site exploration will continue

Site and technology Development - Exploration Mine

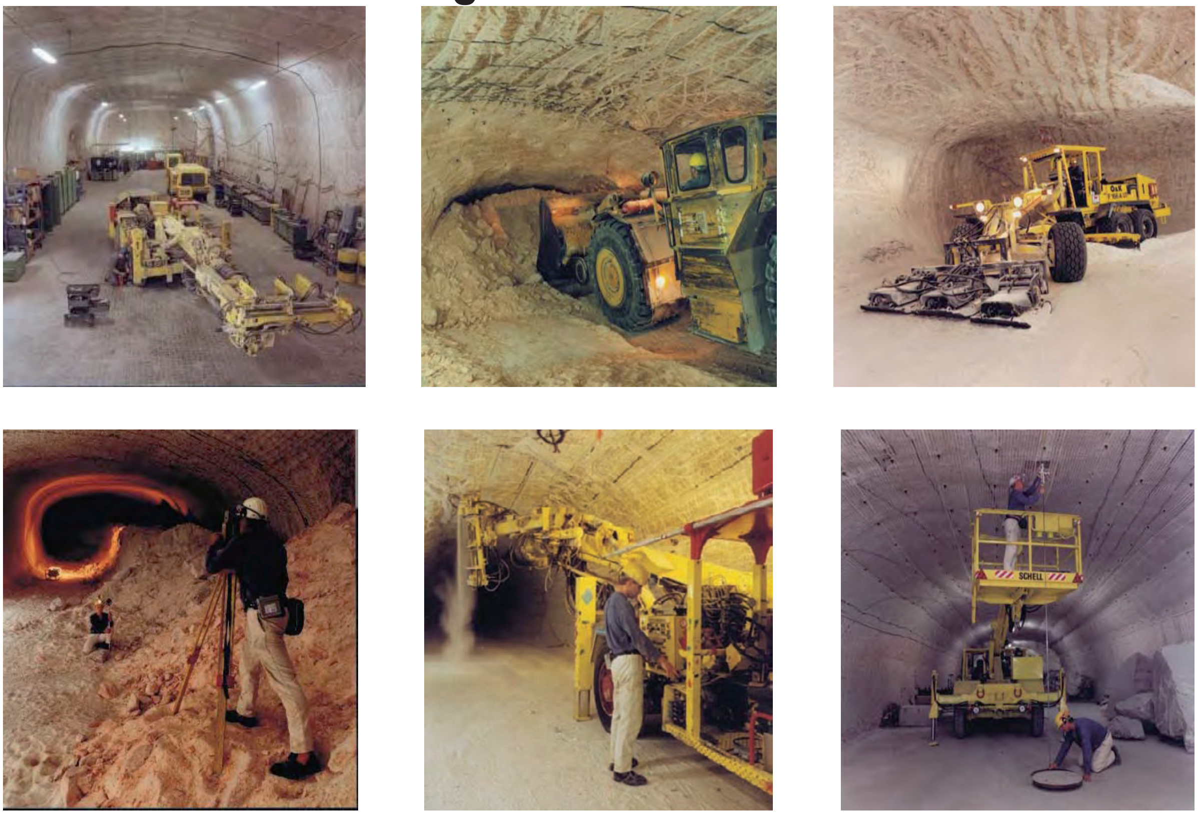
Site and technology Development – Surface Survey



Site and technology Development – Underground Survey



Gorleben - Underground



Site and Technology Development

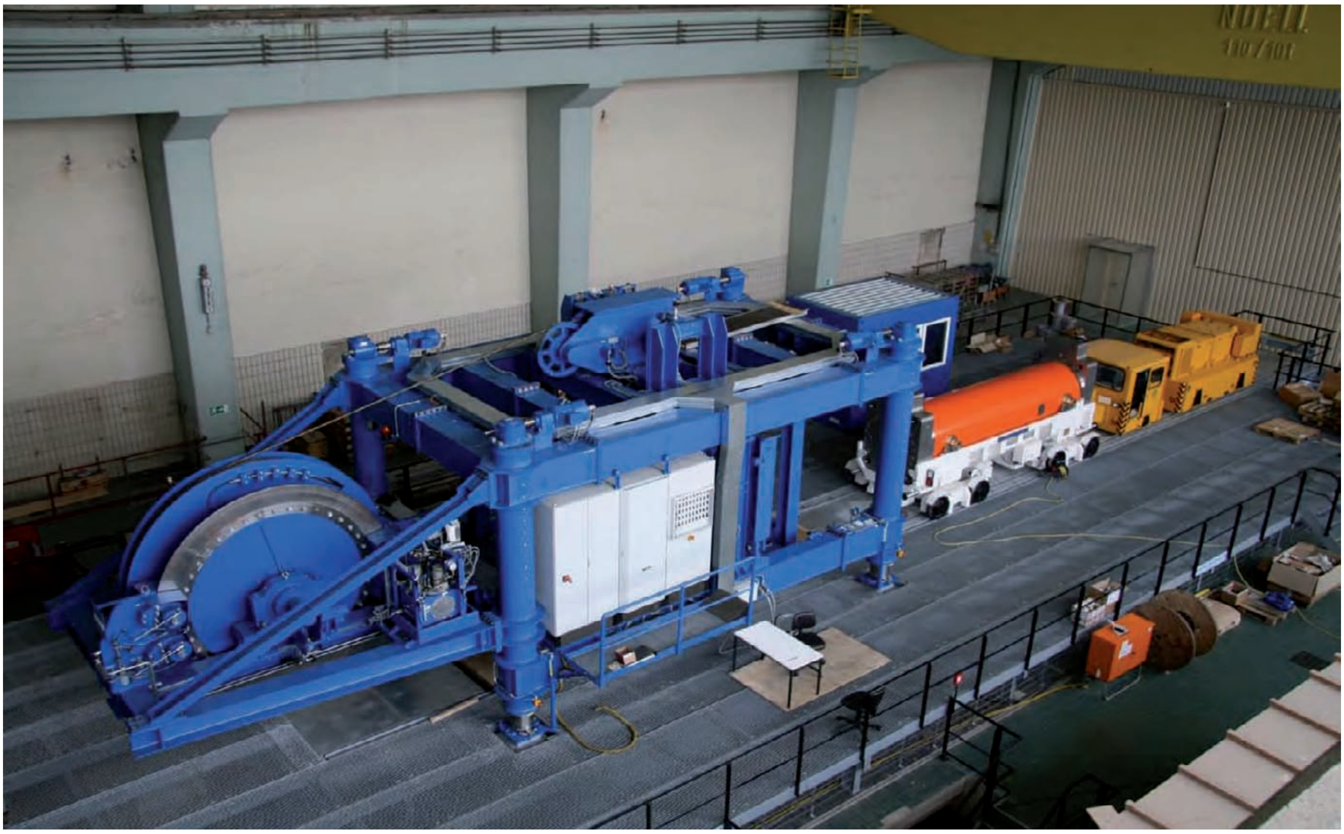
Concurrently with site development, the technology for waste disposal was developed and demonstrated

- **A pilot conditioning plant was designed and built**
- **Two interim storage facilities for ~ 4000 THM were commissioned**
- **The technology for SF and HLW shaft hoisting to the disposal level was developed and demonstrated**
- **The full underground waste handling and disposal system was developed and tested**
- **In recent times an optimized alternative for HLW and SF borehole disposal was demonstrated *(follows)***

Site and technology Development – Conditioning Plant

Site and technology Development – Waste Disposal

Site and technology Development – Waste Disposal

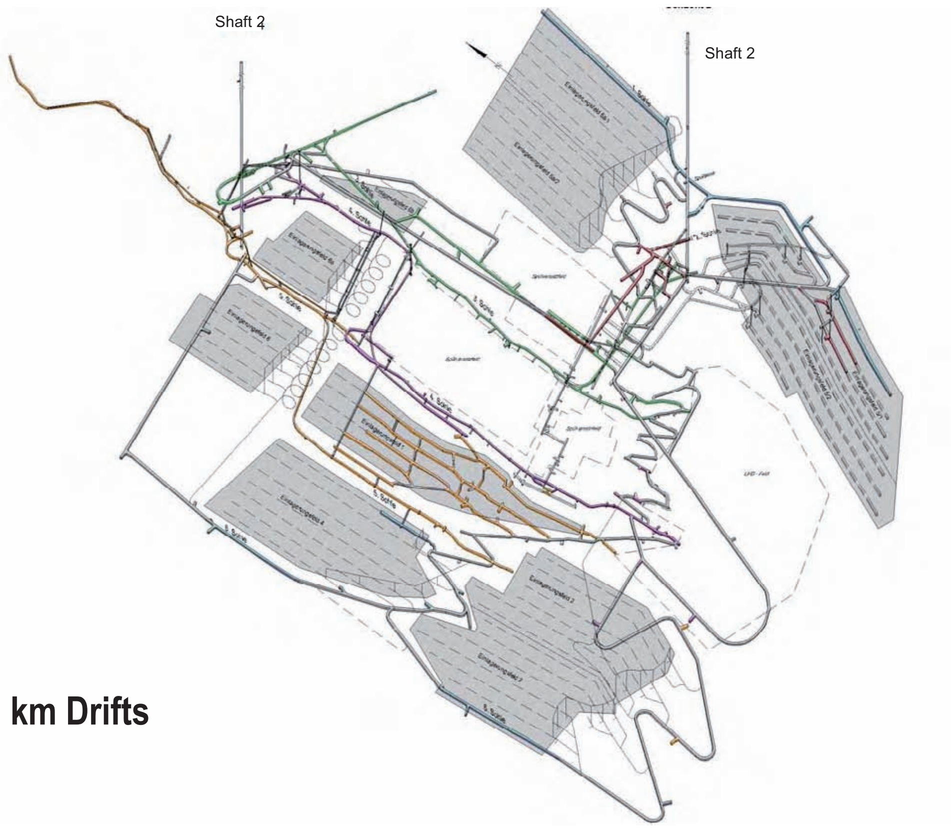


The Present – Site Development and Repository Construction

The Present – Site Development and Repository Construction

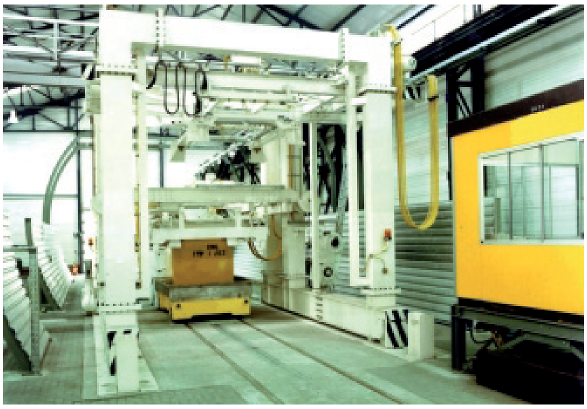
1965 – 1976	Iron ore production approx. 7 mil. t;
	Deposit: ~ 1.4 billion t
1975	Preliminary survey as candidate site
1982	Site Suitability statement and License Application submitted
09/92 - 03/93	Public hearing (75 hearing days)
14.06.00 /	Consensus Agreement
17.07.01	- Finishing licensing procedure
	- Withdrawal immediate enforcement
01.08.01	Radiation Protection Ordinance amendment
	License application amendment
05.06.02	LICENSE GRANTED
2002-2008	LITIGATION
2010	REPOSITORY CONSTRUCTION
2014	DISPOSAL START

The Present – Site Development and Repository Construction

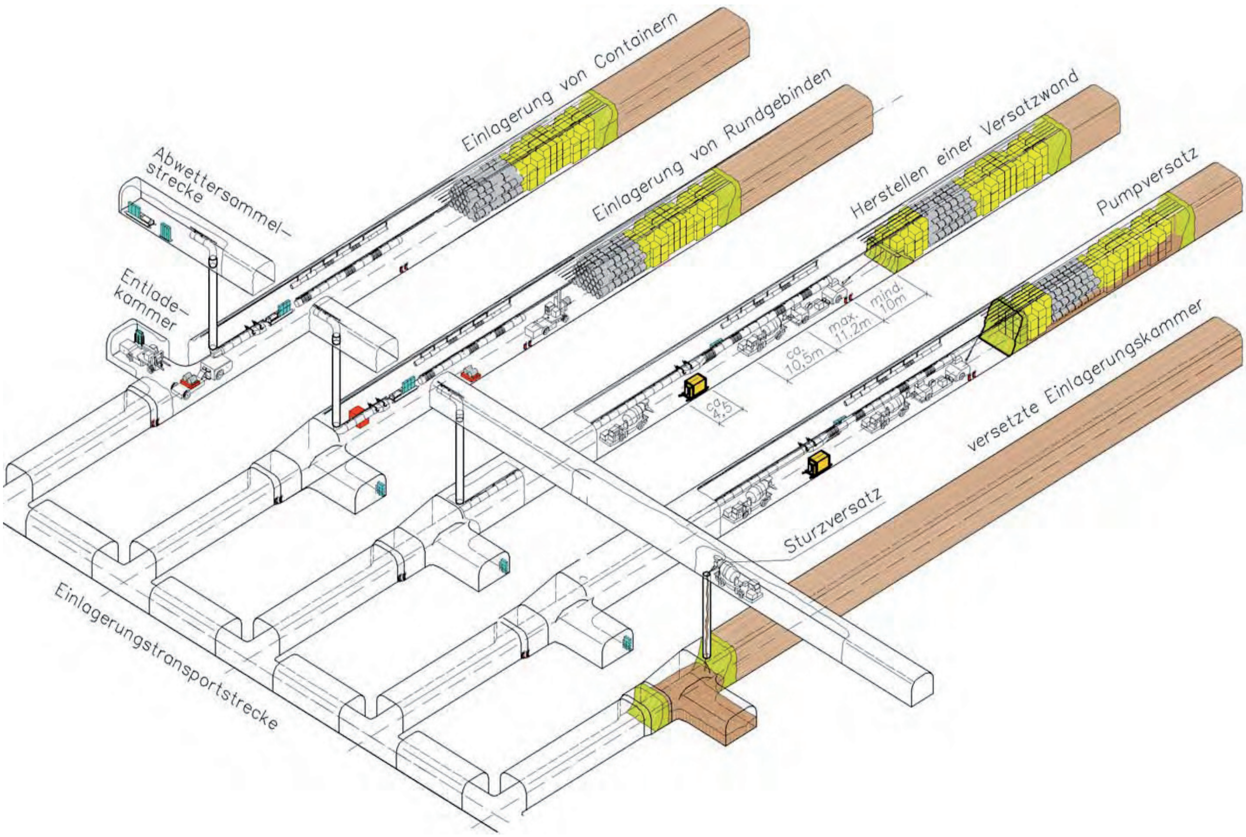


- 40 km Drifts

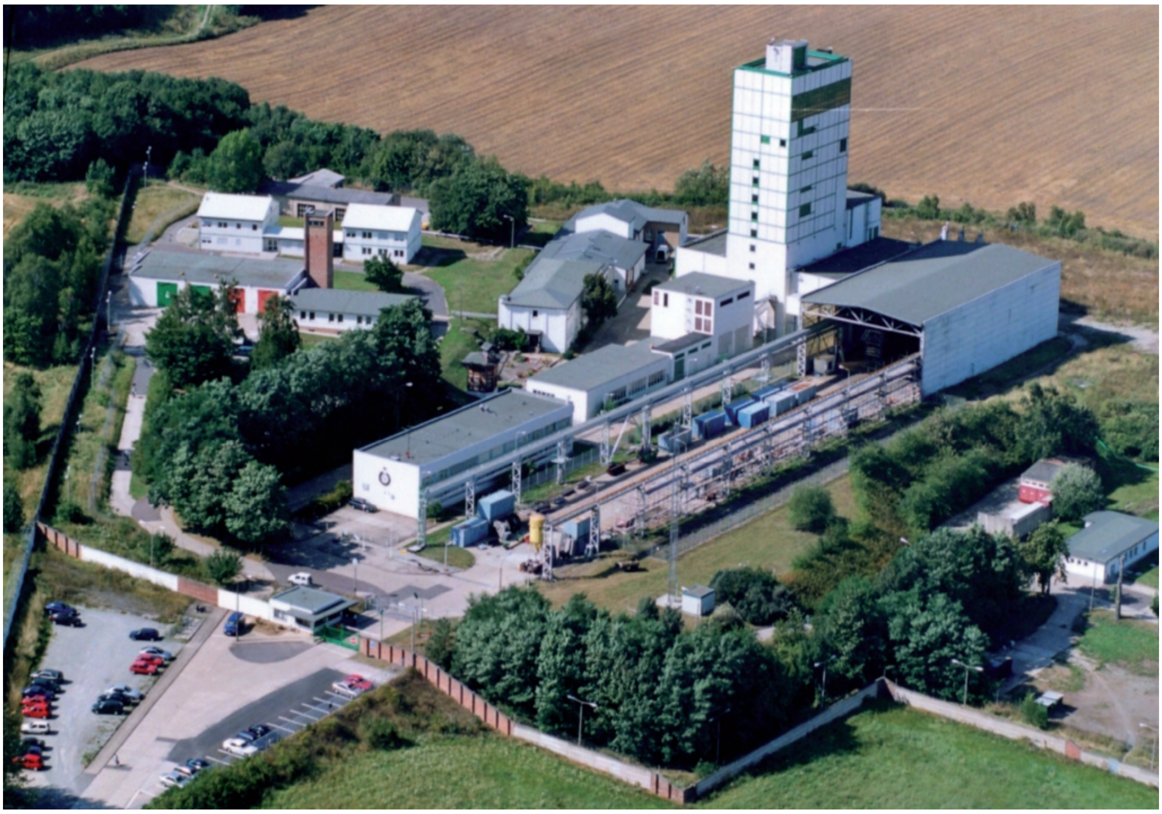
The Present – Site Development and Repository Construction



The Present –Site Development and Repository Construction



The Present –Repository Closure

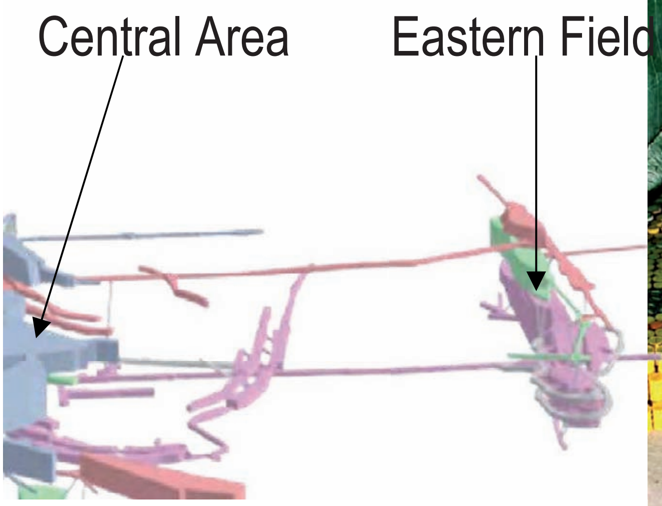


The Present – Repository Closure

1970	Bartensleben mine selected as repository
1971	Start of trial disposal (LLW)
1974	Approval of repository construction
1981 / 1986	1st and 2nd permanent operation licenses
10 / 1990	Morsleben repository a Federal Facility under BfS, operated by DBE
1991	Disposal stop, refurbishment
1994	Disposal restarted
09 / 1998	Waste acceptance interrupted
05 / 1999	Waste disposal terminated
11 / 2000	Advanced backfilling - repository closure to follow
2010	Public hearing
2012	License for closure ?

The Present – Repository Closure

The Present – Repository Closure



The Present – Repository Closure

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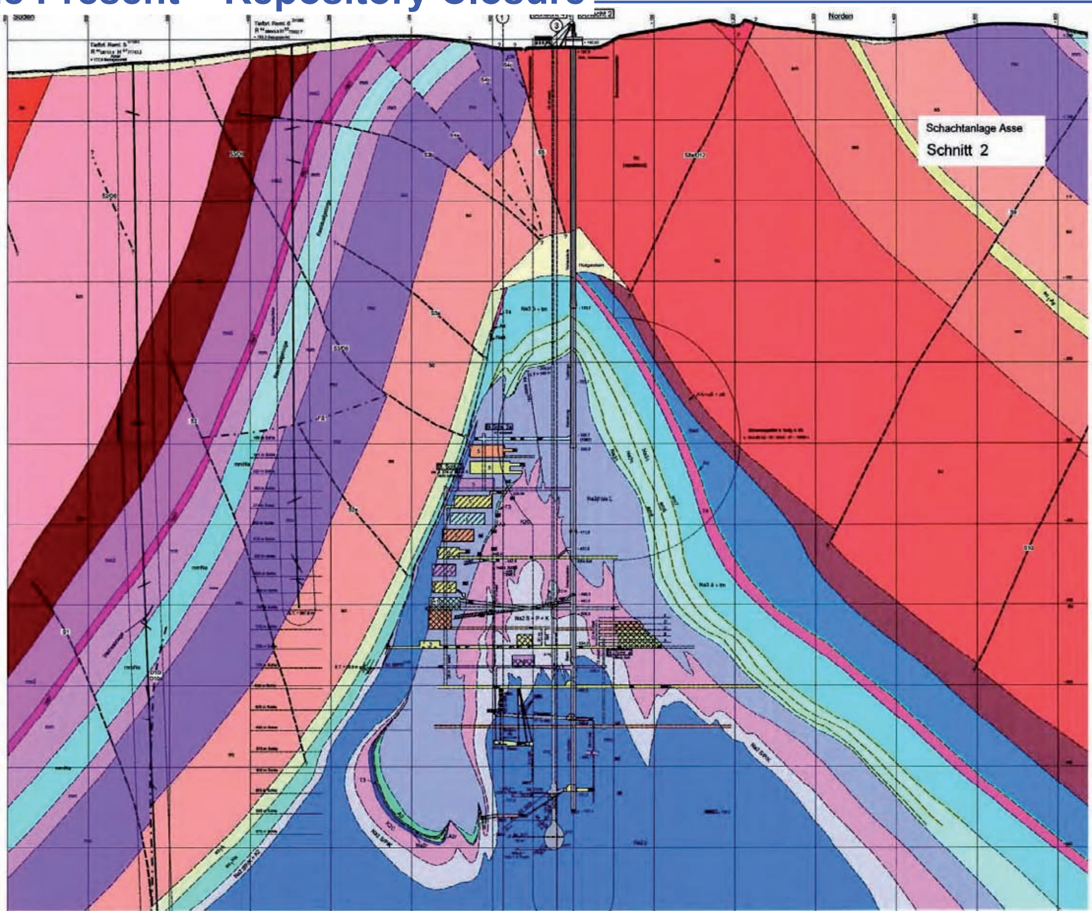
The Present – Repository Closure

The Present – Repository Closure

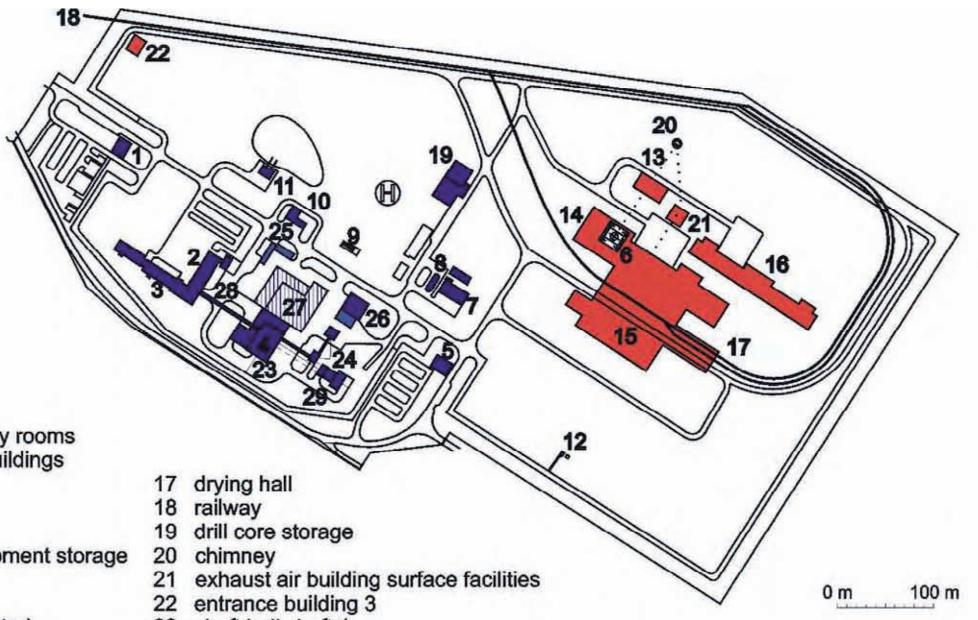


The Way Ahead

Fortunately, significant progress has been achieved in recent times in all German repository projects:

- ***The Konrad deep geological repository (LILW) is under construction and swiftly progressing***
- ***Konrad will join the WIPP as the second operating geological repository at around 2014***
- ***The public hearing for closure of the Morsleben LILW repository will be carried out later this year***
- ***On March 3, 2010 Germany informed the IAEA that exploration of the Gorleben site is being reassumed***
- ***Survey results for site suitability statement (positive or negative) shall be available at around 2014***
- ***A preliminary safety case for Gorleben is being initiated, aimed at delivering a site suitability statement by 2012***

The Way Ahead – Gorleben Repository ?



Legend:
1 entrance building 1
2 heating plant and dry rooms
3 offices and social buildings
4 shaft 1
5 entrance building 2
6 shaft 2
7 magazine and equipment storage
8 fuel storage
9 pumping station (fresh and waste water)
10 electric power transmission
11 drain water pumping station
12 weather monitoring station
13 diffusor
14 shaft hall shaft 2
15 shipment - arrival
16 technical offices, laboraties
17 drying hall
18 railway
19 drill core storage
20 chimney
21 exhaust air building surface facilities
22 entrance building 3
23 shaft hall shaft 1
24 salt shipment - departure
25 garages / friction hoist
26 cleaning hall / storage for equipment to pull over new ropes
27 workshop and spareparts
28 gateway - brigde to shaft 1
29 mine ventilation fresh air building

existing
new
planed while exploration

OPTIMIZATION OF THE DIRECT DISPOSAL CONCEPT BY VERTICAL BOREHOLE EMPLACEMENT OF SF ELEMENTS

W. Bollingerfehr, W. Filbert

DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany

INTRODUCTION

In 1963, the predecessor of the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe - BGR) issued a recommendation to dispose of the resulting radioactive waste in Germany in rock salt formations. After a three-stage, intensive site selection procedure by the Federal Government and the Federal State of Lower-Saxony during which more than 140 sites were assessed, the Gorleben site was selected in 1977 as the national center for reprocessing, conditioning, and disposal of radioactive waste. From 1979 on, a comprehensive surface survey program was carried out to characterize the salt dome and the surrounding area which had never been impaired by mining activities. In view of the very promising surface exploration results which strongly suggested the suitability of the site to host a repository, DBE (German acronym for "German Company for the Construction and Operation of Waste Repositories") started the excavation of a large-scale exploration mine on behalf of the Federal Government in 1986.

Design and construction of the exploration mine was carried out in such a way that all important elements, e.g., the access shafts and the surface and underground infrastructure, could later be used as part of the repository without major alterations and refurbishments. If the suitability of the site is confirmed and a respective license issued, transformation of the site exploration facility into a repository mine can rapidly be carried out.

A reference concept for the disposal of high-level radioactive waste (HLW) and spent fuel (SF) was developed accordingly. It comprises the direct disposal of SF in horizontal drifts and the final disposal of waste from SF reprocessing in vertical boreholes in a salt mine (Fig. 1).

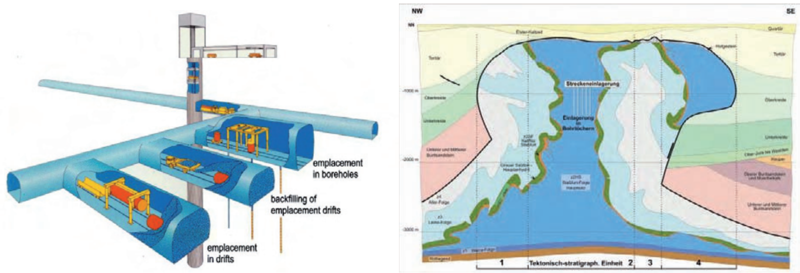


Figure 1: Reference concept (left) and simplified geological map of the Gorleben salt dome (right)

Irrespective of the technical achievements, a moratorium on the underground exploration of the Gorleben site was issued in 2000 due to political decisions taken by the Federal Government back then. Exploration has not resumed since then. However, after the Federal elections of 2009, the newly formed Federal Government has recently expressed its intention to complete the underground explora

tion of the site without further delay. It is assumed that completion of the Gorleben exploration could be achieved within five years. Two more years will then be required to evaluate the exploration results and to draw up the final suitability statement for the site. If the suitability of the Gorleben salt dome is then confirmed, the licensing procedure can be initiated.

Concurrent with site exploration from the surface and subsequent construction of the exploration mine, a large-scale R&D program was carried out to develop the technologies required for the safe operation of a future repository. According to the regulatory framework in Germany, license application for a radioactive waste repository requires the demonstration that all facilities and equipment needed for the disposal operation can be provided and safely operated. Consequently, the development of safety relevant repository equipment has been an important part of the repository-related R&D work for the past decades. The objective is to have the science and technology to license and later operate a repository available when needed.

A first equipment demonstration program in the early nineties concentrated on the direct disposal of SF. The so-called POLLUX® concept was developed as an alternative to the previous concept of SF reprocessing and disposal of vitrified HLW. In regard to SF, the POLLUX® concept anticipates the packaging of fuel rods of up to ten spent PWR fuel assemblies (about 5 tHM) into a self-shielding cask with a gross weight of about 65 metric tons. Together with the weight of the transport cart and ancillary equipment, this requires shaft hoisting equipment for a payload of 85 metric tons. One main aspect of the first equipment demonstration program, therefore, was to convincingly show that the shaft hoisting of such payloads was feasible and could be realized in compliance with nuclear safety requirements. In addition to this, the other relevant handling procedures and equipment needed for the direct disposal of SF were also included in the demonstration program.

In addition to the development of equipment for an eventual repository operation, all technical facilities that are necessary for the implementation of the POLLUX® concept, apart from the repository, have been built to prove the feasibility of this concept, i.e. interim storage facilities for casks containing SF, a pilot conditioning plant, and a special POLLUX® cask for final disposal.

BSK 3 CONCEPT

For the past few years, alternative technical approaches for the emplacement of vitrified HLW and SF have been investigated in order to harmonize and optimize future disposal operations. Among others, borehole emplacement was also considered for consolidated SF. After initial promising studies, the German industry decided to develop a new disposal canister to support the further development of a borehole concept. The new canister was named "BSK 3" according to the acronym for the German word for fuel rod canister (Brennstabkokille) and can contain the fuel rods of 3 PWR fuel elements or 9 BWR fuel assemblies /1/. The corresponding BSK 3 concept, jointly developed by GNS and DBE TECHNOLOGY GmbH (DBE TEC)[1], still relies on the separation of fuel rods from the structural parts of the fuel assemblies, but - different to the POLLUX® reference concept - fuel rods are packed into a BSK 3 canister which has the same diameter as an HLW canister.

After the new BSK 3 disposal concept had been developed in a series of paper studies, it was decided to carry out a comprehensive demonstration program to confirm the expected advantages. The main expectations were:

[1] For statutory reasons, all R&D work after 2000 was assigned to DBE TECHNOLOGY GmbH, a subsidiary of DBE mbH, the German Company for the Construction and Operation of Repositories for Waste, Ltd.

- Improved control of the heat transfer to the host rock by combining the emplacement of heat-generating packages (SF and vitrified HLW) and waste with negligible heat generation also designated for borehole disposal according to the reference concept
- Reduced areal extension of the repository by three-dimensional utilization of the host rock, at the same time reducing the exploration effort
- Reduction of potential gas problems due to significantly reduced amount of metal when using unshielded containers
- Complete isolation of the waste in the impermeable host rock by the converging salt is an important safety feature of a salt repository. As the void around the BSK 3 canisters in the borehole is small, isolation can be attained within less than a year whereas enclosure of the POLLUX® casks may take several decades.
- Reduction of the variety of container and cask systems required due to the fact that the SF canister has the same external diameter as the vitrified HLW canister. The BSK 3 concept will lead to an emplacement technology that is harmonized and standardized to a large extent and will use essentially the same equipment for hoisting and transport for all packages designated for disposal in a repository for HLW and SF.
- Earlier disposal and/or higher specific thermal loads of the waste with a potential to reduce the intermediate storage periods to less than 10 years as was estimated by GNS due to the lower HM content of the unshielded containers compared with the POLLUX® cask.

Technical approach for transport and emplacement of BSK 3

In view of these advantages, an R&D project to develop and test the systems and components for the transport, handling, and disposal of BSK 3 canisters was launched with financial support from the German Federal Government and the German nuclear industry. The main objective was to demonstrate the functionality and reliability of the equipment and to obtain the data and information required for licensing this new back-end technology. In the context of the EURATOM 6th Framework Program, the project was also embedded into ESDRED (Integrated Project Engineering Studies and Demonstration of Repository Designs), a comprehensive effort with thirteen partner organizations from nine European countries financially supported by the European Commission./2/

The system for handling and emplacing BSK 3 canisters was developed by DBE TEC in cooperation with GNS and equipment manufacturers and comprises: 1) a transfer cask which provides appropriate shielding during transport and emplacement, 2) a transport unit consisting of a mining locomotive and transport cart, and 3) an emplacement device. Fig 2 shows the components of the entire transport and emplacement system in an underground emplacement drift.

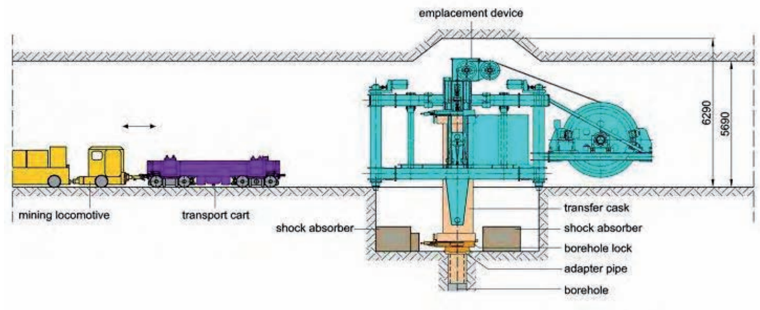


Figure 2: Outline of the BSK 3 disposal system

The BSK 3 canister will be inserted into a transfer cask in a hot cell at the surface, e.g. at the conditioning plant, shipped to the repository, hoisted to underground on a transport cart, and towed into the disposal drift. The emplacement device, positioned above the emplacement borehole, carries out the emplacement operation as described in detail below. For the demonstration tests, a BSK 3 canister mock-up with the geometry and weight of the original canister but without SF content was used. The transfer cask was designed to provide mechanical strength and gamma and neutron radiation protection to allow workers to approach the cask in case equipment repair becomes necessary. The transfer cask body is a thick-walled cylinder made of nodular graphite cast iron (GJS). Neutron moderation and shielding is provided by polyethylene. Two locks made of stainless steel are bolted to the cask body. The flat slide latches integrated into the locks run in slide bars. When in locked position, the flat slide latch is kept in place by two locking bolts set into the sidewalls. The transfer cask is not fitted with a mechanism to operate the locks. Lock opening and closing is carried out at the base of the transfer cask by the borehole lock mechanism and at the top by the emplacement device (shielding cover). The emplacement device is equipped with all components necessary for safe transfer cask handling and BSK 3 canister emplacement.

In the course of an emplacement sequence, the BSK 3 canister is transported inside a transfer cask on a transport cart to its designated position in an emplacement drift. The transfer cask is then lifted off the transport cart by the emplacement device and turned into an upright position after the transport cart has been removed. In the next step, the cask is lowered onto the borehole lock and locked in position. A shielding cover is lowered onto the upper transfer cask lock before the top of the cask can be opened and a grab can take hold of the BSK 3 canister. The lock at the transfer cask bottom and the borehole lock are opened simultaneously, and the BSK 3 canister – held by the canister grab – is lowered into the borehole. The canister grab is then removed and the transfer cask and the borehole lock closed. After turning the transfer cask back into horizontal position, the transport cart is hauled again into the emplacement device and the transfer cask is placed on the cart. Finally, the transport cart with the transfer cask is driven out of the emplacement drift and back to the surface for reloading.

The demonstration and test program for the BSK 3 system

All full-scale demonstration tests were performed in a former turbine hall of a power station in Landesbergen near Hanover in the Northern German state of Lower-Saxony. Within less than 2 years, all components had been designed in detail, manufactured, and delivered to the test site and had been evaluated and approved by external experts. The components of the emplacement system were assembled on a platform 10 m above the ground floor. A 10-m-long vertical steel metal casing simulated the emplacement borehole. For the test program, the BSK 3 canister was lowered into the "borehole" by the grab of the emplacement device and, unlike in a real repository, removed again thereafter for the next test run. Fig. 3 shows a photo of the test site with all the components required for transporting and emplacing BSK 3 canisters.

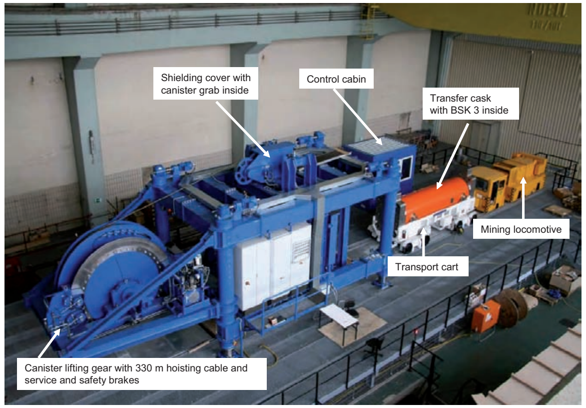


Figure 3: BSK 3 full scale test stand with components (photo of the Test Site in Landesbergen, Germany)

The demonstration program started in July 2008 and continued until July 2009. It comprised demonstration tests, simulation tests, and tests to identify potential operating failures and to develop preventive and corrective measures. Furthermore, backfilling tests were carried out. As the aim was to develop an emplacement technology for all types of radioactive waste, additional transport and emplacement tests with HLW canister dummies were carried out as well.

Results of demonstration tests

The demonstration tests comprised all the process steps, starting with the acceptance of the BSK 3 canister and concluding with the emplacement of the canister into the vertical borehole. In total, more than 1,000 complete emplacement operations had been carried out by the end of the test program. The entire system and each component proved to be safe, reliable, and robust. The masses involved in the BSK 3 concept are slightly lower than those in the POLLUX® concept. It can thus be assumed that all shaft transport and hoisting devices developed for the POLLUX® concept are applicable for the BSK 3 concept as well.

Simulation tests and test of operational disturbances

Several technical and safety-related features were tested additionally. To simulate more realistic conditions within the borehole, the BSK 3 dummy was lowered on a salt layer covering the head of a previously "emplaced" canister. The challenge was to safely open the grab after the canister had been emplaced, even if the canister was not in a strictly upright position. It was demonstrated that the grab of the emplacement device could safely be unhooked from the canister in all cases although the canister was not in a strictly vertical position but touching the wall of the borehole (Fig. 4).

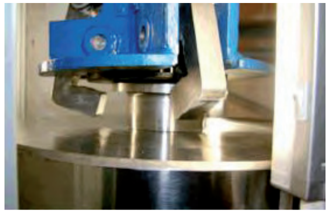


Figure 4: Opening of the grab in the borehole

After one borehole has been filled, the emplacement device will be transported to the next borehole by means of the transport cart. This process was also simulated at the full-scale test facility

In case of derailing, the transport cart loaded with the transfer cask needs to be set back onto the rails by means of conventional equipment. Corresponding demonstration tests were carried out successfully.

Additional emplacement tests with HLW canister dummies

The full-scale demonstration program was extended by additional tests with HLW dummies. The idea was to demonstrate the technical feasibility of handling HLW canisters with the same equipment as was used for BSK 3 canisters. For this purpose, a so-called triple pack was designed and fabricated; a steel envelop containing three HLW dummies with almost the same outer diameter and the same height as the BSK 3. A further series of emplacement processes (110) was successfully performed with this triple pack, confirming the reliability of the emplacement system for this type of canisters as well.

Demonstration tests regarding the technology for backfilling emplacement boreholes

From the point of view of radiation protection and with regard to thermal aspects, the gap between BSK 3 and the borehole wall needs to be backfilled, even in the area close to the borehole cellar. In a repository in salt, crushed salt will be used as backfill material. The objective of this additional demonstration test was to develop the corresponding technology and to investigate whether the space around the BSK 3 could be completely filled or not; just to confirm existing assumptions. A prototype backfill-canister was fabricated and the crushed salt inserted into the borehole. The max. grain size of the crushed salt was 8 mm. The test showed that the space between BSK 3 canister and borehole wall can be completely filled. This is of particular importance for the degree of accuracy of safety assessments.

CONCLUSIONS AND OUTLOOK

Several years after the demonstration test of all the elements of the German reference concept for spent fuel disposal (POLLUX concept) had been concluded, a new, alternative system was developed and tested comprehensively. The reliability of the handling technologies for the BSK 3 concept has been confirmed in aboveground “cold” full-scale demonstration tests as well. From a technical point of view, both concepts are now ready for testing underground to simulate typical “mining conditions” with higher temperatures and a dustier environment.

While the operational handling technology for the disposal with the POLLUX® and the BSK 3 concept have been tested at full scale aboveground, the testing of the related conditioning technologies is still pending.

ACKNOWLEDGMENTS

The work referred to in this paper was made possible through the generous financial support of the German Federal Government, represented by the German project management agency (PTKA), of the German nuclear industry, represented by GNS, and of the European Commission.

REFERENCES

/1/ H. SPILKER, “Status of the Development of Final Disposal Casks and Prospects in Germany,” DISTEC '98, International Conference on Radioactive Waste Disposal, September 9-11, 1998, Hamburg (1998)

/2/ W. K. SEIDLER, ESDRED – Final Summary Report and Global Evaluation of the Project, Paris, January 2007

Optimization of the Direct Disposal Concept by Vertical Borehole Emplacement of SF Elements

Wilhelm Bollingerfehr, Wolfgang Filbert,
DBE TECHNOLOGY GmbH, Peine, Germany

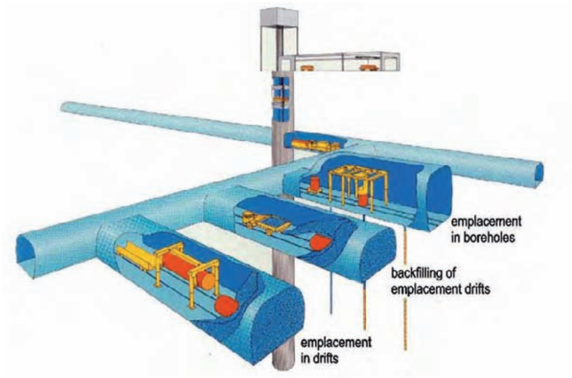
US/German Workshop on Salt Repository Research

Jackson, Mississippi
March, 25 – 27

Outline of Presentation

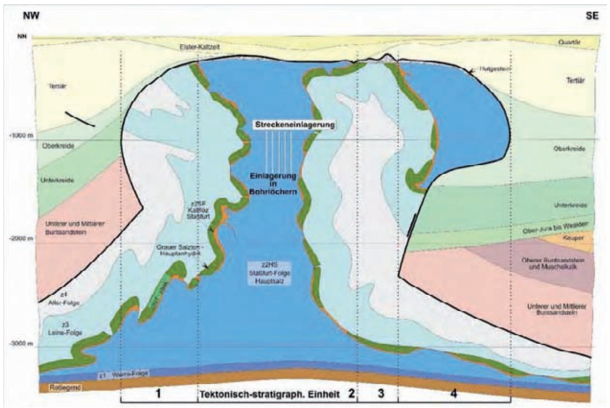
1. Introduction
   - Reference Disposal Concept
   - Previous Demonstration Programme
2. Optimization of Spent Fuel Direct Disposal
   - Motivation and Technical Approach
   - New Emplacement System
   - Demonstration and Test Programme (video)
   - Additional DemonstrationTests
   - Main Achievements
3. Summary and Outlook

German Reference Disposal Concept



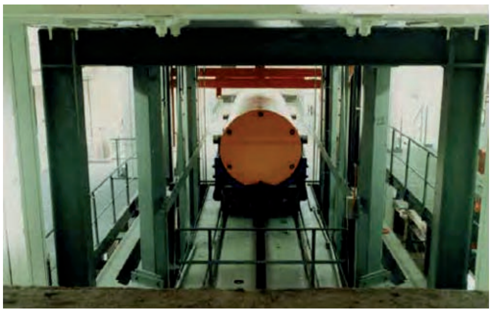
German Reference Concept for the Direct Disposal of HLW and Spent Fuel in Rock Salt

- Deep geological disposal (depth: 870 m)
- Emplacement of HLW in boreholes and spent fuel casks in drifts
- Backfill material: crushed salt

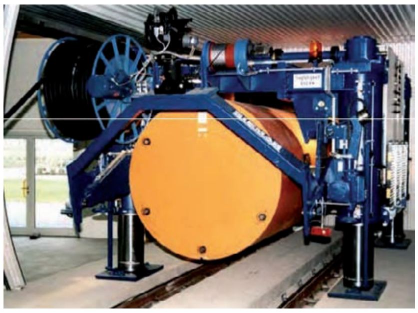


Transmission of the German repository reference concept into a simplified geological mapping of the Gorleben salt dome

POLLUX Transport and Emplacement Demonstration Programme



Shaft transport with payloads up to 85 t



Emplacement technique

In-situ heater experiment (10 years)

Handling experiment with neutron sources

Advantages of Borehole Emplacement Concept

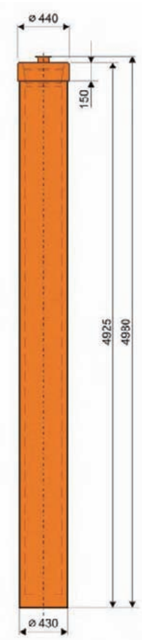
- Improvement of heat transfer from waste canister to the host rock (rock salt) due to close contact
- Compared with the POLLUX emplacement concept a faster process (creeping of host rock) to achieve the complete enclosure of the waste canister by the host rock
- Reduction of required footprint of the repository by using the host rock in three dimensions
- Economical benefit by saving container and operating costs
- Reduction of potential gas generation (corrosion) due to reduction of metallic material mass

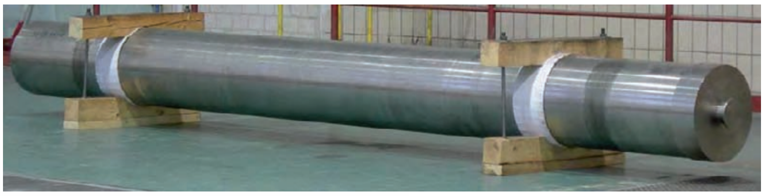
Optimization of Spent Fuel Direct Disposal

Challenge: How to harmonise and optimise the transport and emplacement technology for both categories of waste (vitrified waste and spent fuel)?

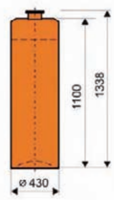
Approach: Development of one single technology applicable for the handling and emplacement of both categories of waste

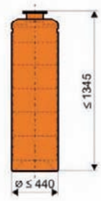
Waste Canister Types





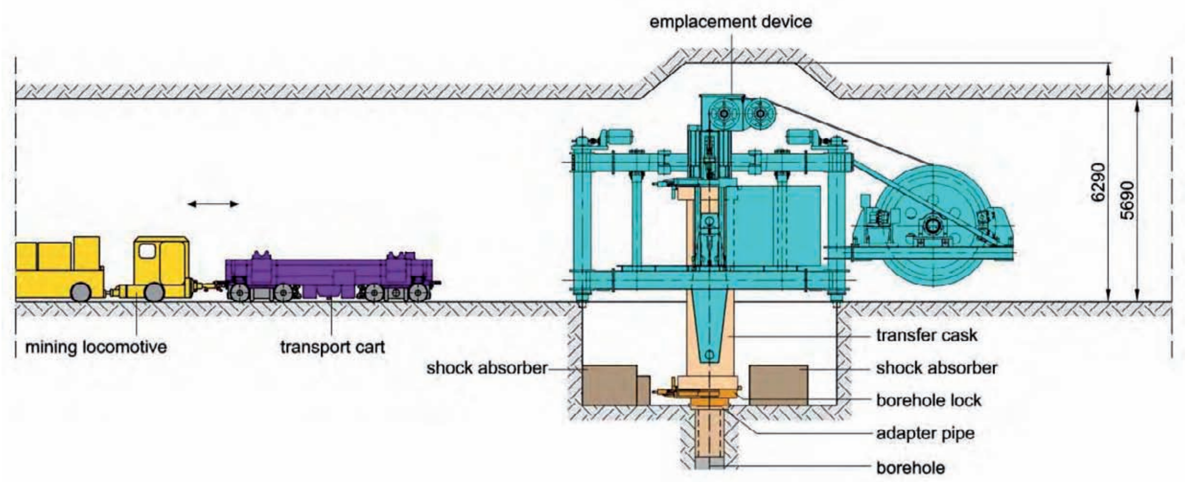
BSK 3-Dummy





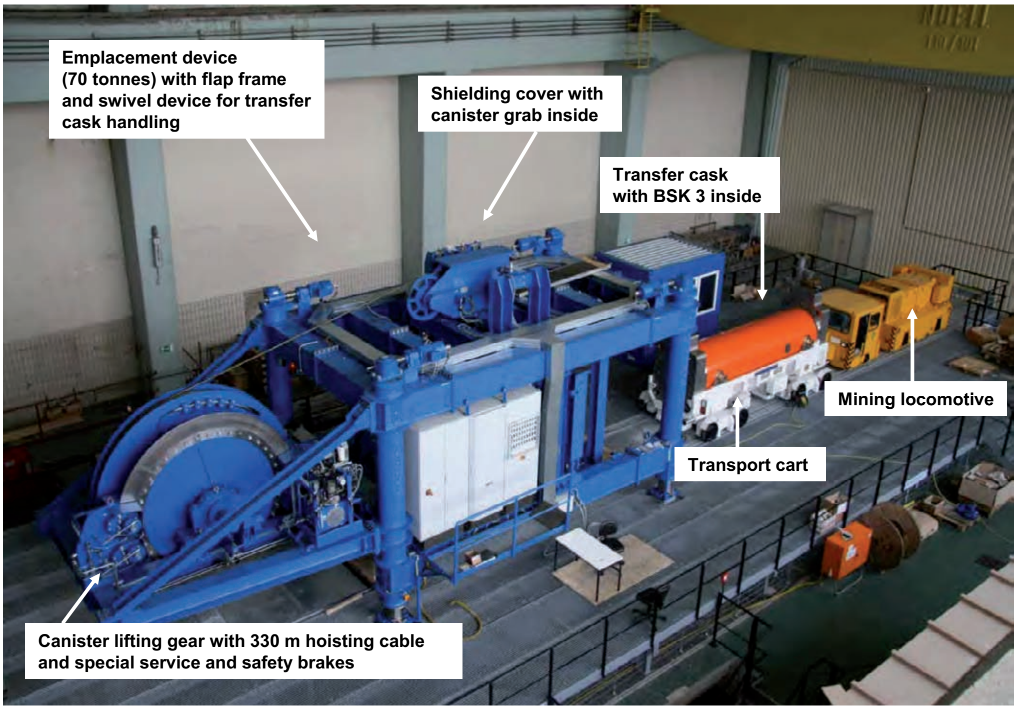
	BSK 3	**HAW**	**CDS C**
Mass:	5.20 t	0.50 t	0.85 t

New Borehole Emplacement System



Main components of equipment to transport and emplace BSK 3 canister in a geological repository in rock salt

Industrial Demonstrator at Landesbergen



Objectives of Demonstration Programme

- Demonstration at an industrial scale of the technical feasibility of the transportation and emplacement of BSK 3 canisters into deep vertical boreholes
- Investigation of the safety and reliability of the BSK 3 emplacement system
- Demonstration of safe management of operational disturbances
- Performance of simulation and backfilling tests
- Derive conclusions and recommendations for the application of the BSK 3 emplacement system in a repository

Video

Grand Opening on September 9, 2008

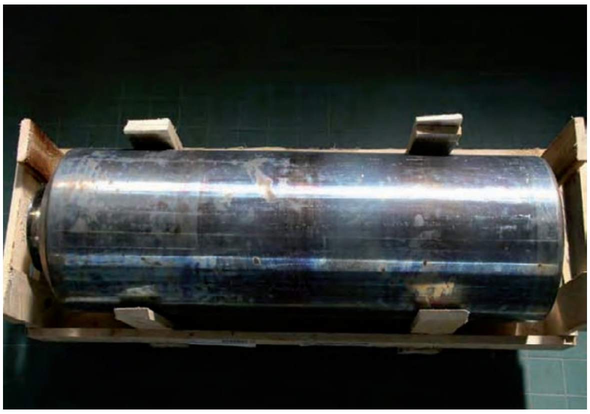
Demonstration of Emplacement Device Transportation

movement of emplacement device by means of transport cart and locomotive

Demonstration Tests with HLW Triple Pack

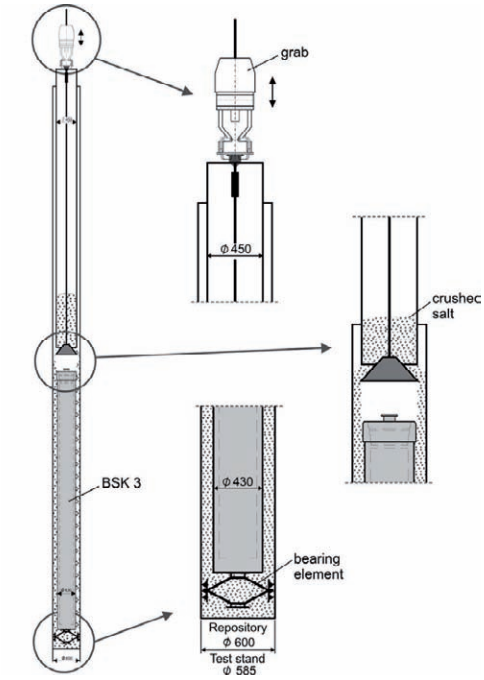
HLW Triple Pack
(3 HLW dummies in steel envelope)

- mass and geometric dimensions like BSK 3



single HLW dummy

Backfilling Tests



sketch of backfilling system

remaining small triangular space
(BSK 3 leaning against borehole wall)

backfilling process
(view on BSK 3 through a window)

Main Achievements

- Development and fabrication of the BSK 3 transport and emplacement system
- External experts confirmed compliance of all technical documents with German mining regulations and Atomic Energy Act
- Confirmation of safety and reliability of the individual components by means of endurance test (>1000 emplacement sequences)
- Demonstration of safe management of operational disturbances
- Demonstration of HLW canister (triple pack) emplacement
- Demonstration of backfilling technique for vertical boreholes

Summary and Outlook

- One single transport and emplacement system for spent fuel and vitrified waste canisters developed
- Demonstration tests at an industrial scale showed reliability of each component and of entire system
- All components operated as designed
- Entire system for transport, emplacement and backfilling of SF and HLW available for industrial application

<u>Future step:</u>

- Confirmation of system reliability and safety in repository environment (salt mine)

Acknowledgments

DBE TECHNOLOGY GmbH

Thank you
for your attention.

GROUNDWATER AND TRANSPORT MODELLING USING THE CODES D³F AND R³T

Jörg Mönig, Anke Schneider, Klaus-Peter Kröhn
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany

Abstract

The codes d³f and r³t

The d3f (distributed density-driven flow) software package was developed at six universities in the years 1995 to 1999 within the framework of a project, funded by the German Ministry of Education and Research (BMBF), with the aim to enable the calculation of density-driven groundwater flow in large, hydrogeologically complex model areas for long periods of time [2]. Groundwater flow with relevant density impacts occurs not only in the overburden of salt formations, but also in coastal areas.

d³f is suited for the two- and three-dimensional modeling of flow through porous or equivalently porous media assuming a confined aquifer system of fluid-saturated porous medium in which both the porous medium and the fluid are incompressible. Advection, diffusion and dispersion are regarded as transport processes. Fluid density and viscosity are functions of the salt concentration and temperature. Salt concentrations can be considered up to saturation. The hydrogeology of the model area may show strong heterogeneities and anisotropies. The model area may contain sources and sinks.

Flow and transport equations are solved in a coupled manner on the basis of the UG software (Unstructured Grids, Heidelberg University) which works with triangular and tetrahedronal as well as quadrilateral and hexahedral meshes. Discretization is performed by means of a finite volume method while an upwind algorithm may be selected. The equation system is solved with a multigrid algorithm in combination with a BiCGStab method. Grid refinement and time-step sizes are controlled by a-posteriori error estimators.

The r³t (radionuclides, reaction, retardation, and transport) code was developed from 1998 to 2003 within a project funded by the German Ministry of Economics and Labor (BMWA) [3]. The overall objective of the r³t project was the development of a computer code to simulate pollutant transport which meets the following demands: simulation of two- and three-dimensional transport through porous or equivalently porous media, consideration of advection, diffusion, dispersion and interaction processes which are relevant to long-term safety analysis, applicability for radionuclide migration as well as for chemotoxic pollutants. Transport modeling with r³t is based on the velocity field resulting from d³f simulations.

For radionuclides the decay is considered within decay chains. The individual interaction processes which affect the pollutants transport are modeled as follows: equilibrium and kinetically controlled sorption, both linear (Henry) and nonlinear (Langmuir, Freundlich), respectively; precipitation and diffusion into immobile pore water; complexation; colloidal transport and matrix diffusion via effective parameters. The code was completed by anisotropical, element-specific diffusion and by element-specific porosity. r³t simulations may be coupled with the geochemical code PHREEQC.

The codes can be run on LINUX PCs, workstations, clusters as well as on massively parallel computers and have graphical pre- and post-processors. Within the framework of a project funded by the German Ministry of Economics (BMWi), the development of some new features of d³f and r³t are in progress, such as modeling phreatic surfaces, fractures and heat transport.

Applications

Several test cases and applications were performed within other BMWi-funded projects. Only some examples are to be mentioned here. One of the first test cases was the simulation of an experiment performed of the Rijksinstituut voor Volksgezondheid en Milieuhygiene (RIVM), the Netherlands [10]. Here, NaCl-brines of different concentrations were injected into a box filled with glass balls and fresh water. The salt concentrations were measured by 16 electrodes. The results of the simulation of the experiment L2D01, where a brine with a concentration of 3.84 g/kg was injected into two ports in the bottom of the box, are shown here. The propagation of the salt could be reproduced very well by d³f-simulations [1].

Another example modeled was he field site Cape Cod, Massachusetts. About 59 years of land disposal of sewage effluent resulted in contamination of the aquifer with zinc (Zn). Extensive measurement campaigns and field-tests were undertaken during the last years of operation of the sewage plant and for the first years after closure [6], [7], [8]. Modeling zinc transport at Cape Cod appears to be a most challenging task. A key process to explain the characteristic form of the zinc plume is the pH-dependent sorption of zinc. The pH-value is defined as the negative common logarithm of the proton concentration. Here, the protons are assumed to be transported like a tracer. It is generally agreed that the sorption of zinc is proportional to the pH-value of the groundwater. A correlation between the pH-value and a referring K_d-value can be derived from an adsorption isotherm. The development of the zinc plume and the pH-distributions until closure of the sewage plant after 59 years of operation was simulated [4].

The comparison of the 2d models clearly shows that the pH-value dependent retardation of zinc is captured in the r³t-model. This applies for the time during plant operation as well as for the subsequent period. The model simulated even the drastic increase of the zinc concentration after closure of the sewage plant causing the drop of the pH-value. While the 3d model has only an arguable value for interpreting the situation at Cape Cod, it clearly shows the ability of r³t to capture the pH-dependent transport behavior of zinc even in 3d.

In Germany, flow and transport in the overburden of the Gorleben salt dome are investigated for more than 20 years. d³f was used to simulate the density driven groundwater flow based on a 2d hydrogeologically complex model provided by the German Federal Institute for Geosciences and Natural Resources (BGR) as a vertical cross section [9]. The model has a length of 16.370 km and a depth of 395 m. Here, three hydrological units are distinguished, aquifers consisting mainly on several types of sands and aquicludes and aquitards with large clay fractions. The permeabilities vary from 10^{-12} to 10^{-16} m². The main flow is directed from south to north.

Using the resulting flow field, the transport of 28 radionuclides relevant for a German repository was simulated using r³t. It was assumed, that these nuclides enter into the overburden at a point located in the center of the salt dome. The objective was to investigate the preferred pathways and transport times of different radionuclides with respect to their sorption properties. The results for Cs-135, I-129 and Np-237 are presented. While the K_d-values of iodine are extremely small, cesium and neptunium are strongly sorbed on clay, whereas the sorption of cesium on sandy materials is much stronger. Consequently, the simulation results show large differences. While cesium is hardly spreaded, the iodine is transported through the lower aquitard in the northern part, driven by gravitation. Neptunium, in contrast, passes through the aquifer above owing to its lower sorption on sand. Accordingly, the transport times of the nuclides considered vary over more than two orders of magnitude [5].

As a 3d example the overburden of the salt dome of Höfer in northern Germany was modeled in 2003 [10]. Depending on the amount of data, two aquifers, one aquiclude and one aquitard, could be distinguished. The general flow direction is from north-east to south-west.

The simulations were performed with d³f on a hexahedron grid with about 1 million nodes. As expected, the salinity is spreading to the south-west. One can see that the regulatory limits for salinity of potable water are never reached, since the higher velocities in the second aquifer leads to a high dilution,. The resulting velocity field shows a large convection cell in the upstream-direction of the salt dome.

With the objective to test the implementation of the heat transport equations, our project partners at the university of Frankfurt performed simulations with 134 millions of grid elements on more than 2000 processors of a parallel computer – with surprising results.

References

[1] Birthler, H.; Fein, E.; Schneider, A.: Validierung von Einzeleffekten in Grundwassermodellen. Abschlussbericht. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-150, Braunschweig, Germany.

[2] Fein, E.; Schneider, A. (eds.) (1999): d3f – Ein Programmpaket zur Modellierung von Dichtestroemungen. Abschlussbericht. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-139, Braunschweig, Germany.

[3] Fein, E. (ed.) (2004): Software Package r3t. Model for Transport and Retention in Porous Media. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-192, Braunschweig, Germany.

[4] Fein, E., Kröhn, K.-P., Noseck, U., Schneider, A.: Modelling of Field-Scale Pollutant Transport (2008). Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-238, Braunschweig, Germany.

[5] Keesmann, S., Noseck, U., Buhmann, D., Fein, E., Schneider, A.: Modellrechnungen zur Langzeitsicherheit von Endlagern in Salz- und Granitformationen (2005). Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-206, Braunschweig, Germany.

[6] Kent, D.B., Abrams, R.H., Davis, J.A., Coston, J.A., LeBlanc, D.R.: Modeling the Influence of Adsorption on the Fate and Transport of Metals in Shallow Ground Water: Zinc Contamination in the Sewage Plume on Cape Cod, Massachusetts (1999). In: Morganwalp, D.W. und Buxton, H.T. (edts.): U.S. Geological Survey, Water-Resources Investigations Report 99-4018C.

[7] Kent, D.B., Abrams, R.H., Davis, J.A., Coston, J.A., LeBlanc, D.R.: Modeling the transport of zinc under variable chemical conditions in a contaminated aquifer (2000). Draft for Water Resources Research 13.

[8] Kent, D.B., Abrams, R.H., Davis, J.A., Coston, J.A., LeBlanc, D.R.: Modeling the influence of variable pH on the transport of zinc in a contaminated aquifer using semi empirical surface complexation models (2000). Water Resources Research, Vol. 36, No. 12.

[9] Schelkes, K.: Modelluntersuchungen zur Bewegung des Grundwassers bei vom Salzgehalt anhängiger Wasserdichte - Fallstudien und Modellvalidierung im Hinblick auf die Langzeitsicherheit von Endlagern für radioaktive Abfälle, Abschlussbericht zum Forschungsvorhaben 02 E 8301 (1995). Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany.

[10] Schneider, A., Birthler, H., Fein, E.: Modellrechnungen zur großräumigen dichteabhängigen Grundwasserbewegung (2004). Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-191, Braunschweig, Germany.

[11] The International INTRAVAL Project, Phase 1 Case 13: Experimental Study of Brine Transport in Porous Media (1992). Swedish Nuclear Power Inspectorate (SKI), Organization for Economic Co-Operation and Development, Paris, France.

Groundwater and transport modelling using the codes d^3f and r^3t

Jörg Mönig, Anke Schneider, Klaus-Peter Kröhn
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Theodor-Heuss-Str. 4
D-38011 Braunschweig, Germany

US-German Workshop on Salt Repository Research, Design and Operation
May 25-28, Jackson, Mississippi, USA

Overview

- state of code development
  - flow code d^3f
  - transport code r^3t
- examples
- ongoing developments

General Information

flow code d³f
distributed density-driven flow

- development since 1995
- developed in a BMBF-funded project
  at the universities of Stuttgart/Heidelberg, Erlangen, Freiburg, Bonn, Hannover and ETH Zuerich

transport code r³t
radionuclides, reaction, retardation, and transport

- development since 1998
- developed in a BMWA-funded project
  at the universities of Heidelberg, Freiburg, Bonn and ETH Zuerich

Motivation

- 2d/3d, large, hydrogeologically complex areas, long time periods
- (equivalent) porous media
  - heterogeneous, anisotropic layers
  - permeabilities may vary over some orders of magnitude
- salt concentrations up to saturation

New Features

(development stage)

- fractured media
- heat transport
- phreatic flow

Properties of d³f

- advection, diffusion, dispersion
- salt and heat transport
- fluid density and viscosity depending on concentration and temperature
- completely coupled equations (no Boussinesq-approximation)
- permeability: constant, function or stochastic
- user-defined functions (initial and boundary conditions, parameters)

Properties of r³t

- sorption
  - equilibrium
  - kinetically controlled sorption (linear and non-linear)
- smart K_d-concept: complexation
- colloidal transport
- precipitation
- immobile porewater
- element dependent porosities
- element dependent diffusion
- anisotropical diffusion
- contaminant dependent decay
- coupled with PHREEQC

Numerics

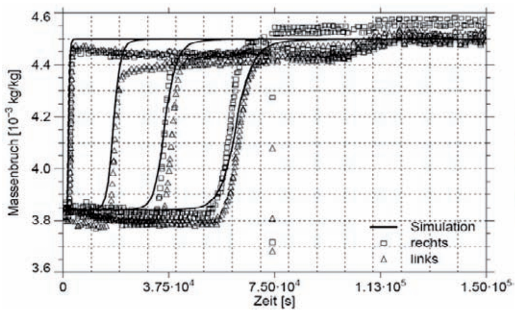
- finite volume discretization
- grids
  - unstructured
  - tetrahedral and hexahedral elements, prisms for thin layers
  - adaptive in space and time (a-posteriori error estimators)
- upwind strategies
- linear multigrid solver, BiCGStab, toolbox: ug (Uni Frankfurt)
- operator splitting (radioactive decay)
- interactive, graphical pre- and postprocessors toolbox: Grape
- completely parallelized: LINUX-PC, UNIX-workstations, clusters, massively parallel computers

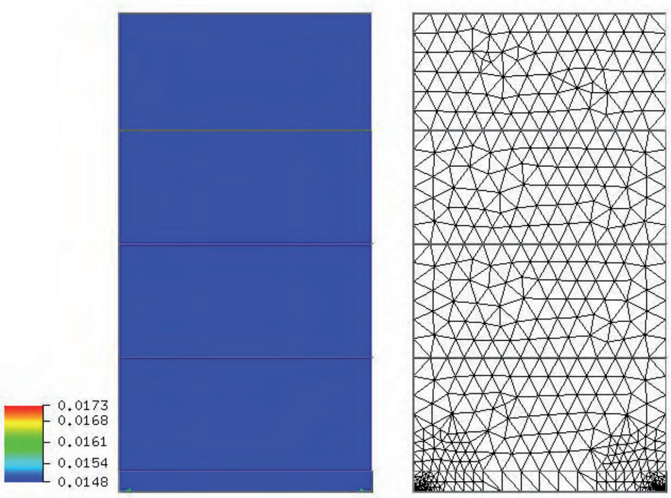
adaptive grid

concentration grid

RIVM experiment

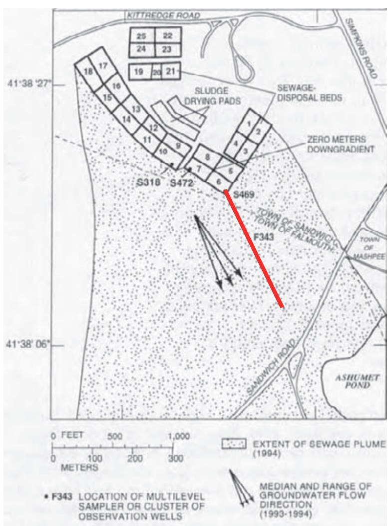
- 2-d vertical test equipment
- artificial porous medium
- bottom: injection of brine
- top: outflow





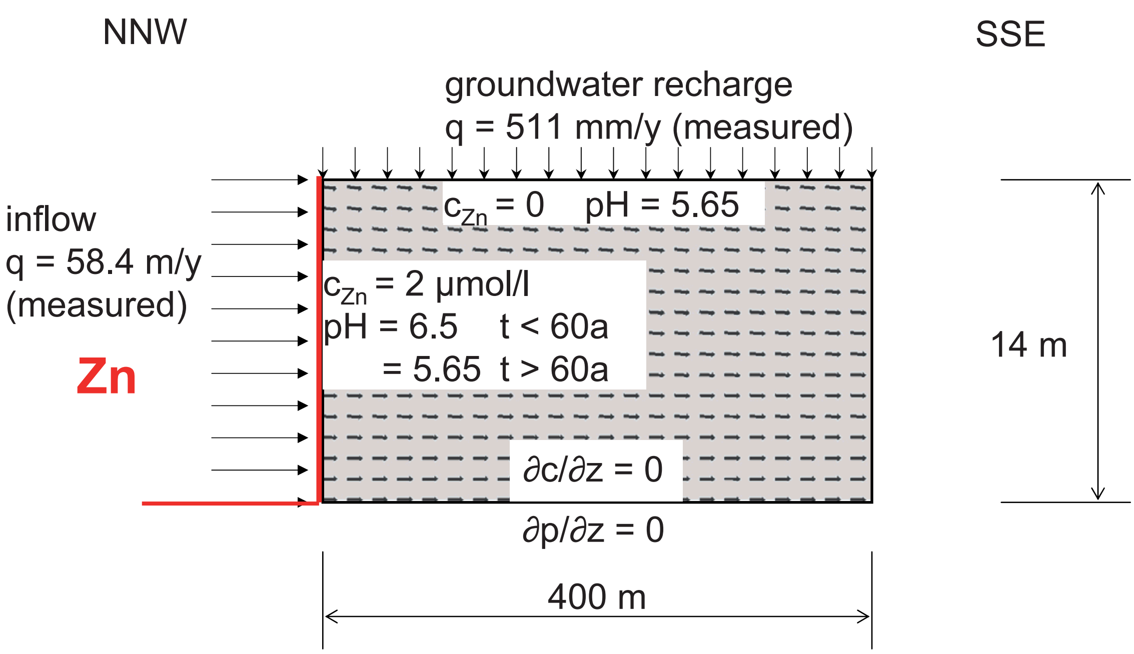
Sewage Treatment Facility at Cape Cod, Massachusetts, USA

- sewage facility open from 1936 to 1995
- contamination with sewage effluent for 60 years
- after shut down no further pollution
- potential flow + groundwater recharge
- transport of Zn with pH-dependent sorption

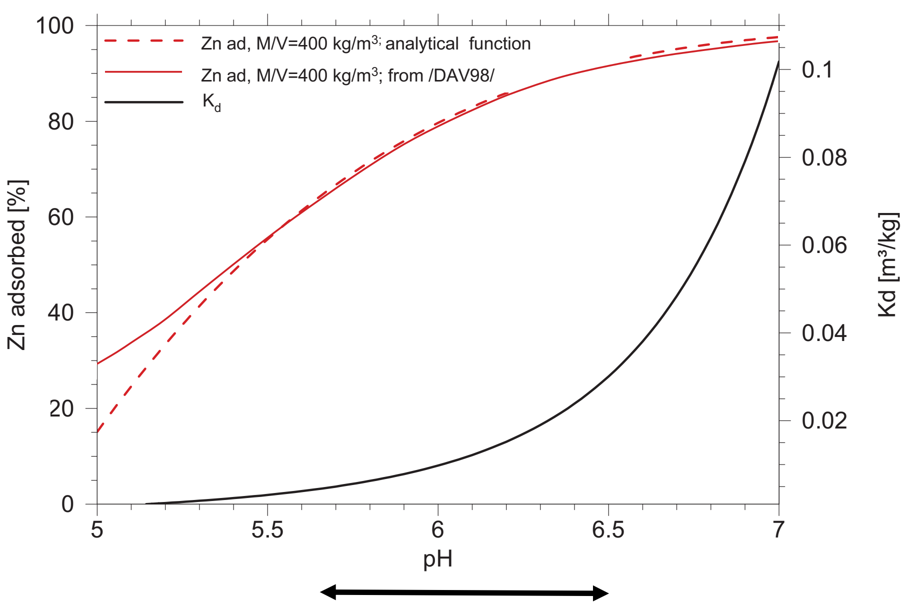


(Kent, 1999)

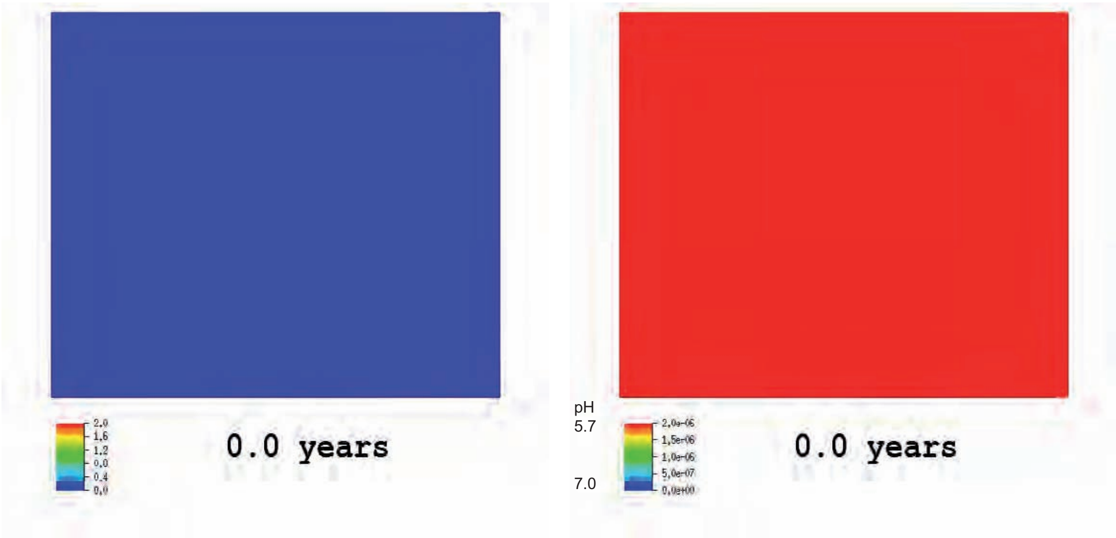
Flow- and Transport Model



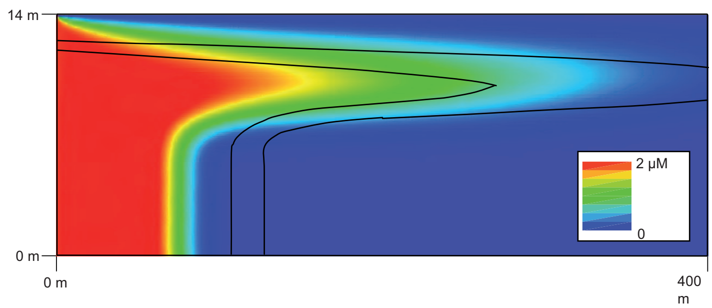
Adsorption Isotherme



Zn-Concentration and pH-Values



Comparison of r³t Results with USGS Simulations



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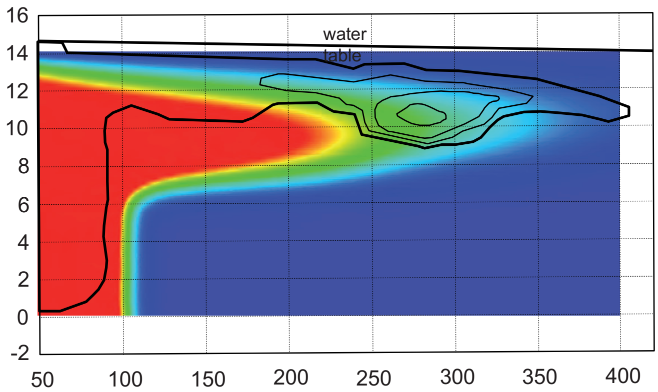
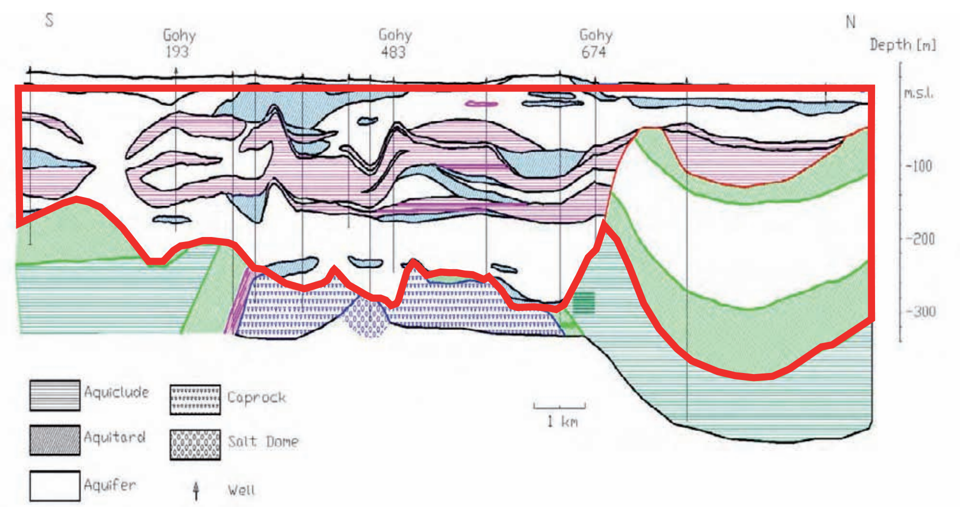
Comparison between r³t-Simulations and Measurements



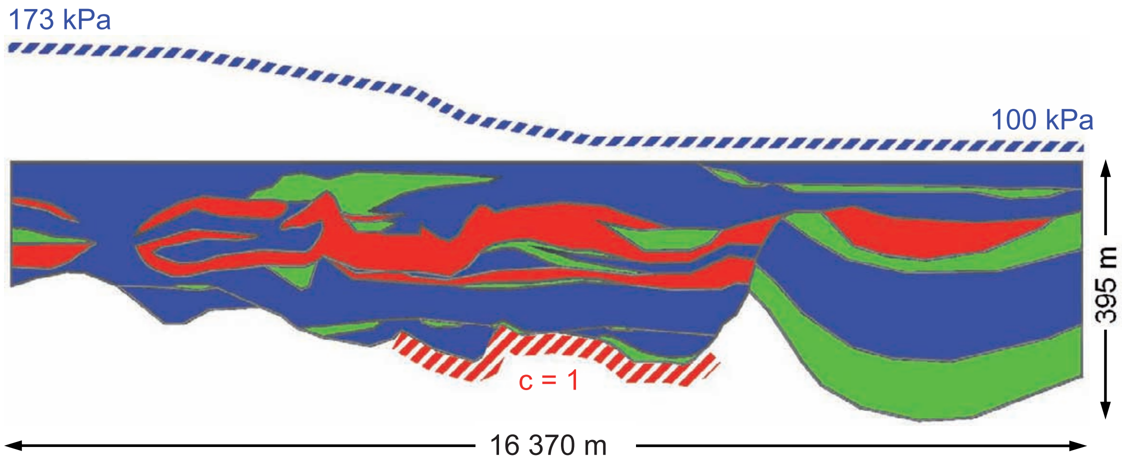
Zn-Concentration 61 years after implementation

the Gorleben salt dome



hydrogeological cross-section of the model domain, vertically exaggerated
source: Schelkes, BGR, 1995

hydrogeological model



10 times exaggerated

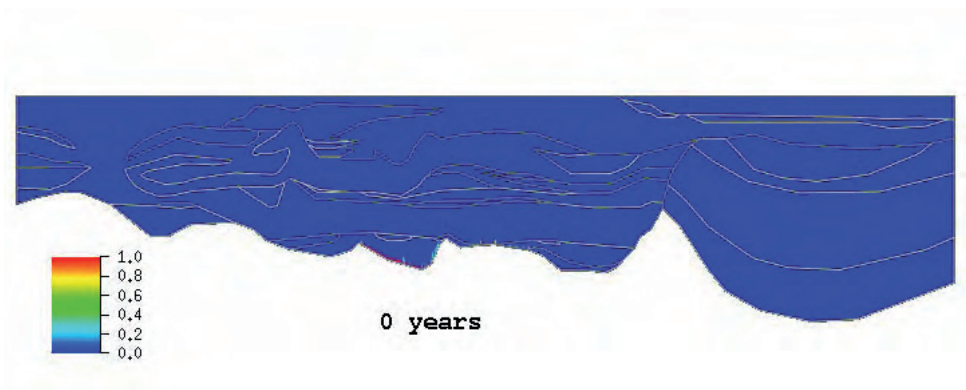
top: atmospheric pressure, fresh water inflow hatched in red: contact with salt dome

other boundaries: impermeable

- Aquifer
- Aquitard
- Aquiclude

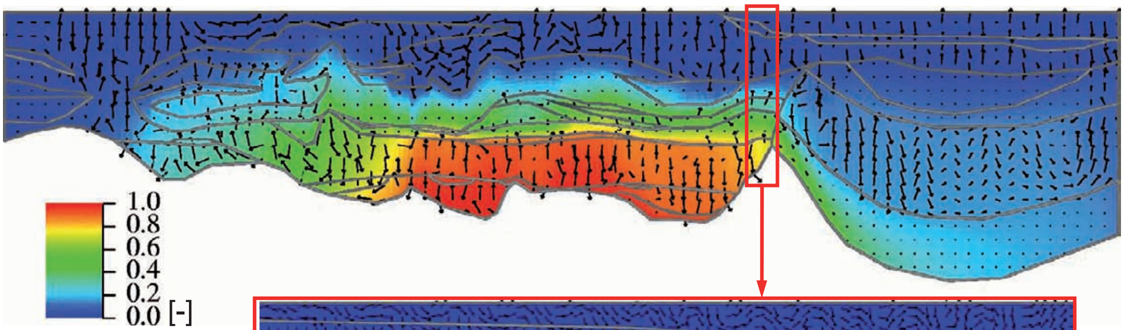
293

flow and salt transport (d³f)



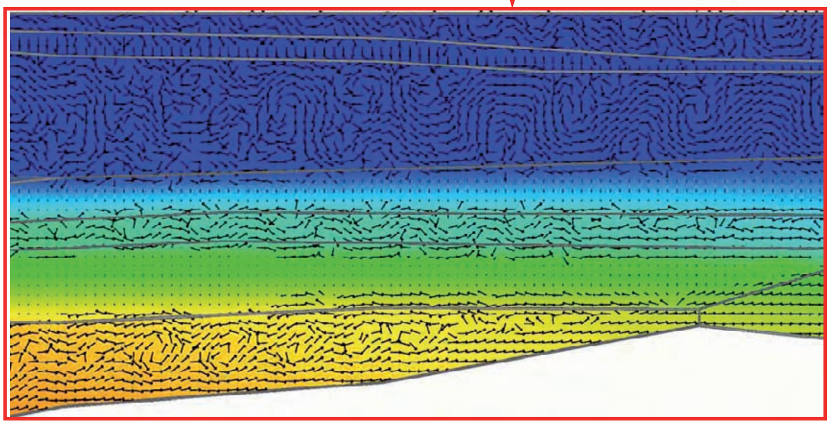
294

salt concentration and flow field at the steady state (d³f)

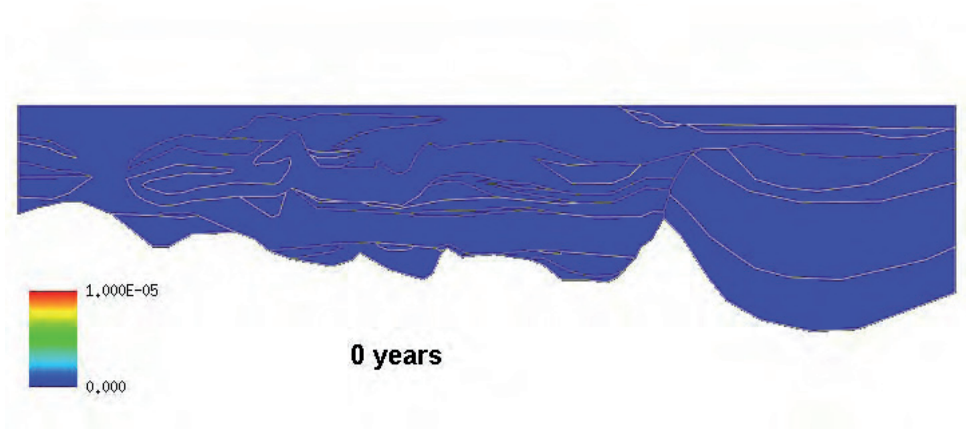


relative concentration:
$c_r = 1 \triangleq$

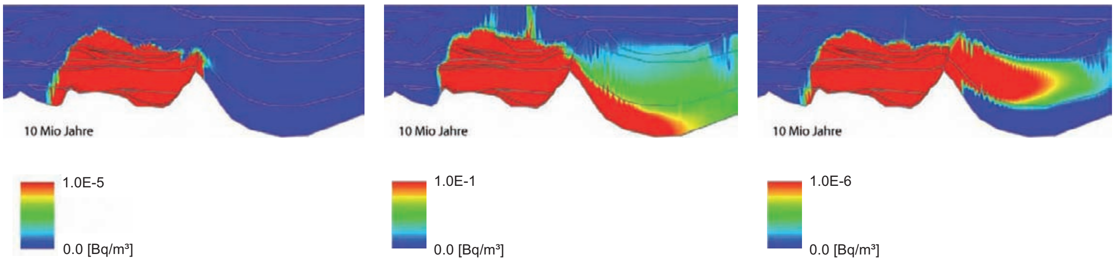
$c_{abs} = 0.26$ kg/kg



transport of Cs-135 (r³t)

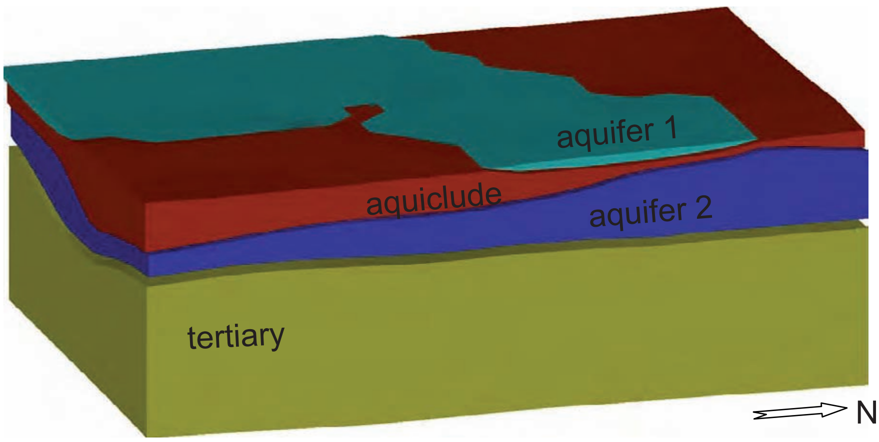


distribution for different radionuclides after 10 mio years



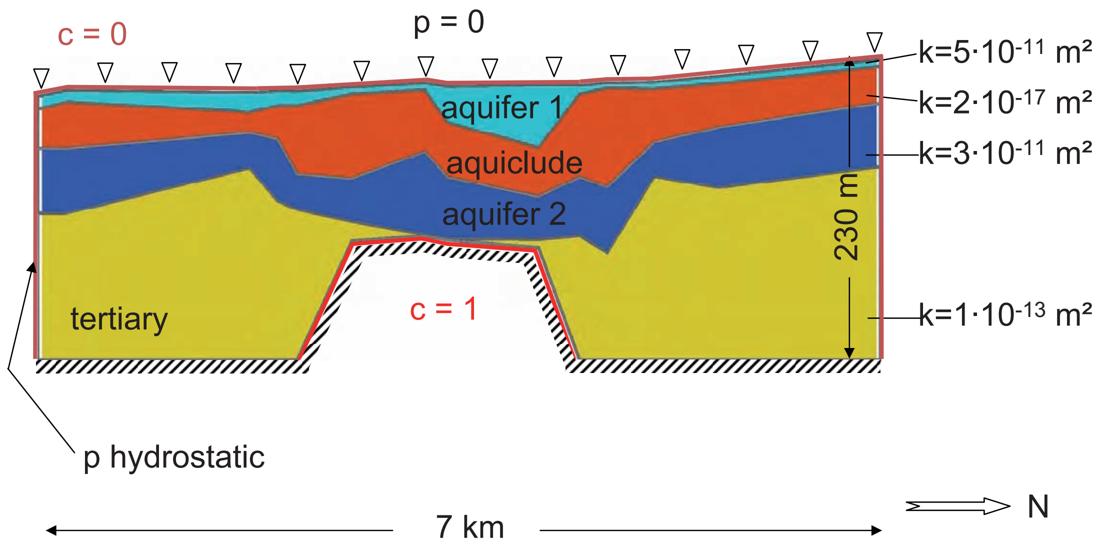
	Cs-135	I-129	Np-237
half-life [a]			
	$2.0 \cdot 10^{6}$	$1.57 \cdot 10^{7}$	$2.144 \cdot 10^{6}$
K_d-value [m³/kg]			
sand	0.07	0.002	0.01
silt, clay	0.4	0.002	0.3

Höfer Salt Dome, 3D Model

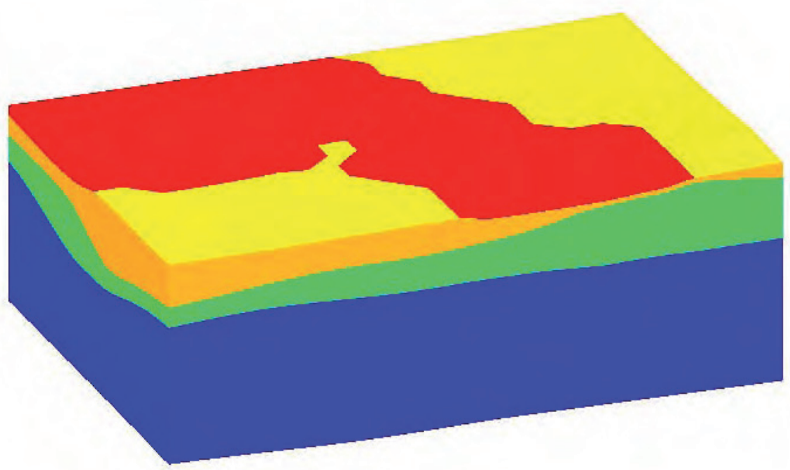


Data: Kali & Salz, Kassel,
Niedersächsisches Landesamt für Bodenforschung (NLfB), Hannover

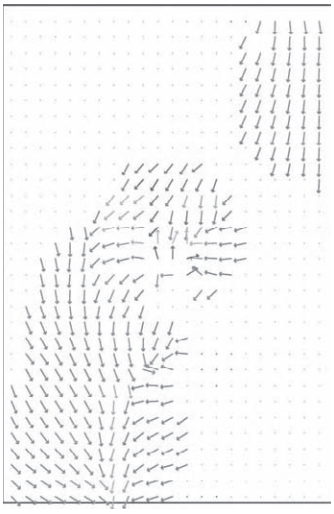
Höfer salt dome: vertical cross section



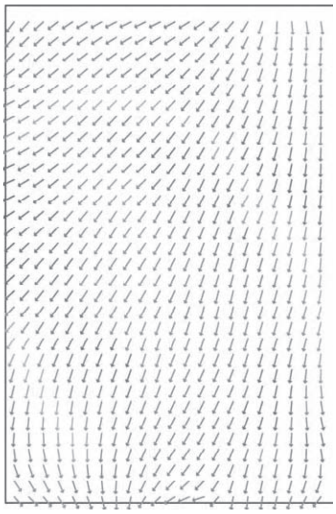
Höfer salt dome



Höfer salt dome, velocity field

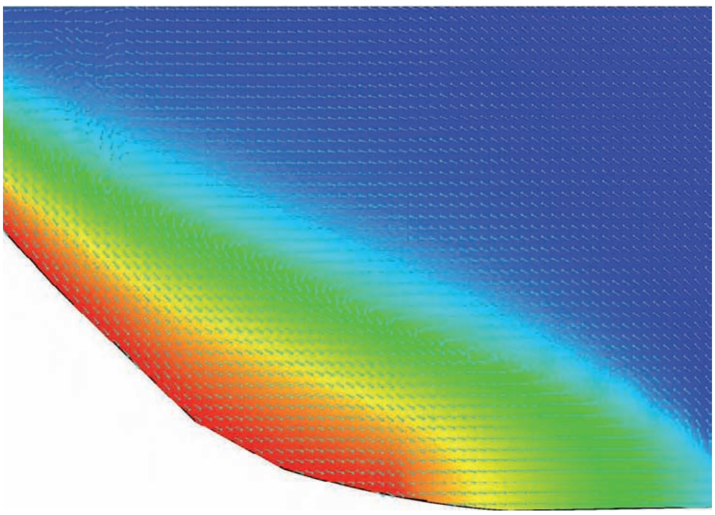


first aquifer



second aquifer

Höfer Salt Dome

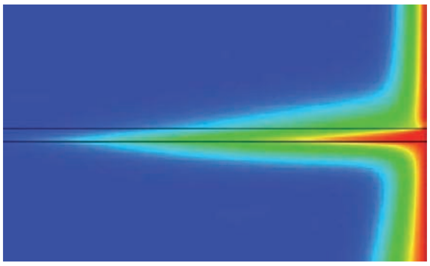


convection cell

fractures - dimensional adaptivity

representation of fractures

- equi-dimensional representation
  - correct
  - requires high net resolution
- lower dimensional representation
  - neglecting effects
  - less computational effort



provided by Sabine Stichel,
Goethe University of Frankfurt

approach

- equi-dimensional representation in fine grids
- lower dimensional representation in coarse grids

criteria to select approach automatically (development stage)

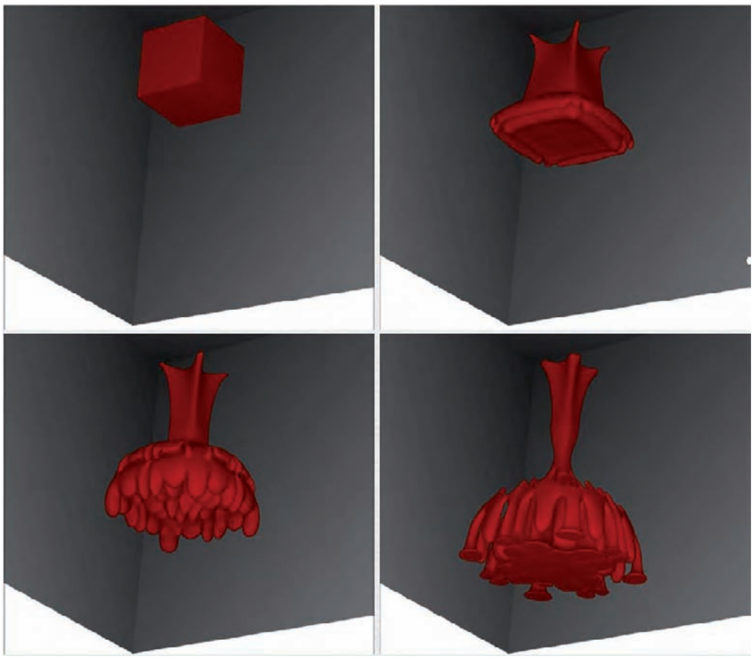
computational power

academic example:

initially cubic domain of higher density due to salinity and temperature

Model specifications

- ~ 134 million elements
- 2048 processors
- ~ 18 h computing time
- ~ 2.6 TB of data



provided by Michael Lampe, Goethe University of Frankfurt

ongoing developments

- phreatic surface
- fractured media – fracture networks
- heat transport
- advancing of solvers and postprocessor
- GIS-interface

Thank you for your attention!

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

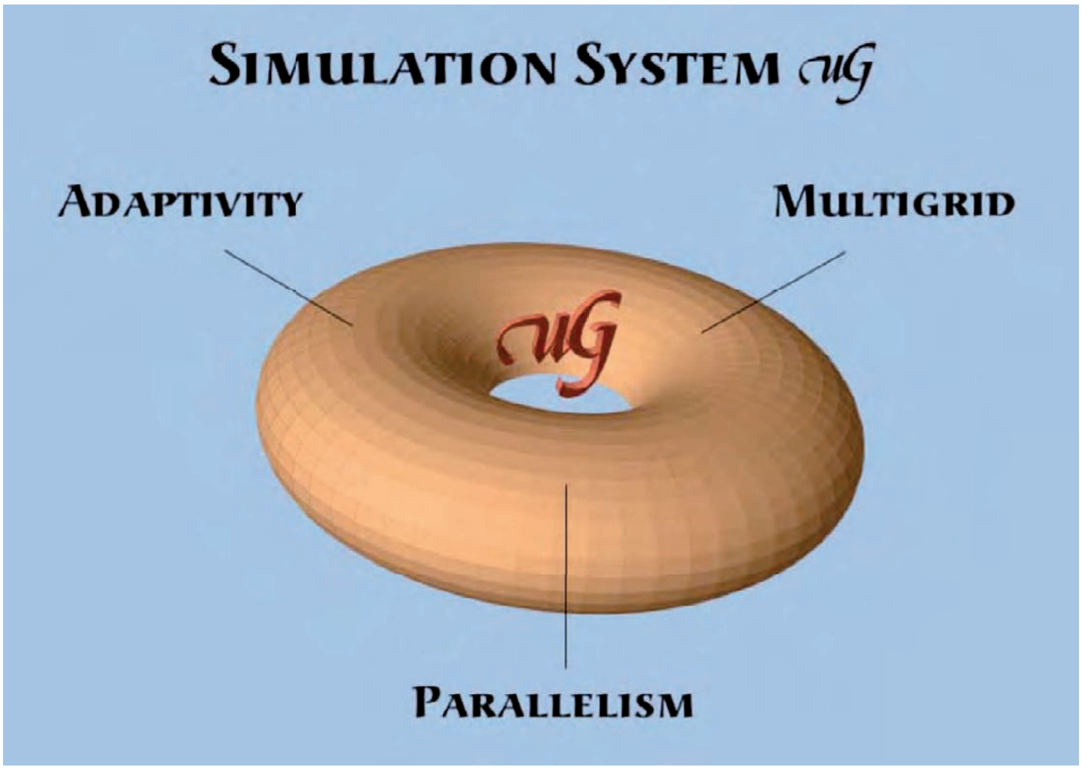
THERMOHALINE FLOWS IN FRACTURED POROUS MEDIA

P. Frolcovic, J. Geiser, A. Grillo, K. Johannsen, M. Lampe, D. Logaschenko, S. Stichel, G. Wittum
Johann Wolfgang Goethe-Universität Frankfurt

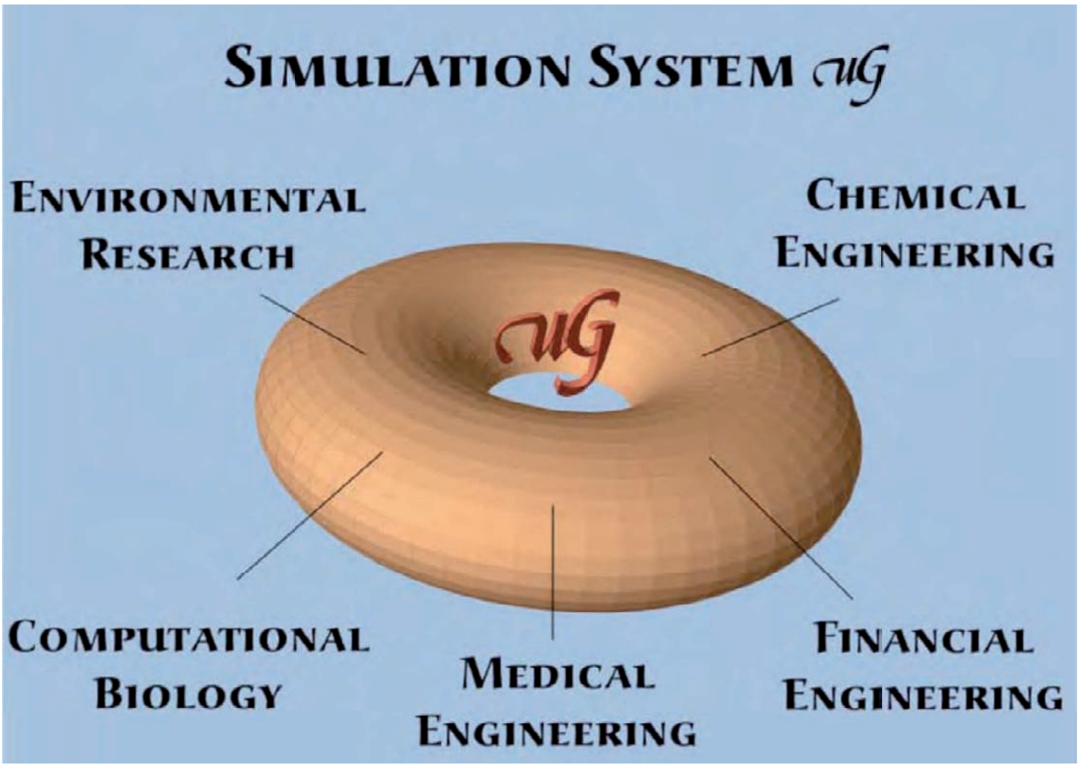
Thermohaline Flows in Fractured Porous Media

P. Frolkovic, J. Geiser, A. Grillo, K. Johannsen, M. Lampe, D. Logaschenko, S. Stichel, G. Wittum
in cooperation with
S. Attinger, E. Fein, J. Flügge, A. Fuchs, W. Kinzelbach, J. Mönig, F. Radu, A. Rübel, A. Schneider, R. Stork

Gabriel Wittum
G-CSC
University of Frankfurt



Gabriel Wittum
G-CSC
University of Frankfurt



- Multiscale Modeling <-> Numerics

Gabriel Wittum
G-CSC
University of Frankfurt

Automotive Simulation

- Crash simulation

  (Porsche, Daimler)

- Optimization of fuel injection (Porsche)

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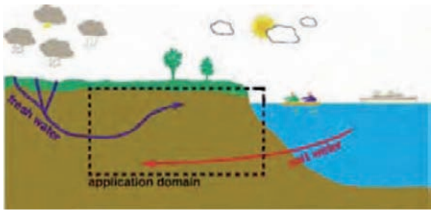
G-CSC
University of Frankfurt

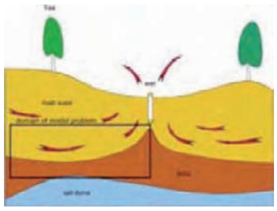
Distributed Density Driven Flow

D³F

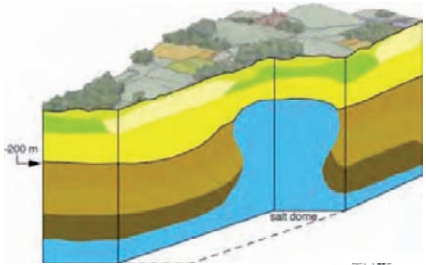
- Saltwater intrusion



- Upconing



- Flow around saltdomes



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G-CSC
University of Frankfurt

D³F

- Distributed Density Driven Flow

  Solver for

$$\frac{\partial(n\rho(c))}{\partial t} + \nabla \cdot (\rho(c)\vec{v}) = Q_p(c),$$

$$\frac{\partial(n\rho(c)c)}{\partial t} + \nabla \cdot (\rho(c)(c\vec{v} - \mathbb{D}\nabla c)) = Q_c(c)$$

+ b.c.; with $\vec{v} = -K/\mu(c)(\nabla p - \rho(c)\vec{g})$.

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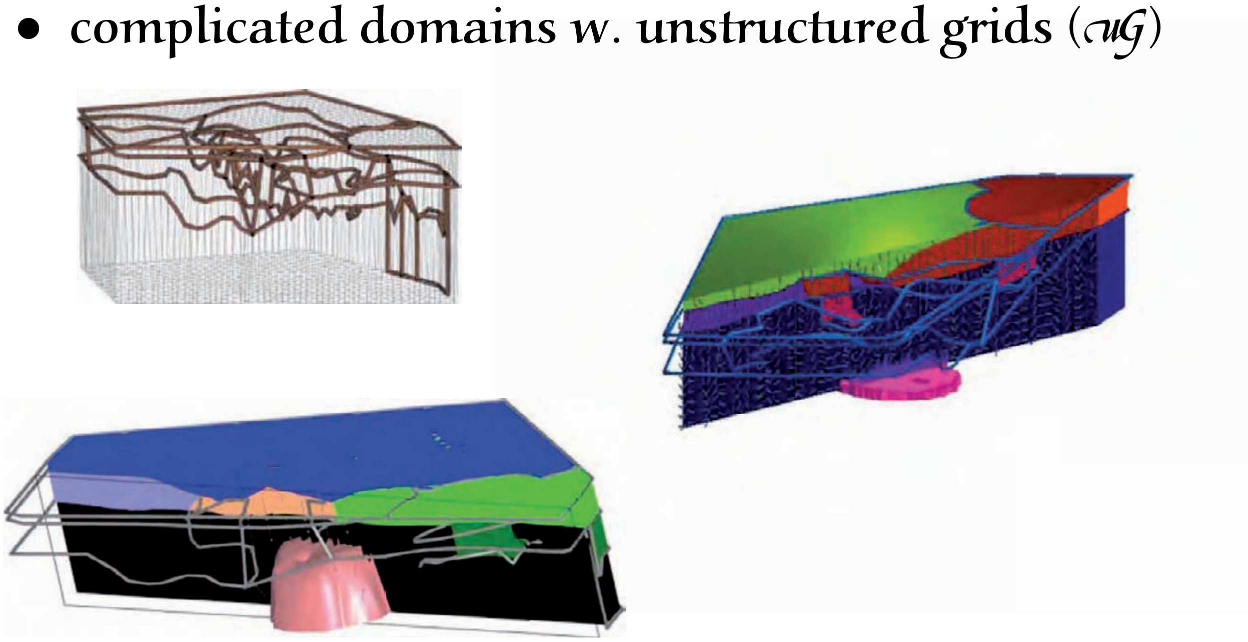
D3F

- complicated domains w. unstructured grids (uG)



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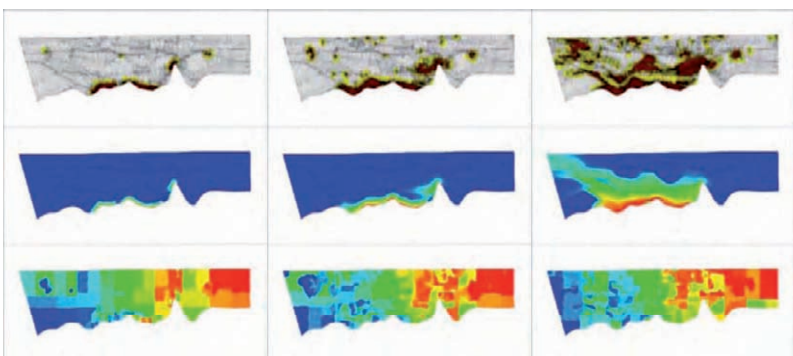
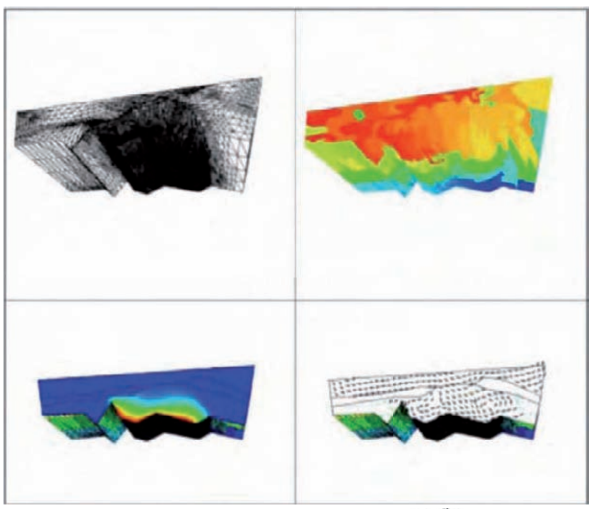
G-CSC
UNIVERSITY OF FRANKFURT

D3F

- Full density dependent non-linear dispersion
- fully parallel and adaptive





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G-CSC
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D3F Parallel Efficiency

- Uniform refinement

  weak scaling

P	h	UKN	NIT[#]	TIT[s]	S_S[#]	E_S
1	1/8	147.074	19	37.31	1	1.0
8	1/16	1.082.498	23	45.83	5.4	0.67
64	1/32	8.414.978	35	54.12	24	0.37
512	1/64	66.602.498	22	58.54	282	0.55

- Adaptive refinement

  weak scaling

h	UKN	TNLS[s]	TADAPT[s]	TLB[s]	TMIG[s]
1/16	21.016	52.3	1.93	0.97	3.57
1/32	102.280	224.	13.2	3.99	13.2
1/32	433.908	657.	44.6	11.2	41.8
1/64	1.750.708	2708.	160.	27.9	108.

- Lang, S., Wittum, G.: Large scale density driven flow simulations using parallel unstructured grid adaptation and local multigrid methods. Concurrency Computat., 17, 11, 1415 - 1440, Oct. 2005.

R3T

- RRRT: Package solving systems of up to 160 coupled convection-diffusion reaction equations

  RRRT: Radionuclides

  R**R**RT: Reactions

  RR**R**T: Retardation

  RRR**T**: Transport

Validation

- Extensive validation

  Especially designed experiments (saltpool)

  Johannsen, K., Kinzelbach, W., Oswald, S., Wittum, G.: The saltpool benchmark problem - numerical simulation of saltwater upconing in a porous medium, Advances in Water Resources, 25 (3) (2002) pp. 335-348.

  Field cases measured (Cape Cod, E. Fein)

New Work

- Thermohaline flows
- fractured media

Gabriel Wittum
G-CSC
University of Frankfurt

Thermohaline Flows

- Solving

$$
\begin{aligned}
\phi_f \frac{\partial \widehat{\rho}_f}{\partial t} + \nabla \cdot (\widehat{\rho}_f \mathbf{q}_f) &= 0, \\
\phi_f \frac{\partial (\widehat{\rho}_f \omega_s)}{\partial t} + \nabla \cdot (\widehat{\rho}_f \omega_s \mathbf{q}_f + \mathbf{J}_d) &= 0, \\
\phi_f \widehat{\rho}_f \Theta \frac{\mathrm{D}_f \widehat{S}_f}{\mathrm{D}t} + (1-\phi_f)\rho_r \Theta \frac{\partial \widehat{S}_r}{\partial t} + \nabla \cdot (\mathbf{J}_T - \widehat{\mu}_{sw} \mathbf{J}_d) &= 0,
\end{aligned}
$$

with $\mathbf{q}_f = -\frac{k}{\nu_f}(\nabla p - \rho_f \mathbf{g})$ (Onsager)

$$
\begin{aligned}
\mathbf{J}_d &= -\phi_f \rho_f D \nabla \omega_s - \phi_f \rho_f D \frac{k_p}{p} \nabla p - \phi_f \rho_f D S \omega_s (1-\omega_s) \nabla \Theta, \\
\mathbf{J}_T &= -\phi_f \rho_f D Q \nabla \omega_s - \phi_f \rho_f D Q \frac{k_p}{p} \nabla p - \left[L_{TT} - \phi_f \rho_f \frac{D Q h_{sw}}{\Theta \frac{\partial \widehat{\mu}^i_{sw}}{\partial \omega_s}} \right] \nabla \Theta.
\end{aligned}
$$

Thermohaline Flows

Solving

$$
\begin{aligned}
\phi_f \frac{\partial \widehat{\rho}_f}{\partial t} + \nabla \cdot (\widehat{\rho}_f \mathbf{q}_f) &= 0, \\
\phi_f \frac{\partial (\widehat{\rho}_f \omega_s)}{\partial t} + \nabla \cdot (\widehat{\rho}_f \omega_s \mathbf{q}_f + \mathbf{J}_d) &= 0, \\
\phi_f \widehat{\rho}_f \Theta \frac{\mathrm{D}_f \widehat{S}_f}{\mathrm{D}t} + (1-\phi_f)\rho_r \Theta \frac{\partial \widehat{S}_r}{\partial t} + \nabla \cdot (\mathbf{J}_T - \widehat{\mu}_{sw} \mathbf{J}_d) &= 0,
\end{aligned}
$$

Alfio Grillo, Michael Lampe, Gabriel Wittum: Modelling and Simulation of temperature-density-driven flow and thermodiffusion in porous media. Journal of Porous Media, 2010 to appear.

Thermohaline Flows

- opposite effects of temperature and salt concentration

  Temperature ↑

  salt water ↓

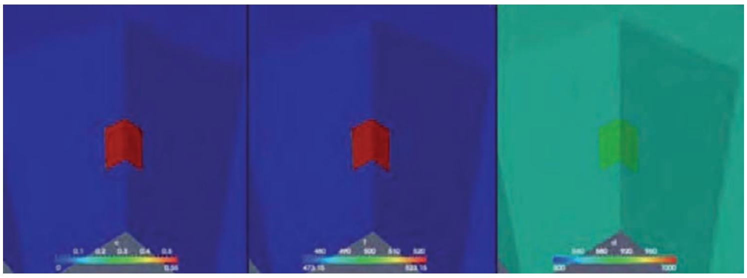
- connection of mass flux with temperature gradient (Soret effect)
- connection of heat flux with concentration gradient (Dufour effect)

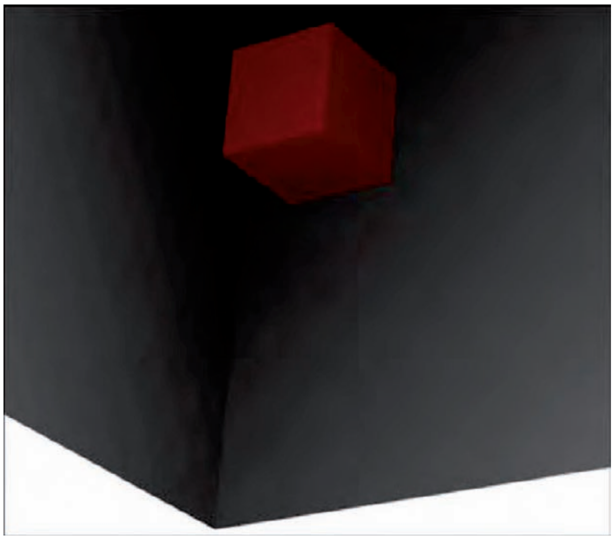
Example

- Moving parcel, benchmark problem from Oldenburg, Pruess, 1999 (2d)

Thermohaline Flows

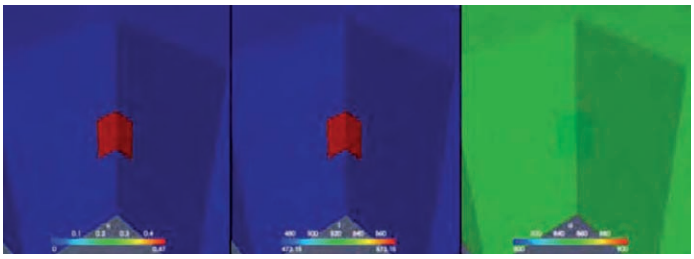
- negative buoyancy

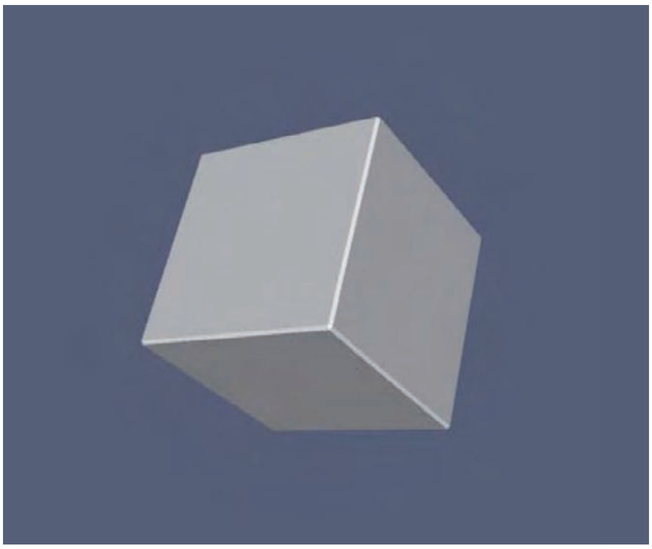




Thermohaline Flows

- positive buoyancy





Fractured Media

- Low dimensional formulation

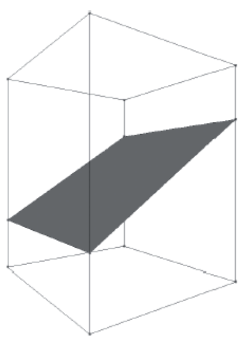
  Multiphase flow

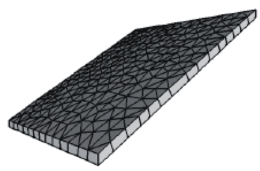
  R. Helmig; O. Kolditz; V. Reichenberger; ...

- Multiscale modeling and numerics: Dynamic coupling between micro and macroscales

Flow in Fractured Media

- low dimensional <-> full dimensional



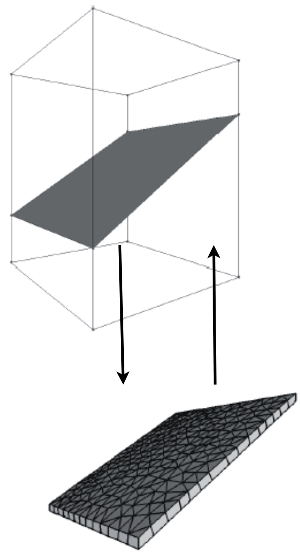


Representation of fractures:

1. Polyhedral faces + pointwise thickness
2. expand to volume

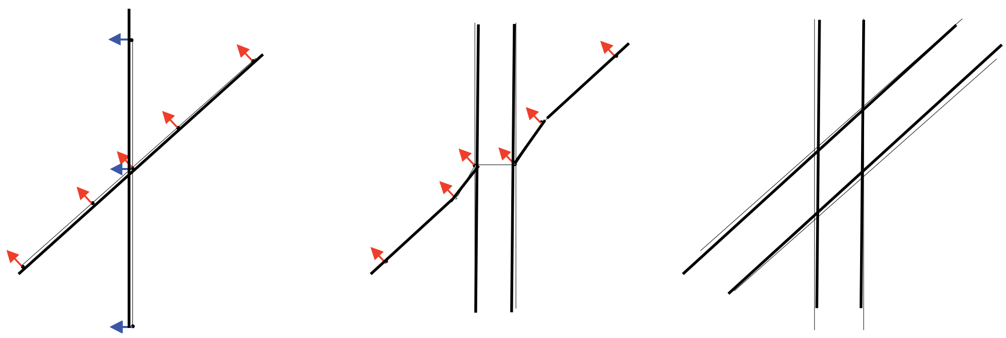
Flow in Fractured Media

- Problem: Multigrid refinement
  coarse grid: low dimensional
  fine grid: full dimensional



Flow in Fractured Media

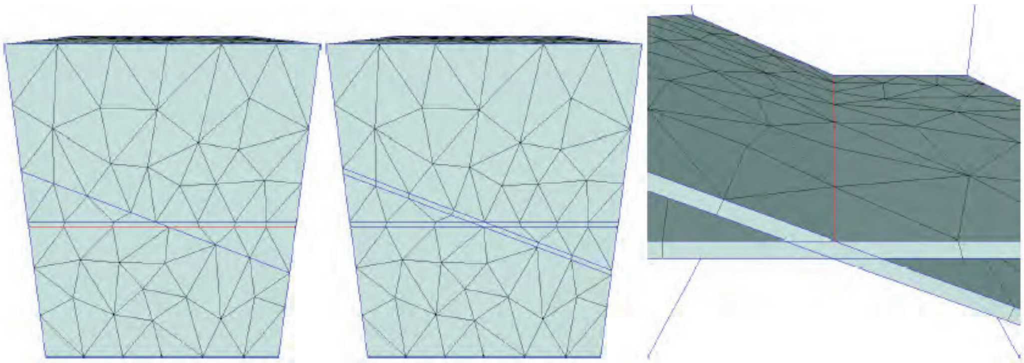
- Geometry



initial rep expansion correction

Flow in Fractured Media

- Grid follows the anisotropic direction rectangularly



successful treatment of anisotropy possible: ARTE

Fuchs, W., 2003

Gabriel Wittum
G-CSC
University of Frankfurt

Low Dimensional Model

- Density driven flow model

  average across fracture

$$\langle F \rangle(t,x,y) := \frac{1}{\epsilon}\int_{-\epsilon/2}^{\epsilon/2} F(t,x,y,z)\mathrm{d}z.$$

+transmission conditions

Gabriel Wittum
G-CSC
University of Frankfurt

Transmission Conditions

- Full dimensional:

  Continuity of normal fluxes of fluid and brine

$$
\begin{aligned}
-\rho(c_f)\frac{K_f}{\mu}\left(\frac{\partial p_f}{\partial n}-\rho(c_f)g_n\right) &= -\rho(c_m)\frac{K_m}{\mu}\left(\frac{\partial p_m}{\partial n}-\rho(c_m)g_n\right)\\
-D_f\left(1-\frac{\rho'}{\rho^{pW}}c_f\right)\frac{\partial c_f}{\partial n} &= -D_m\left(1-\frac{\rho'}{\rho^{pW}}c_m\right)\frac{\partial c_m}{\partial n}.
\end{aligned}
$$

  Continuity of pressure and concentration

$$p_f = p_m, \quad \text{and} \quad c_f = c_m$$

Gabriel Wittum
G-CSC
University of Frankfurt

Transmission Conditions

- Low dimensional

  the auxiliary vector fields

$$\mathbf{Q}_\alpha := \rho^{pW}\,\mathbf{q}_\alpha - \rho'\mathbf{J}_\alpha, \quad \text{and} \quad \mathbf{P}_\alpha := c_\alpha \mathbf{q}_\alpha + \mathbf{J}_\alpha\,;$$

with

$$
\begin{aligned}
\mathbf{q}_\alpha &= -\frac{\mathbf{K}_\alpha}{\mu}[\nabla p_\alpha - \rho_\alpha(c_\alpha)\mathbf{g}],\\
\mathbf{J}_\alpha &= -\left(\frac{\rho^{pW}}{\rho^{pW}+\rho'\,c_\alpha}\mathbf{D}_\alpha\right)\nabla c_\alpha
\end{aligned}
\qquad \rho' = \frac{\rho^{pB}-\rho^{pW}}{\rho^{pB}}
$$

are continous across the fracture interfaces

$$Q_{fn}^{(k)} = Q_{mn}^{(k)}, \quad \text{and} \quad P_{fn}^{(k)} = P_{mn}^{(k)}$$

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G-CSC
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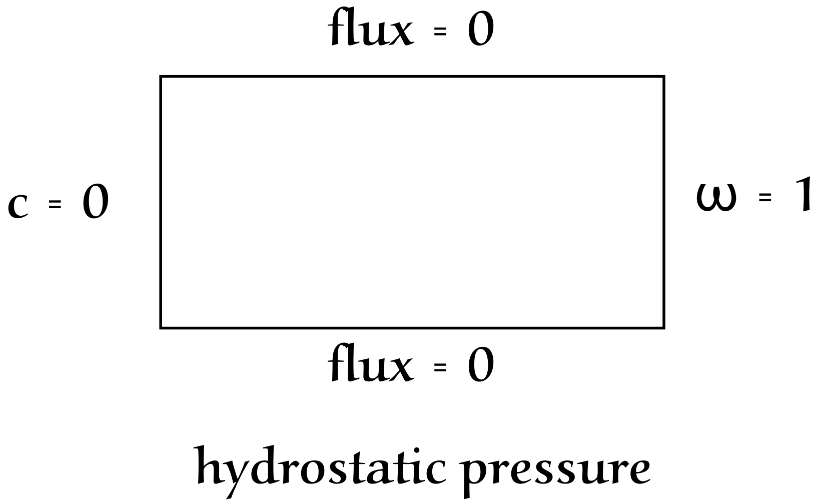
Henry's Problem (2d)



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Henry's Problem

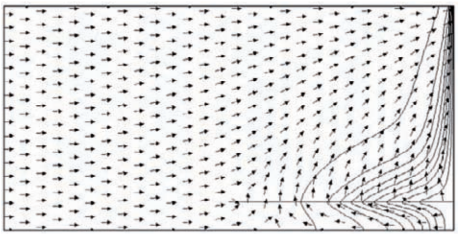
- Parameters

Symbol	Quantity	Value	Unit
D_d	Diffusion coefficient	$18.8571 \cdot 10^{-6}$	$[\mathrm{m}^2\ \mathrm{s}^{-1}]$
$D_m = \phi_m\ D_d$	Diffusion coefficient in the medium	$6.6 \cdot 10^{-6}$	$[\mathrm{m}^2\ \mathrm{s}^{-1}]$
$D_f = \phi_f\ D_d$	Diffusion coefficient in the fracture	$13.2 \cdot 10^{-6}$	$[\mathrm{m}^2\ \mathrm{s}^{-1}]$
$\mathbf{g}$	Gravity	9.81	$[\mathrm{m\ s}^{-2}]$
K_m	Permeability of the medium	$1.019368 \cdot 10^{-9}$	$[\mathrm{m}^2]$
K_f	Permeability of the fracture	$1.019368 \cdot 10^{-5}$	$[\mathrm{m}^2]$
ϕ_m	Porosity of the medium	0.35	-
ϕ_f	Porosity of the fracture	0.7	-
μ	Viscosity	10^{-3}	$[\mathrm{kg\ m}^{-1}\ \mathrm{s}^{-1}]$
ρ_w	Density of water	$1 \cdot 10^3$	$[\mathrm{kg\ m}^{-3}]$
ρ_s	Density of brine	$1.025 \cdot 10^3$	$[\mathrm{kg\ m}^{-3}]$
a_α^t	Transversal dispersivity length	0	[m]
a_α^l	Longitudinal dispersivity length	0	[m]

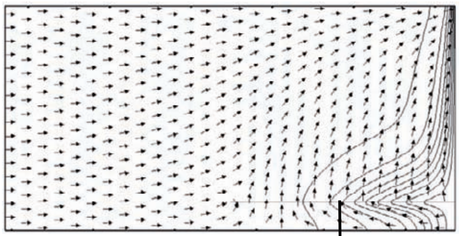
Gabriel Wittum
G-CSC
University of Frankfurt

Henry-Problem w. Fracture

ε = 3 mm, T = 5h

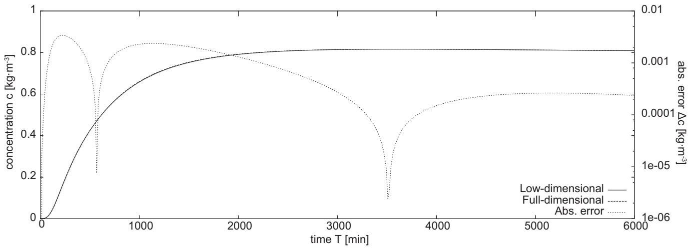


full dim. rep.



low dim. rep.

x = 1.5 m



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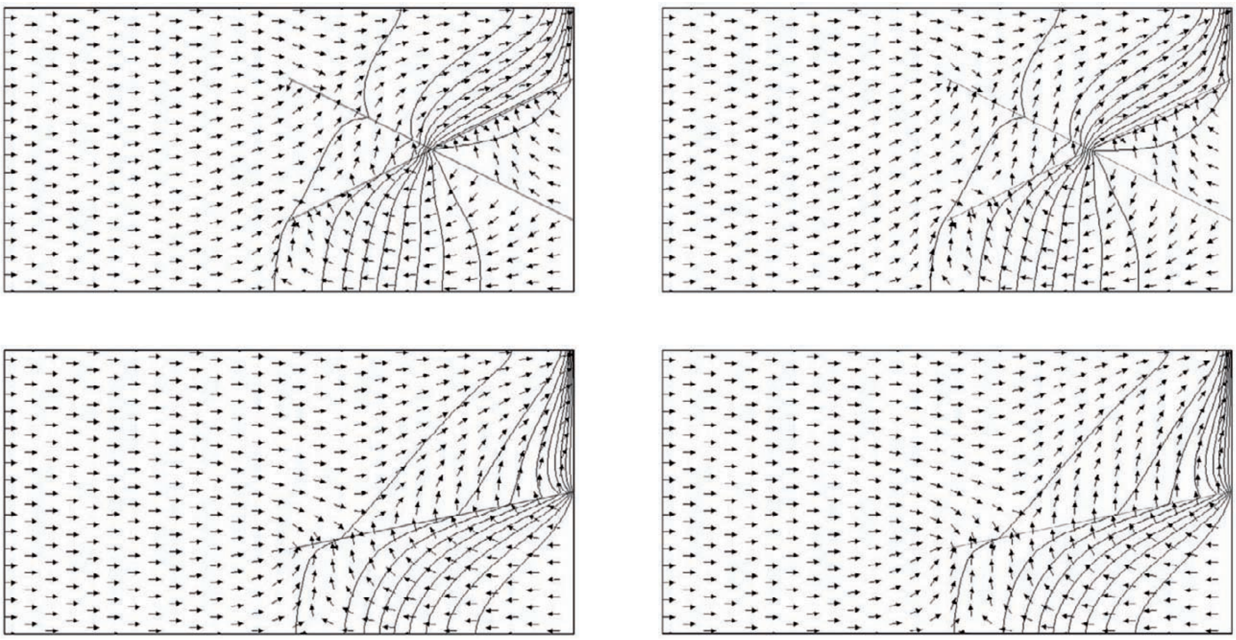
Henry-Problem w. Fracture



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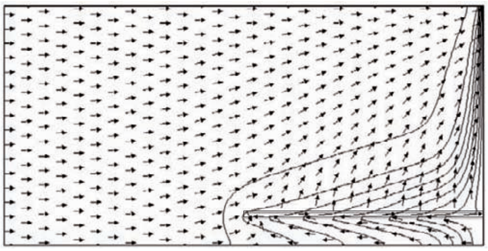
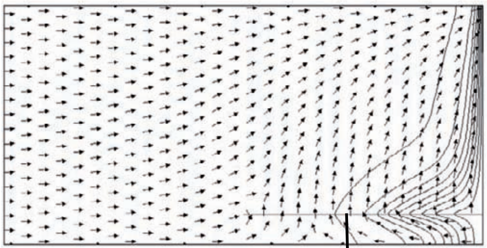
Henry-Problem w. Fracture

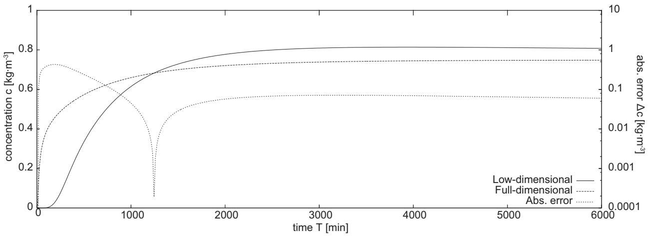
ε = 24 mm, T = 5h



full dim. rep.



low dim. rep.



x = 1.5m

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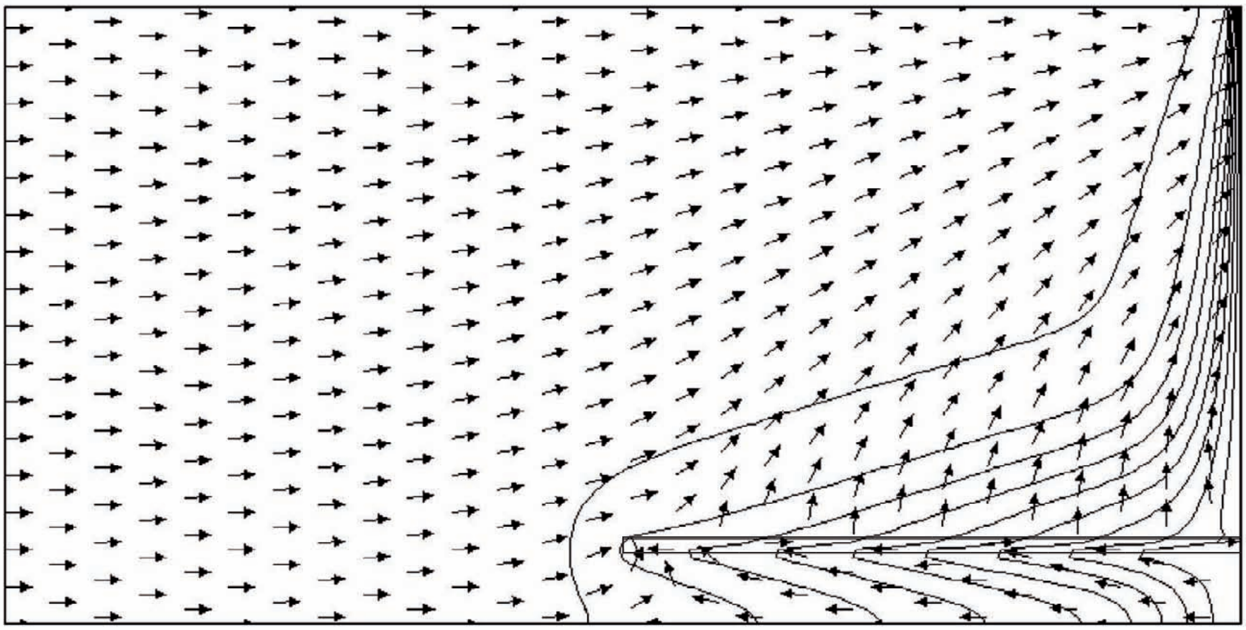
Henry-Problem w. Fracture

ε = 24 mm, T = 5h



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G-CSC
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Henry-Problem w. Fracture

- Low dimensional representation works fine for thin fractures.
- For larger fractures (24 mm!) vortices may exist in the fracture changing the flow considerably

Gabriel Wittum
G-CSC
University of Frankfurt

Dank

- Projekte E-DuR und A-DuR
- Partner: GRS, Uni Jena, UFZ Leipzig, Uni Freiburg, Uni Bonn, ETHZ
- Projektträger: PTE KA
- BMWi

Gabriel Wittum
G-CSC
University of Frankfurt

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

WIPP HYDROLOGIC INVESTIGATIONS IN THE SALADO FORMATION

Richard L. Beauheim
Distinguished Member of Technical Staff
Sandia National Laboratories

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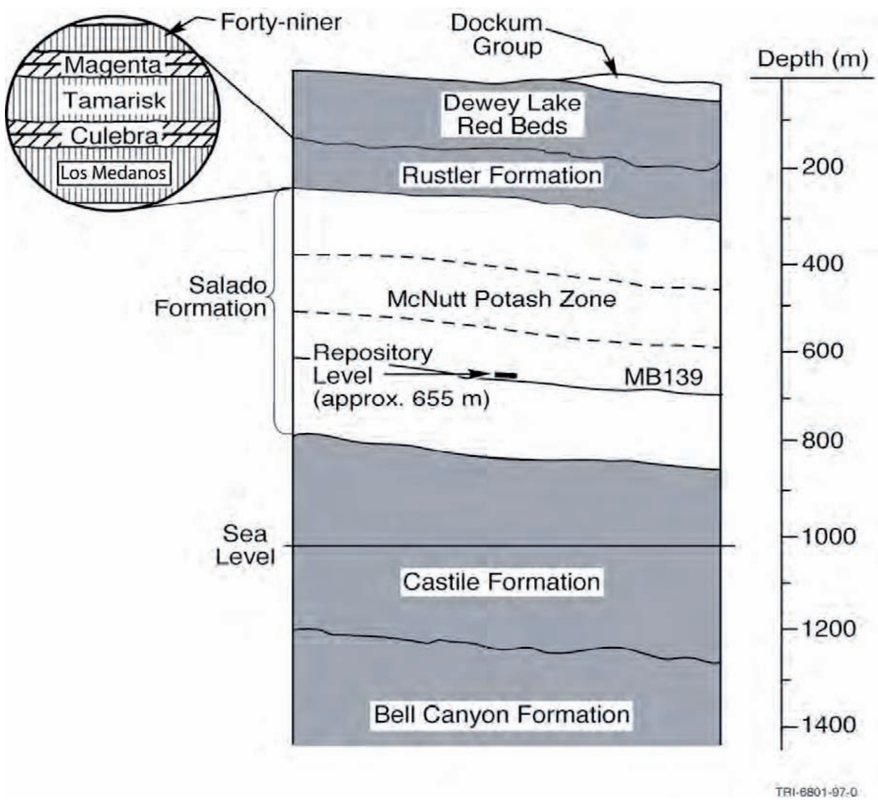
This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy

WIPP Stratigraphy



Questions to be Addressed about Salado

- Brine inflow—how much brine might enter the repository after it is closed?
- DRZ/EDZ—how extensive will the damaged zone around the excavations be, and how will rock properties be altered?
- Gas threshold pressure—if gas is generated in the repository, what pressure must it reach before it can flow into the rock?
- Fracture pressure—at what pressure will the repository host rocks fracture, and will the fractures be horizontal or vertical?
- Brine chemistry—what is the chemistry of the brine(s) that might enter the repository, and what can we infer about its origin(s) and mobility?
- Transport—can radionuclides (in brine or gas) be transported away from the repository in the Salado?

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Experimental Programs

- Permeability testing—addresses brine inflow, DRZ, and transport
- Room Q—addresses brine inflow, DRZ, and transport
- Simulated DHLW heater experiments—addresses brine inflow to HLW boreholes
- Gas threshold pressure testing
- Coupled permeability testing and hydraulic fracturing
- Brine chemistry—also addresses transport

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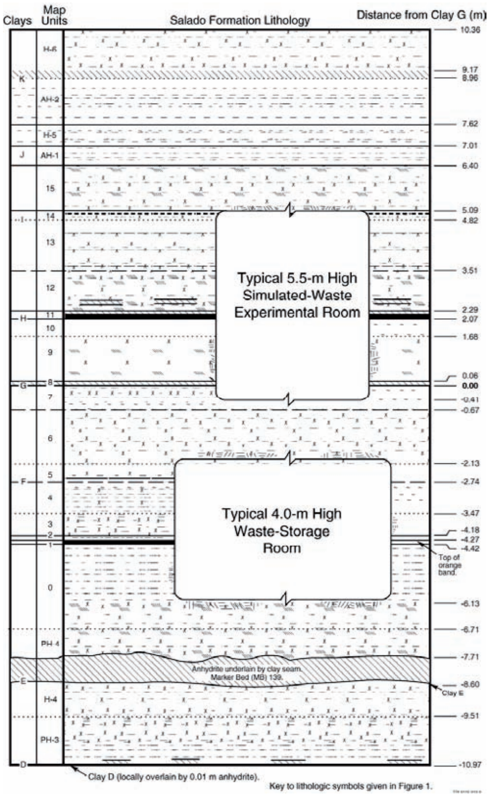
Underground Stratigraphy



- Salado stratigraphy consists primarily of relatively pure halite, argillaceous and/or polyhalitic halite, and anhydrite beds underlain by clay seams
- Individual beds can be traced over the area of the repository in excavations and/or core
- No disruptions in bedding over a meter scale have been found
- Identify geologic variability relevant to hydraulic properties
- Determine representative hydraulic properties for each important rock type

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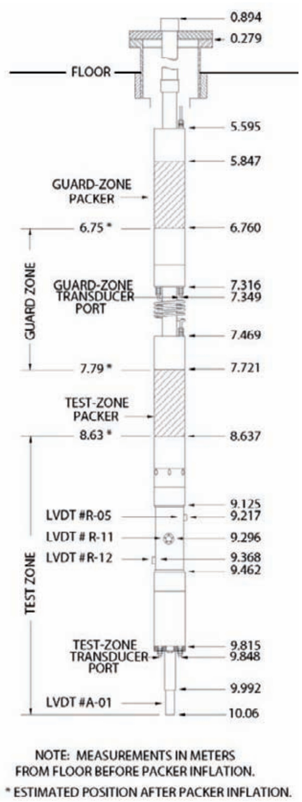
Development of Specialized Equipment for Low-K Testing



- Guard zones to reduce pressure differential across packers
- Maximize tool volume to minimize fluid volume
- Radial LVDT's to measure borehole deformation
- Axial LVDT to measure borehole elongation

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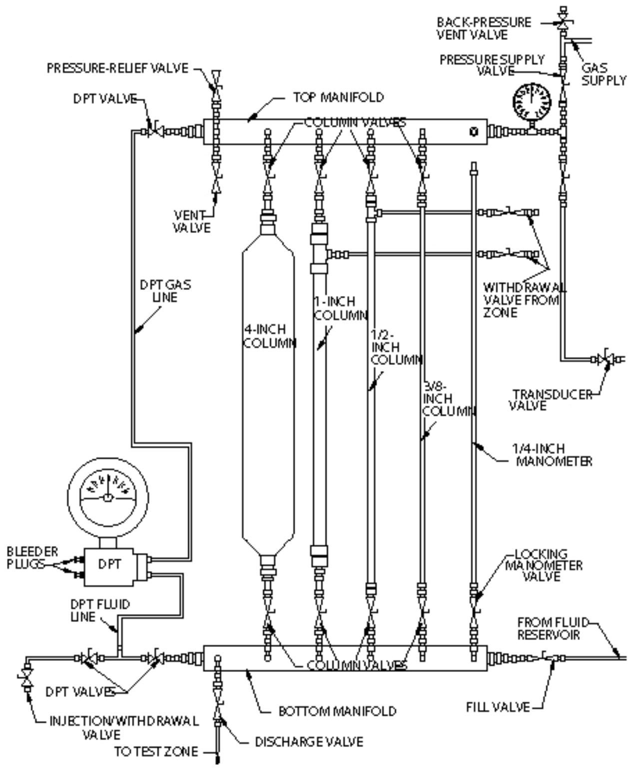
Equipment Design to Maximize Measurement Sensitivity



Multiple reservoir columns for constant-pressure flow tests with different diameters arranged in parallel to allow optimization to flow rates encountered

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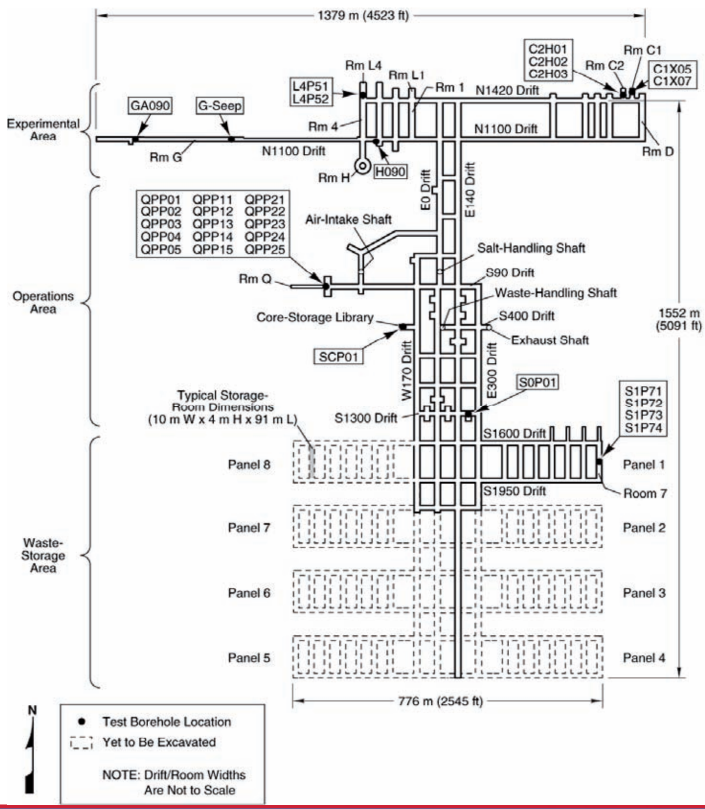
Test Locations



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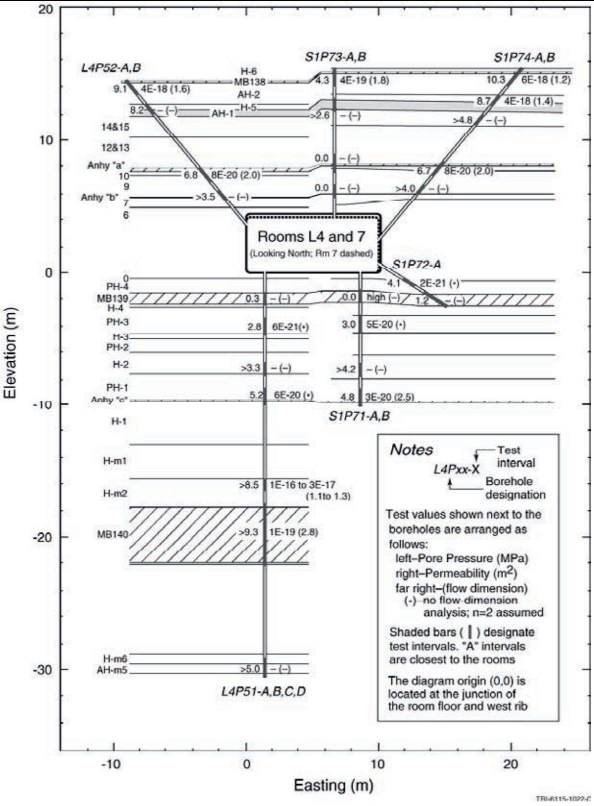
Rooms L4 and 7 Testing



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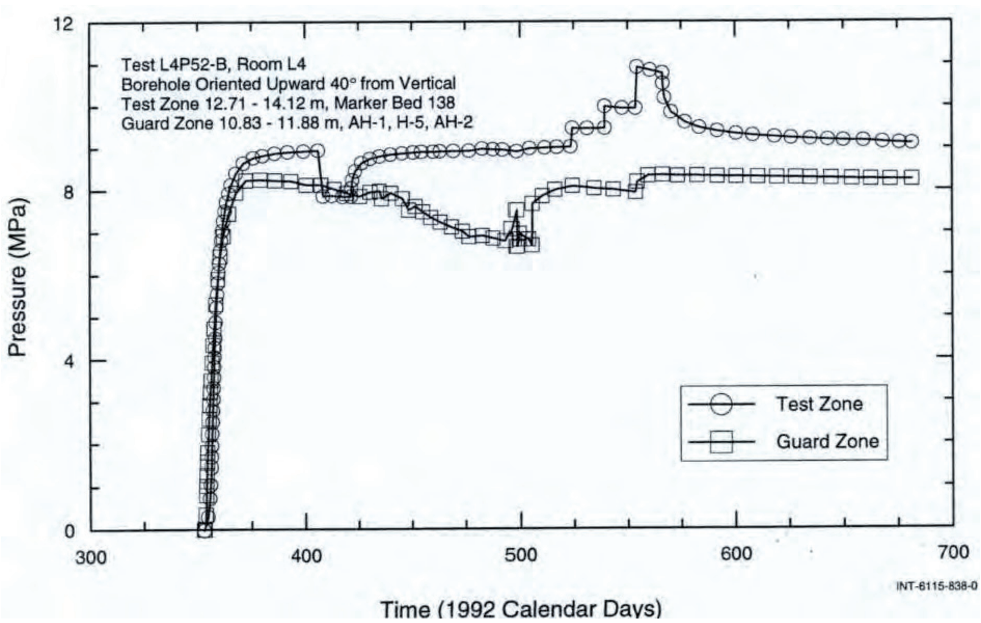
Testing for Pressure-Dependent Permeability



- Perform constant-pressure withdrawal test followed by constant-pressure injection tests at 3 successively higher pressures
- Test showed that permeability increased with test pressure

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Permeability Testing Results

- Anhydrite permeability outside the DRZ ranges from ~10^{-20} to 10^{-18} m^2
- The permeability of pure halite outside the DRZ is too small to measure (<10^{-22} m^2)
- Impure halite permeability is <10^{-20} m^2
- Testing at different pressures (L4P52-B) showed that permeability of anhydrite interbeds is pressure-dependent
- DRZ for permeability seems to be ~2.5 m thick in floor, more in roof
- Depressurization extends tens of meters from rooms

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Room Q

- The Room Q experiment was designed to evaluate brine inflow to the repository and geomechanical effects on hydraulic properties
- Room Q was bored into an undisturbed area to the west of existing WIPP excavations
- Room Q is a 109-m-long cylindrical excavation, 2.9 m in diameter

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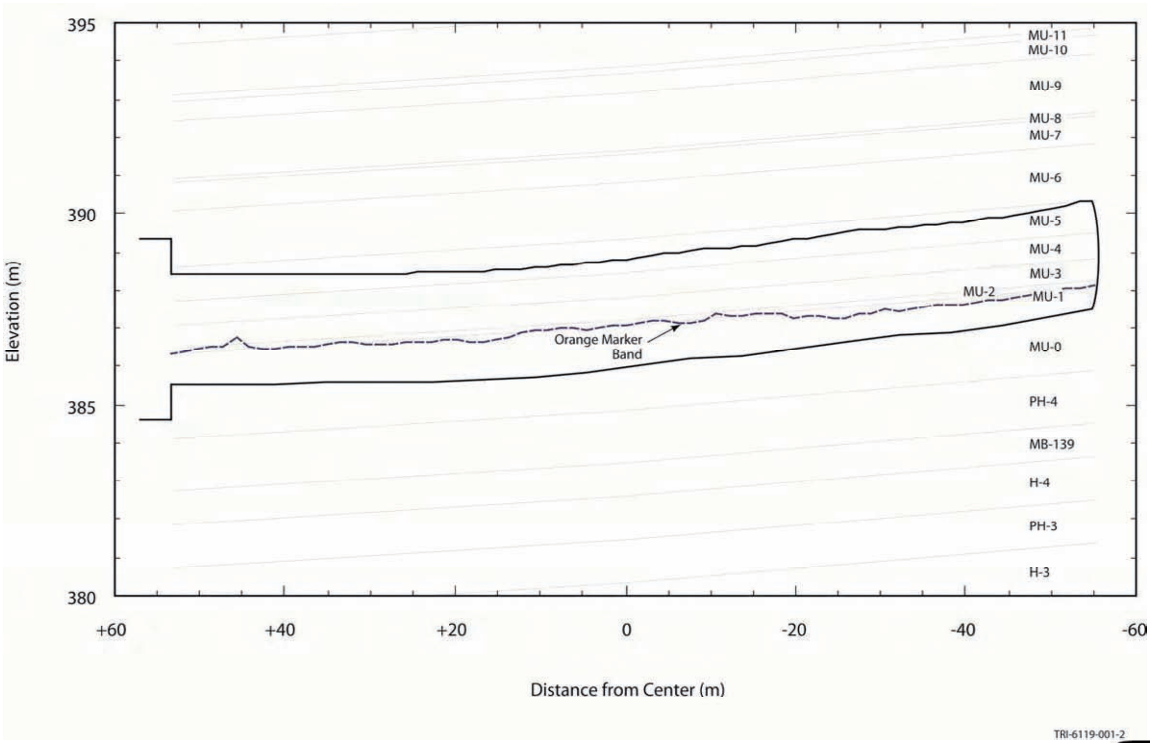
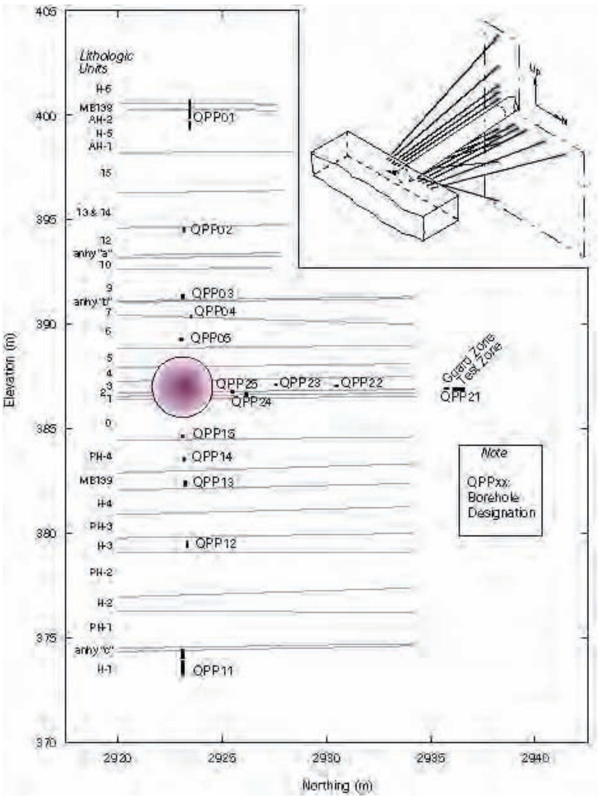
Room Q Entryway

Room Q Cross Section

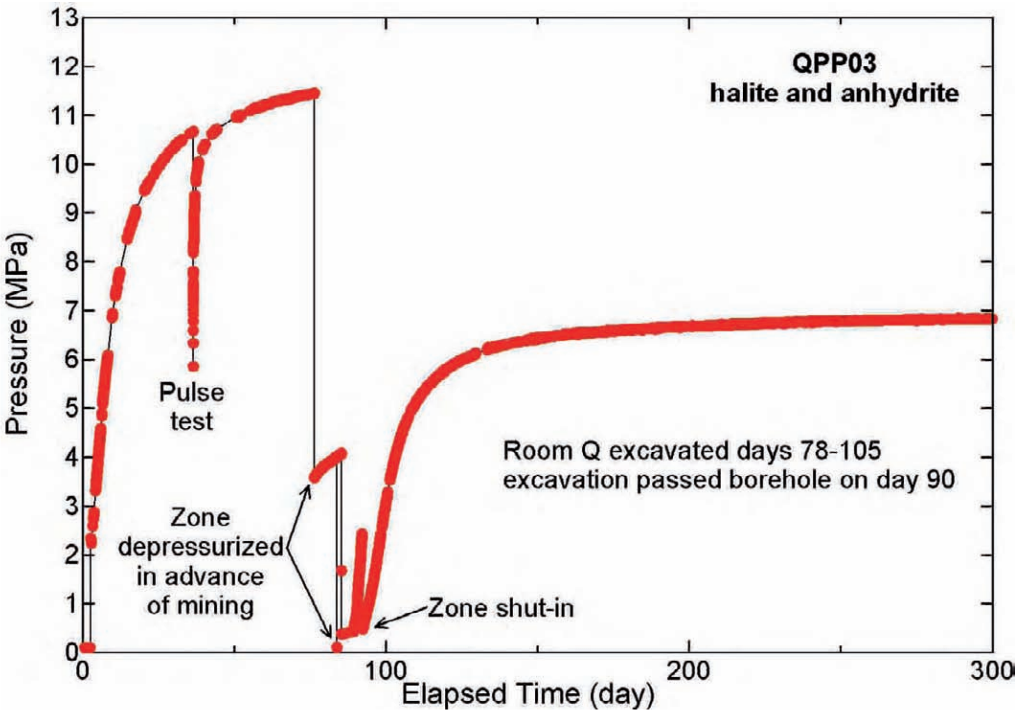


Monitoring Locations Around Room Q



- Before excavating Room Q, 15 boreholes were drilled to terminate in a plane 22.9 m along the length of the room
- 3 arrays of 5 boreholes terminated ~2.4, 3.3, 4.5, 7.6, and 13.6 m from the centerline of the room, vertically above and below and horizontally north of the room
- The ends of the boreholes were isolated with packers to allow pressure monitoring and hydraulic testing

Response 4.4 m from Room Q

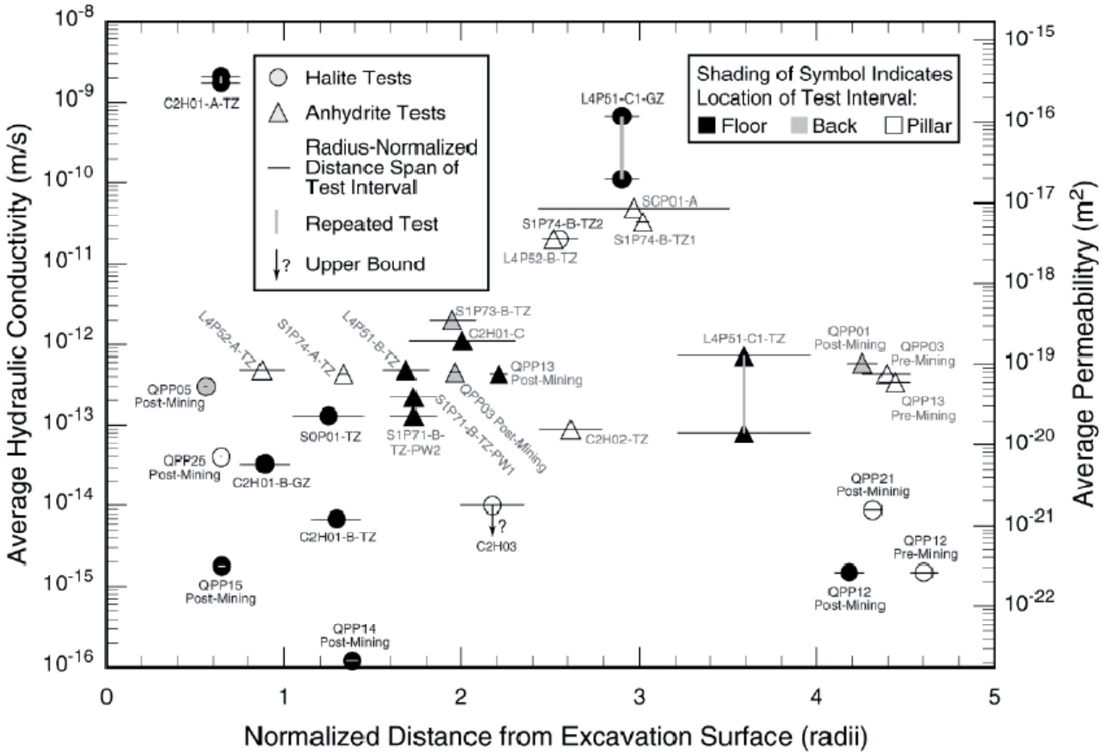


- Permeability and pressure clear before mining
- Pressure reduced by mining

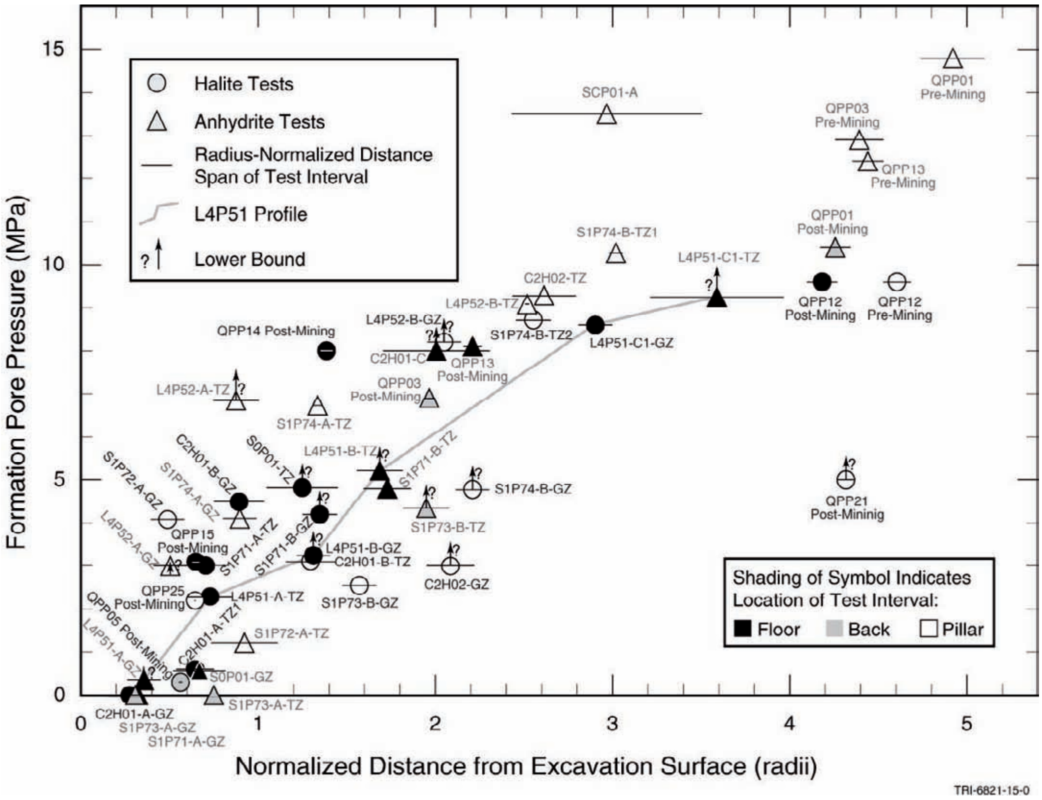
Summary of Room Q Observations

- After Room Q was finally sealed (>600 days after mining), inflow averaged ~200 mL/day
- No clear evidence of permeability or pore pressure in 6 of 12 halite intervals before mining of Room Q; all showed such evidence after mining
- Pore pressure reductions were observed in all boreholes except one
- Pore pressures were reduced by:
  - Stress relief
  - Flow to Room Q
- Pore connectivity (permeability) was increased in boreholes closest to Room Q

Salado Hydraulic Test Results--Permeability



Salado Hydraulic Test Results--Pressure



DHLW Experiments

- 470 and 1500 W heaters were placed in 0.8-m-diameter vertical boreholes to simulate the heat generation from defense high level waste
- 4.3 kg of brine were collected in 441 days from the holes with 470 W heaters
- 36 to 38 kg of brine were collected in 600 days from the holes with 1500 W heaters
- Fluid inclusions migrated toward the boreholes

Coupled Permeability Tests and Hydraulic Fracturing

- Perform permeability tests before and after hydraulic fracturing of anhydrite interbeds
- Objectives
  - Determine pressure at which fracturing occurs, both when stress field is disturbed and undisturbed
  - Determine if pre-existing fractures open, or new fractures form
  - Determine if fractures stay confined to interbeds
  - Determine whether or not stress field is isotropic
  - Compare interbed permeabilities close (MB139) and far (MB140) from excavations
  - Determine how hydraulic fracturing affects permeability

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Permeability and Hydraulic Fracturing Results

- MB139 fractured at a pressure of ~19 MPa and MB140 fractured at a pressure of ~22 MPa—both were affected by the nearby excavations
- Once initiated, fracture propagation pressures were only 12-13 MPa
- Pre- and post-fracturing permeability tests showed:
  - Flow was not radial because of asymmetric stress field below Room C1
  - Permeability and flow dimension increased as a result of fracturing, and were more pressure-dependent than before

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Gas Threshold Pressure

- Gas threshold pressure is the pressure at which gas first enters a brine-saturated medium. It corresponds to the point on a capillary pressure curve at full wetting-phase saturation.
- Gas threshold pressure is the only two-phase property that can be measured in the field
- Literature data show a correlation between permeability and gas threshold pressure
- Based on this correlation and the observed permeability range of WIPP anhydrite interbeds, gas threshold pressures could be as high as 7 MPa. This raised the possibility that hydraulic fracturing might occur before gas could enter the interbeds.

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Gas Threshold Pressure Testing

- Start with a brine-saturated system at equilibrium
- Exchange gas for brine, maintaining pressure
- Allow pressure to stabilize
- Inject gas at a constant mass rate
- Threshold pressure is reached when the pressure buildup deviates from the wellbore-storage line, indicating movement into the formation
- The test can also be repeated at a different injection rate to improve resolution of the threshold pressure estimate

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Conclusions from Gas Threshold Pressure Testing

- Threshold pressure of MB139 is less than 1 MPa
- Gas will be able to enter anhydrite interbeds at pressures well below the hydraulic fracturing pressure

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Summary of Salado Hydrology Investigations

- Anhydrite beds are fractured and have more permeability than other Salado lithologies
- Argillaceous halite may have some permeability where undisturbed by excavation effects
- Pure halite appears to have no permeability except within the DRZ
- Pore pressures are approximately lithostatic where undisturbed by excavations
- Brine inflow to a closed, unheated repository will be minor
- More brine inflow would occur to a repository with heat-generating waste

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Summary of Salado Hydrology Investigations (2)

- Hydraulic fracturing increases anhydrite permeability and makes it more pressure-dependent
- Gas threshold pressure of anhydrite interbeds is below the fracturing pressure
- Gas generated within the repository will be able to dissipate through anhydrite interbeds without fracturing the rock
- Differences in brine chemistry in nearby boreholes show that Salado brine is not mobile—radionuclides will not be transported away from the repository

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Remaining Questions/Issues

- Factors affecting brine flow to heat sources are incompletely understood
- How can we characterize the undisturbed saturation state in anhydrite interbeds?
  - Fully brine saturated?
  - Partially gas saturated?
- How can we characterize the saturation state in the DRZ/EDZ?
- How do we quantify the relationship between repository pressure and fracture dilation and permeability?
- How do we understand/predict gas/brine transport through fractured anhydrite?
- *In situ* measurement of gas threshold pressure needs refinement

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ADVANCED CONCEPTS FOR GROUNDWATER FLOW IN DYNAMIC STRESS FIELDS

Sean McKenna, Joe Bishop, Mike Stone
Sandia National Laboratories

Advanced Concepts for Groundwater Flow in Dynamic Stress Fields

US-German Workshop on Salt Repository Research, Design and Operation

May 25th, 2010, Jackson, MS

Sean A. McKenna[1], Joe Bishop[2], Mike Stone[2]

[1] Geoscience Research and Applications Center,
Sandia National Laboratories, Albuquerque, NM
[2]Computational Structural Mechanics and Applications Department
Sandia National Laboratories, Albuquerque, NM

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Outline

- Approaches to coupled mechanical modeling
- Recent developments
  - High strain rate fracturing
  - Crack propagation
  - Borehole failure (Coupled fluid-mechanics modeling)
  - Cellular automata models of heterogeneous fault zones
  - Multi-physics modeling of HLW repositories
- Summary

Approaches to Modeling Fractures

- Use of Discrete Fracture Network (DFN) models to populate domain prior to applying stress
  - Explicit meshing of fractures (splitting, stopping, change in direction)
  - Lots of realizations to capture statistical behavior
- Particle methods ("meshless")
  - Assume a continuum exists at all times and locations
- Meshed based approaches (fractures form along element boundaries)
  - Maintains continuum within each subdomain as fractures form
  - Resulting fracture network is a function of mesh

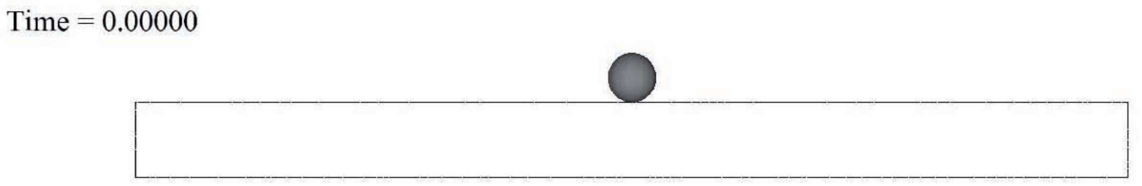
High Strain Rate Fracturing

- Requirements of non-nuclear waste projects led to development of new models for fractured rocks (*pervasive* fracturing)
  - Discretize material with Voronoi polygons (mesh-based approach)
  - Propagate fractures along polygon edges
  - Maintain cohesion between polygon faces until normal stresses exceed cohesive forces
  - Stress field still calculated in detached subdomains

Bishop, 2009, Simulating the pervasive fracture of materials and structures using randomly close packed Voronoi tessellations, *Journal of Computational Mechanics*

High Strain Rate Fracturing

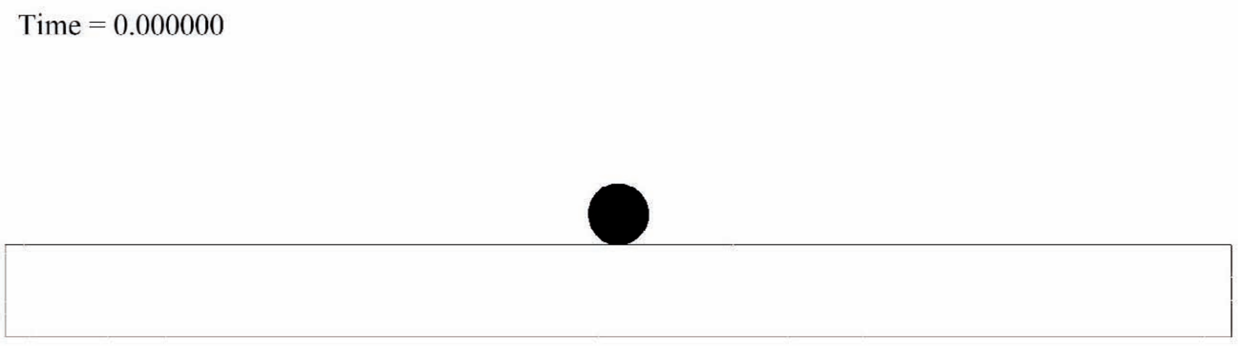
Impact to Medium Time



379

High Strain Rate Fracturing

Initial impact and early



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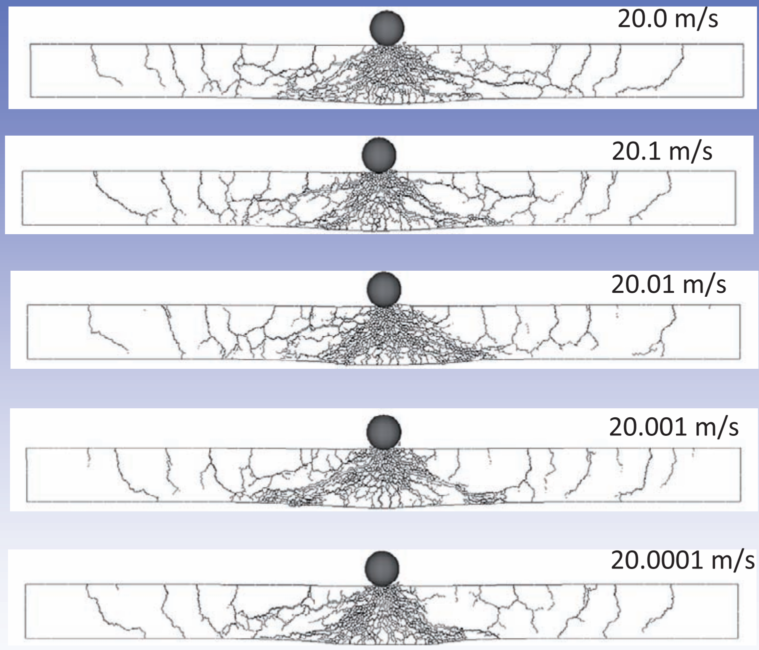
Extreme Sensitivity to Initial Conditions

Base Case

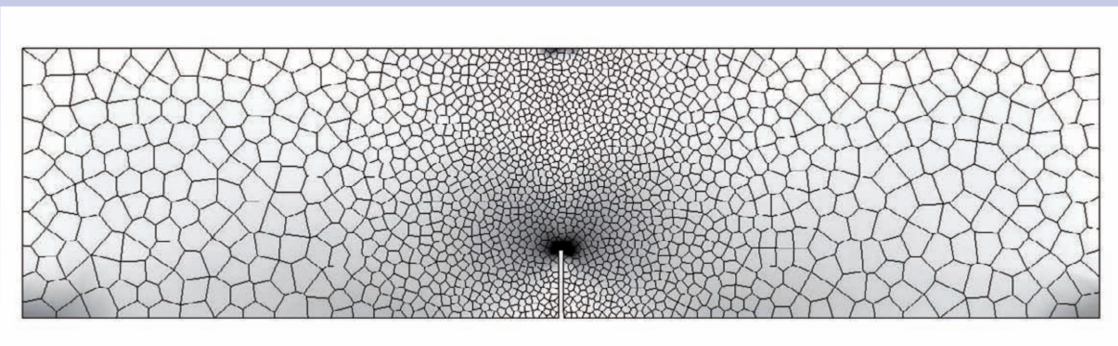


Crack patterns are qualitatively similar but distinctly different.

381

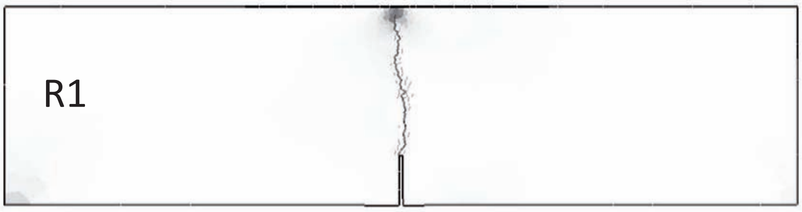
Notch Propagation

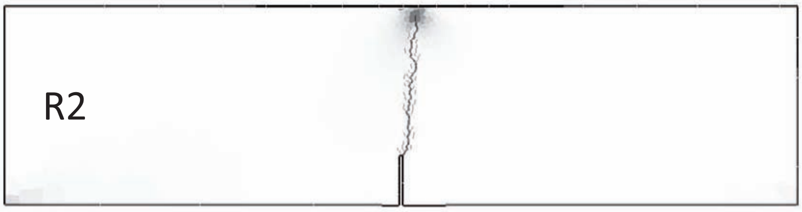
- Three-point experiment where beam has a pre-existing notch
  - Downward stress added at top center of beam
  - Beam is supported on both ends of the bottom

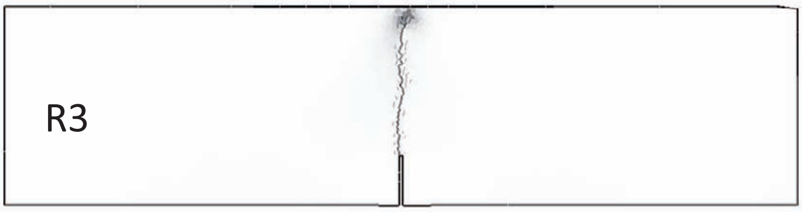


382

Non-Deterministic Process



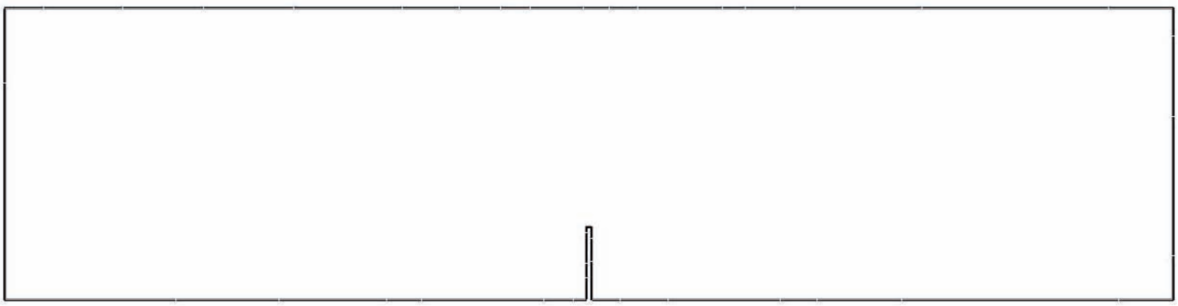


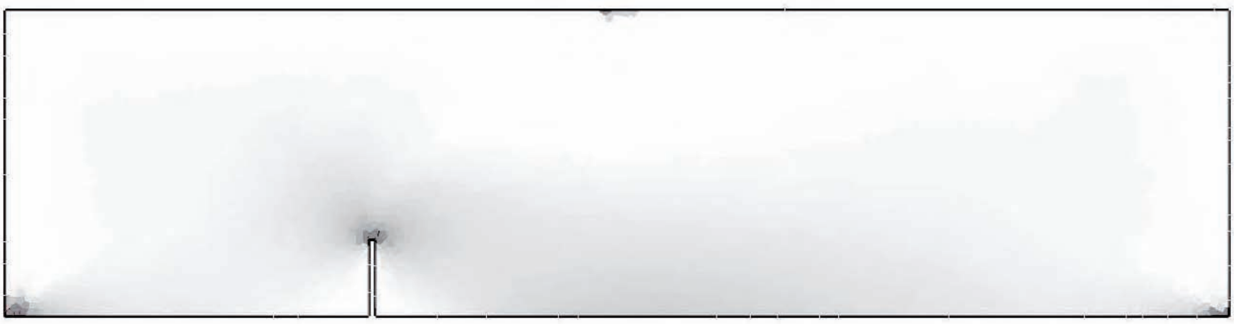


Variations in Voronoi mesh within material create variations in resulting fracture location

Results of three realizations of the mesh for the same experiment

Beam Failure Animation



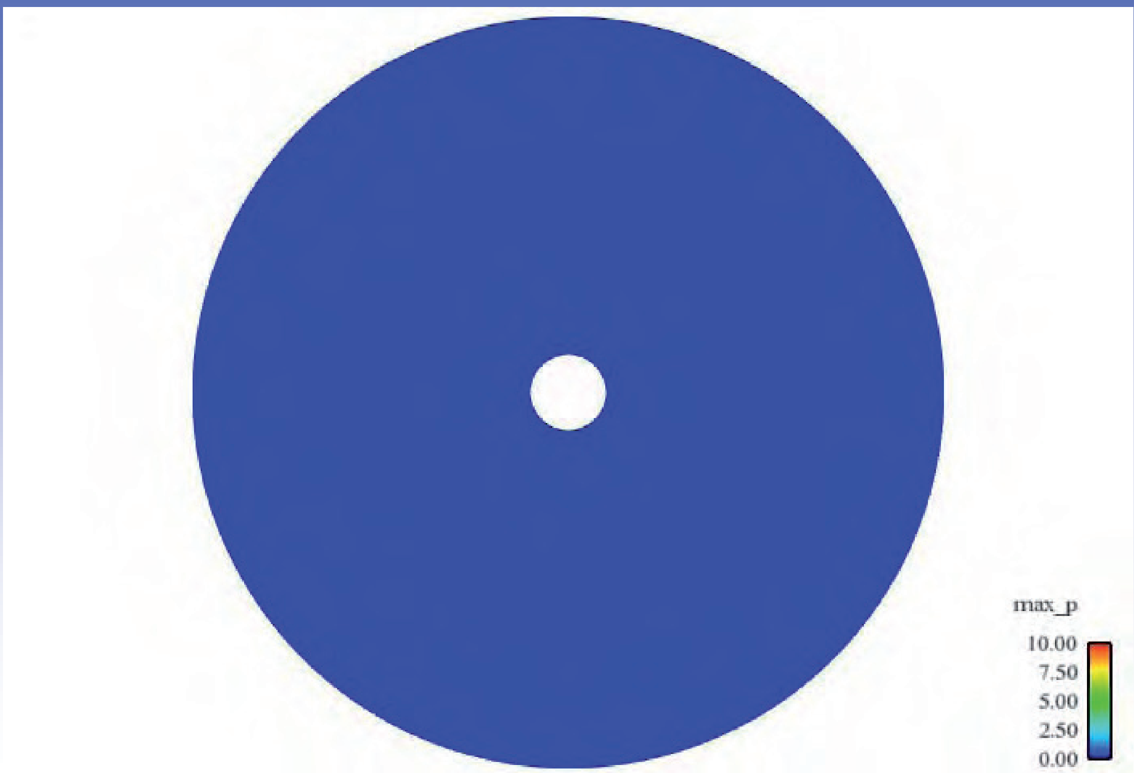


Borehole Failure

- Coupled fluids and mechanics modeling
  - Fluid pressure within borehole is increased until material surrounding borehole fractures
  - Initial models considered only mechanical forces to create fracture propagation
  - Recent work: Coupling of fluid migration and pressures into the fracture propagation model

385

Borehole Failure



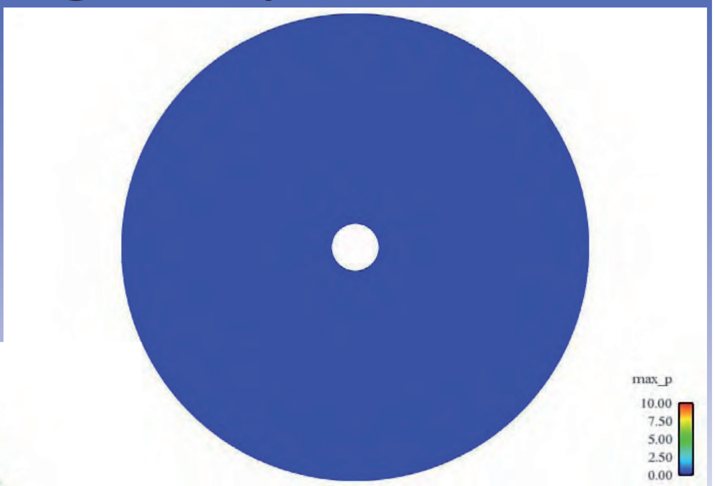
386

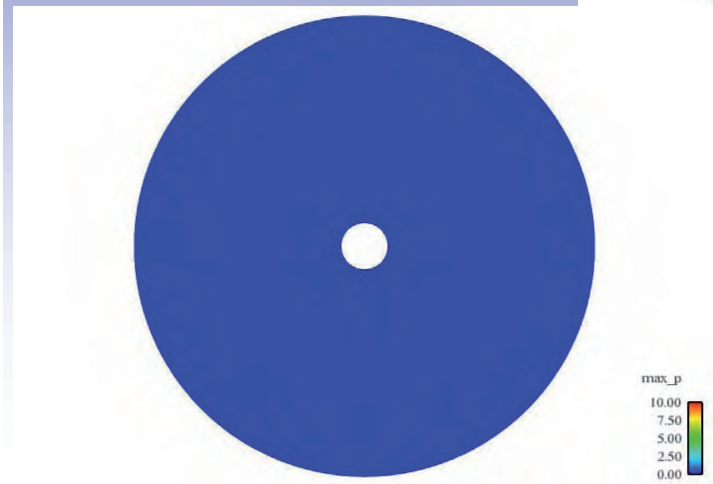
Coupled Fluid-Mechanics

- Iterative coupling between mechanics and fluid flow
  - Solid mechanics calculations (Voronoi elements) provides apertures to the fluid calculations
  - Fluid calculations solves for pressure and flow rate at the fracture network nodes – pressures are returned to the mechanics calculation
- Fluid flow uses cubic-law equations with piece-wise constant apertures

Fluid Coupling Comparison

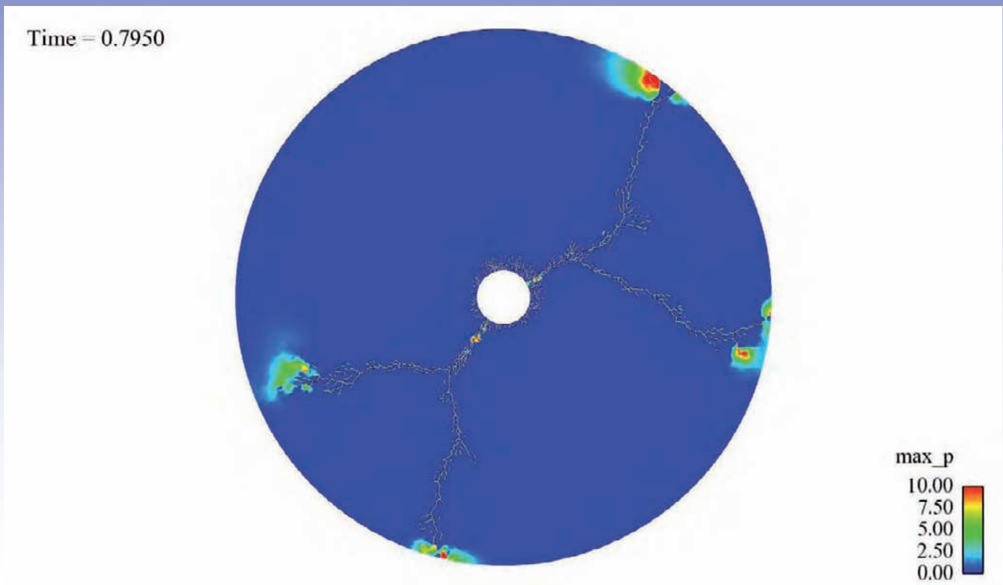
Top movie shows fracture growth without fluid coupling





Bottom movie shows fracture propagation with fluid coupling

Borehole Failure

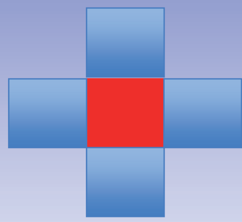


Episodic Fluid Flow in Fault Zone

- Motivation:
  - Reactivation of fault due to injection of fluids (CO_2 sequestration)
- First Step:
  - Pressure redistribution within a heterogeneous fault zone experiencing compressive stress
  - Examine impacts of heterogeneity pattern on pressure redistribution events (size and timing)

Cellular Automata (CA) Model

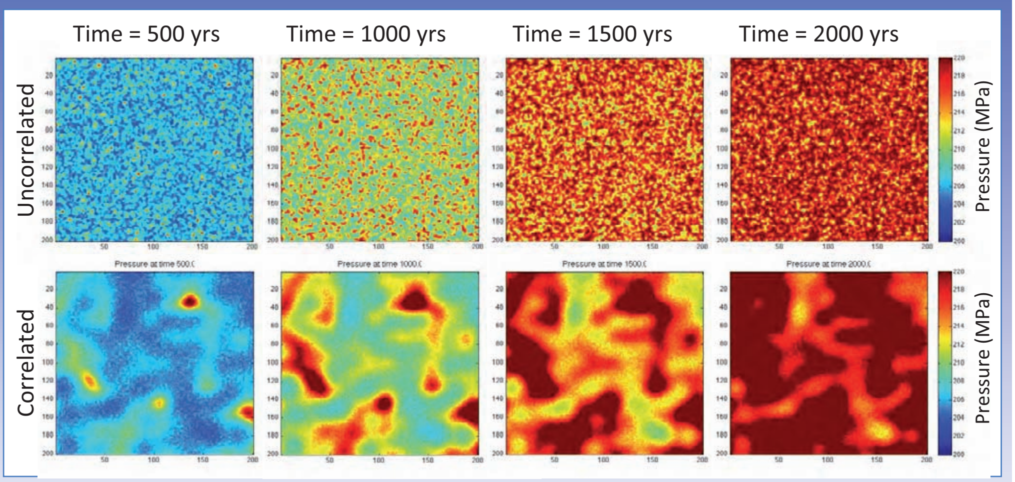
- Heterogeneous compressibility field
- Local pressure redistribution rules



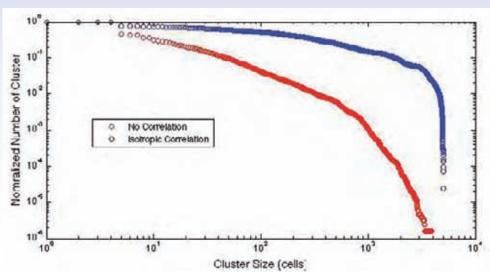
Miller and Nur, 2000, Permeability as a toggle switch in £uid-controlled crustal Processes, EPSL

CA Model Results

<u>Objective:</u>
Identify role of spatial structure of material properties in controlling episodic pressure redistribution within a heterogeneous fault zone.



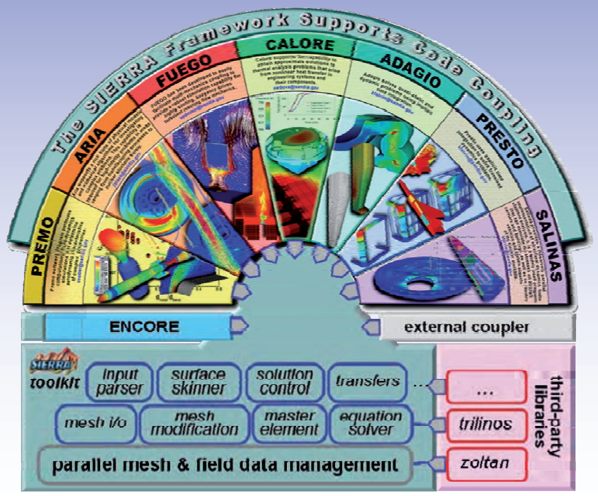
Cellular automata model used to dynamically redistribute pressure under uniform stress regime. Pressure maps (top) comparing uncorrelated and isotropically correlated rock compressibility at four times. Magnitude distributions (right) of all pressure redistribution events (clusters) up to 2500 years comparing both models.



Multiphysics Modeling for HLW

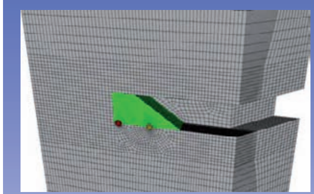
Current State-of-the-Art integrates single physics codes to achieve coarse spatial and time scale simulation…

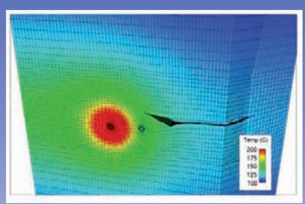
SIERRA leverages 10 years of US DOE Advanced Scientific Computing (ASC) development providing:



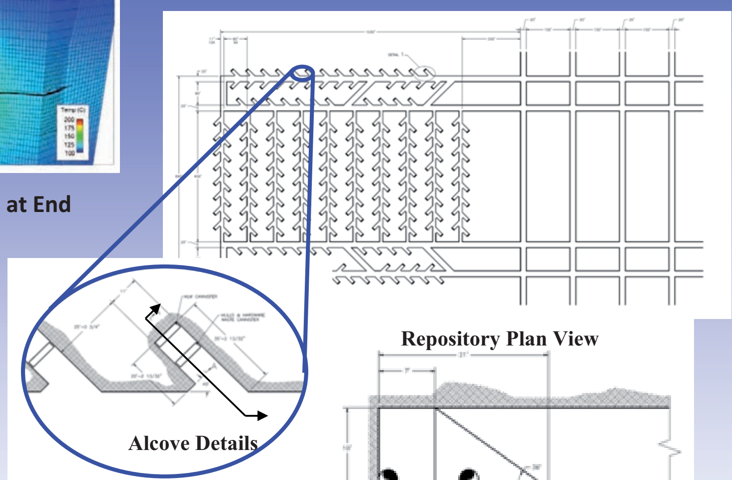
- Framework for coupled multiphysics simulation in a massively parallel environment
  - Scalability from 1 to thousands of processors on a variety of platforms
    - Launching point for fully integrated THCM with adaptive solution control

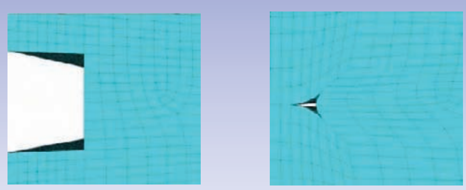
Coupled Thermal-Mechanical Simulation of a Generic Salt Repository



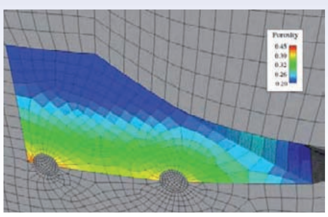


Undeformed and Deformed Storage Tunnels at End of the Simulation With Thermal Contours



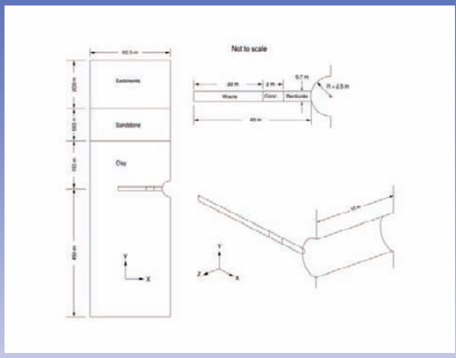


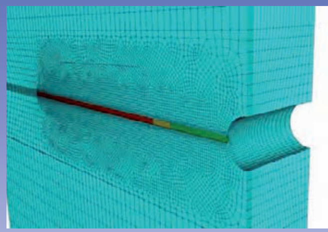
Drift Closure at the Rear Symmetry Plane



Porosity Contours in the Crushed Salt Backfill

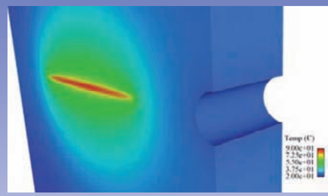
THMC Analysis of a HLW Repository

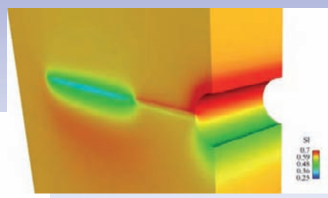




Discretization Near the Storage Horizon

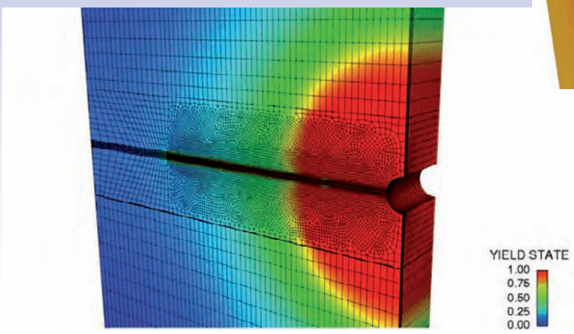
Temperature Contours





Saturation Contours

Extent of the Disturbed Rock Zone



Massively Parallel Coupled THMC Analysis

- **10,000 yr calculation**
- **Two-phase flow**
- **Non-linear material response**
- **Species transport**
- **HLW heat generation**

Summary

- Summary of recent developments in modeling natural and engineered materials
  - Voronoi polygons as an effective means of discretizing media for fracture propagation
  - Coupling of fluid pressures into dynamic mechanics models significantly impacts results (borehole failure)
  - Spatial correlation of material properties added to CA models of episodic pressure redistribution in heterogeneous faults
  - Fully coupled THMC simulation capability for HLW repositories is under development

THE NEXT GENERATION OF COMPUTING FOR WASTE DISPOSAL AND REPOSITORY ANALYSES

Sean McKenna
Sandia National Laboratories

Introduction

In its role of providing technical leadership in programs such as Yucca Mountain and the Waste Isolation Pilot Plant, Sandia has developed a robust methodology for performance assessment derived from critical parameter and process uncertainty. Sustaining this technical leadership will require integration of higher fidelity multi-physics models into the performance assessment approach that can further reduce uncertainties and provide greater confidence in performance margins.

Recent advances in massively parallel computing research have yielded platforms and codes capable of previously unfathomable levels of computational complexity and scale. Single physics models containing tens of millions of variables are now run routinely on machines throughout the DOE complex. However, in many engineering applications, these advances have highlighted limitations in the fidelity of the physics embodied in the underlying models. Predictive simulation of geologic repositories to enable engineering decision making and system performance assessments would benefit from orders of magnitude increases in fidelity of the underlying multi-scale physics. Tightly coupled Thermal-Hydrological-Mechanical-Chemical (THMC) simulation capabilities spanning the vast time and length scales characteristic of geologic repository applications are required to assess their long-term integrity.

Recent investments in the ASC SIERRA Mechanics code suite have supplied the basic building blocks for realizing this multi-physics capability for repository systems engineering. These pieces are being assembled under an existing Enabling Predictive Simulation LDRD to demonstrate an adaptive framework for addressing the disparate time and length scales associated with geomechanics problems such as storage and resource extraction. While this effort represents a substantial commitment toward supporting the geosciences community, it is important to note that it addresses only a portion of the repository systems technology needs. Such a capability is needed to provide the technical underpinnings of a performance assessment code designed to predict behavior over geologic time and length scales.

SIERRA Mechanics

The development of the SIERRA Mechanics code suite has been funded by the DOE ASC program for over ten years. The goal is the development of massively parallel multi-physics capabilities to support the Sandia engineering sciences mission. SIERRA

Mechanics was designed and developed to run on the latest and most sophisticated massively parallel computing hardware; spanning the hardware compute space from a single workstation to compute systems with 1000's of processors. The foundation of SIERRA Mechanics is the SIERRA toolkit which provides finite element application code services such as: (1) mesh and field data management, both parallel and distributed, (2) transfer operators for mapping field variables from one mechanics application to another, (3) a solution controller for code coupling, and (4) included third party libraries (e.g. solver libraries, MPI communications package, etc.).

The SIERRA Mechanics code suite is comprised of application codes that address specific physics regimes. The two SIERRA Mechanics codes which are used in the THMC coupling are Aria and Adagio. The suite of physics currently supported by Aria includes the incompressible Navier-Stokes equations, energy transport equation, species transport equations, as well as generalized scalar, vector and tensor transport equations. The saturated porous flow capability is a recent addition to Aria and multiphase porous flow is under development. Aria also has some basic geochemistry functionality available through existing chemistry packages such as Chemeq and Cantera. The mechanics portion of the THMC coupling is handled by Adagio which solves for the quasistatic, large deformation, large strain behavior of nonlinear solids in three-dimensions. Adagio has some discriminating technology that has been developed at Sandia for solving solid mechanics problems. This technology involves the use of matrix-free iterative solution algorithms that allow extremely large and highly nonlinear problems to be solved efficiently. This technology also lends itself to effective and scalable implementation on MP computers. The THMC coupling is done through a solution controller within SIERRA Mechanics called Arpeggio.

Generic Salt Repository Demonstration Calculation

A scoping study has been recently completed [1] of a generic salt repository for disposal of wastes generated by a conventional nuclear spent fuel recycling facility. Disposal in salt was the original recommendation by the National Academy of Science in 1957 for permanent isolation of heat producing radioactive waste from the biosphere. The scoping study proposed an efficient disposal strategy in which a series of panels are constructed underground. Each panel consists of individual rooms each containing many alcoves. The disposal strategy assumes placement of one waste package at the end of each alcove to be covered by crushed salt backfill for radiation-shielding of personnel accessing adjacent alcoves. The configuration is shown in Figure 1. The backfill effectively insulates the waste package, locally increasing waste package and near field repository temperatures. The thermal output for each of the vitrified borosilicate glass waste canisters is 8,400 W with decay to approximately 30% original power output at 50 years.

A three-dimensional finite element model of a single storage alcove and haulage way was developed utilizing planes of symmetry through the alcove and haulage way. The thermal model (which contained 904736 nodes and 864927 elements) extended above and below the storage horizon much further than the geomechanics model (which contained 294698 nodes and 279537 elements) due to the desire to correctly capture the thermal diffusion away from the heat source. The two different domains and mesh discretizations utilized the field transfer operators in the SIERRA toolkit to pass interpolated nodal temperature and displacement data between Aria and Adagio. The coupling of the solutions, which were run on 96 processors, was accomplished using the Arpeggio controller.

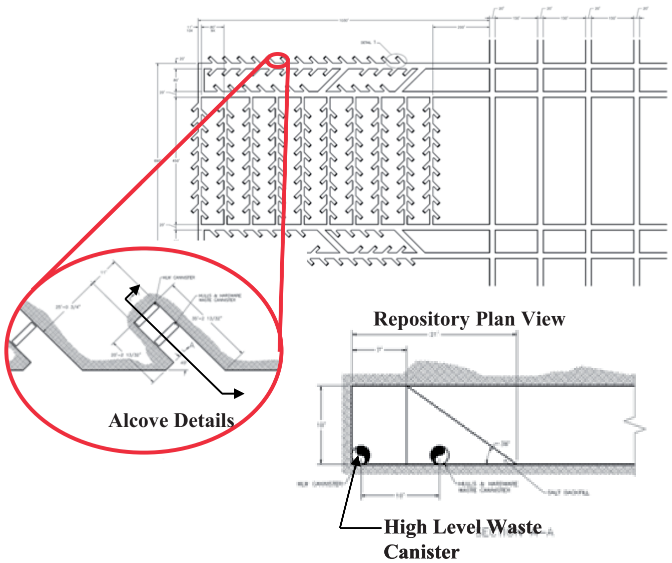


Figure 1. Generic salt repository configuration modeled in current study

Some of the discriminating features of these thermal/mechanical analyses include the use of thermal contact surfaces to model the effect of room closure on the thermal conduction that occurs as the room surfaces deform and come into contact. The mechanical effect of the large deformation is also captured through the use contact surfaces in the mechanical calculation. In addition, the effect of thermal radiation between heated surfaces within the alcove and haulage way is modeled using the capability within Aria to recompute the radiation view factors as the surfaces deform. The mechanical response of the salt is modeled using a power law secondary creep model with an Arrhenius term to account for increases in creep strain rate due to temperature. The compaction behavior of the crushed salt backfill is modeled with a nonlinear pressure vs. volume strain relationship. The thermal properties of the crushed salt backfill

were those corresponding to uncompacted salt. This assumption produces higher waste and salt temperatures than would be calculated assuming the crushed salt to have intact salt thermal properties.

A deformed mesh plot with contours of temperature is shown in Figure 2 at 27 years after waste emplacement. The haulage way and alcove are almost completely closed by 27 years. The need for the large deformation, large strain mechanics formulation is clearly shown by the magnitude of the deformation. The maximum temperature in the waste canister is 622 C which occurs at 2.27 years. The maximum temperature at the canister/salt interface is 408 C occurring at 4.0 years. Figure 3 shows a color fringe plot of porosity in the crushed salt backfill at a time of 27 years. The crush salt backfill develops a non-uniform porosity with most of the compaction occurring near the roof of the alcove. This variation of compaction of the backfill from higher at the roof to lower near the floor is in qualitative agreement with measurements of porosity in the backfill made in the Bambus II project [2]. The minimum porosity is 0.124 which is substantially reduced from the initial emplaced value of 0.42.

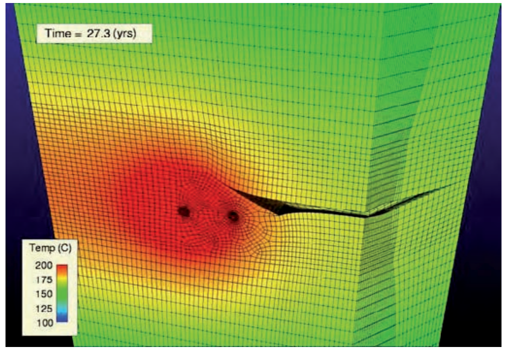


Figure 2. Colored fringe plot of temperature in the deformed salt repository at 27 years.

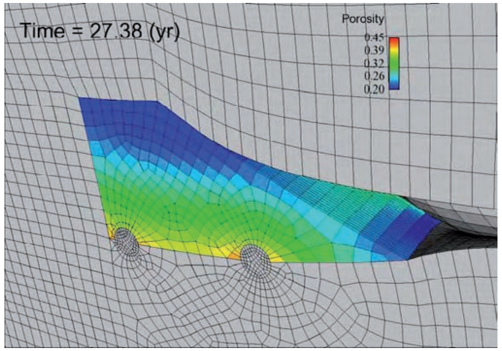


Figure 3. Color fringe plot of porosity in the crushed salt backfill at 27 years. Initial porosity was 0.42.

Gap Assessment for High Fidelity Multi-Physics Geologic Modeling

The ASC investment in platform and code technology through SIERRA Mechanics offers an excellent starting point toward revolutionizing the computational modeling of geologic repositories. In order to capitalize on this opportunity, new capabilities must be developed in the core areas of constitutive modeling for geologic materials, probabilistic methods incorporating inherent heterogeneity, and robust techniques for coupling and solving models of inseparable physical phenomena.

Constitutive Models

The current suite of constitutive models needs to be updated to incorporate new models and capabilities as a result of the multiphysics coupling. In addition, there will be a need to develop new models as the codes are applied to new classes of subsurface problems, different materials, and higher temperatures and pressures than were originally envisioned. The inclusion of damage and failure of the rock will become very important as we look at coupling flow in the subsurface.

Pressure and temperature conditions in subsurface repository environments combined with higher salinity pore fluids, corrosive gases, and potential biological activity require complex treatments for predictions of rock, waste, fluid and chemical interaction. There is a clear need for a quantitative “partial equilibrium” approach for predictions that couple the appropriate kinetic and transport descriptions to enable a full description of geochemical-biological activity across relevant length and time scales.

Probabilistic Modeling Techniques

Geologic materials are inherently heterogeneous and highly spatially variable. Faults and fracture are examples of geologic features that can have a profound effect on the motion of fluids and the mechanics of the region. The true spatial distribution of transport properties, for example, can not be uniquely determined with the sparse information taken from a few well logs. Geostatistical representation of properties, conditioned on available data, is one approach that should be developed as a seamless piece of the Sierra toolkit available to the user.

Likewise, methods and techniques are necessary for quantifying the uncertainty in flow responses due to uncertainty in geologic formation properties. Conventional approaches involving Monte Carlo sampling of numerous realizations of rock attributes and subsequent flow modeling using these realizations is computationally expensive. Another approach researched at SNL is the reformulation of flow equations in the form of stochastic partial different equations (PDEs). Continued development of these tools to address uncertainty, both local and spatially correlated, should be harnessed as an integral part of a leading edge simulation tool.

Multi-Physics Coupling Techniques

Geosystem simulation requires accurate models of a large array of coupled, subsurface processes acting on many scales. Efficient and robust coupling algorithms are essential to enabling the new multiphysics capability envisioned for advanced repository engineering. We have several promising approaches that need to be investigated.

A key ingredient in our approaches is to couple modules for multiphase heat and mass flow, mechanics, and chemistry. Successful coupling of flow and geochemistry over length scales from pore-scale (microns in geochemistry) to regional scale (km in mechanics) remains a problem-dependent art in the few models that have attempted this problem. The ability to use different grids, each suitable for its particular physics module (flow, geochemistry, or mechanics), facilitates numerically resolving phenomena particular to that set of physics. The grid transfer technology in SIERRA needs to be extended to allow transfer between partially overlapping grids composed of heterogeneous element types.

There is also a need to develop sub-time integration, enabling time resolution of phenomena with disparate time scales. This would allow user-defined nonlinear solution control of segregated methods, including the option of a fully coupled solution. This enables unfettered exploration of segregation schemes initially for choosing efficient strategies for different kinds of multiphysics problems. It is also necessary to provide fully and partially coupled Newton schemes applicable to the full system or a segregated subset.

References

1. Washington Savannah River Company, Washington Safety Management Solutions, Sandia National Laboratory and Los Alamos National Laboratory. 2008. A Generic Salt Repository for Disposal of Waste from a Spent Nuclear Fuel Recycling Facility. PREDECISIONAL DRAFT Rev 1. September 2008. GNEP-WAST-MTSD-MI-RT-2008-000245

2. Bechtold, W., Smailos, E., Heusermann, S., Bollingerfehr, W., Bazargan Sabet, B., Rothfuchs, T., Kamlot, P., Grupa, J. Olivella, S., and Hansen, F.D., Backfilling and sealing of underground repositories for radioactive waste in salt (Bambus II project), EUR 20621 EN, European Commission, Directorate-General for Research, Unit J.4 – Nuclear fission and radiation protection, Luxembourg, 2004

Generic Salt Repository Analysis

Showcasing SIERRA Mechanics

The Next Generation of Computing for Waste Disposal and Repository Analyses

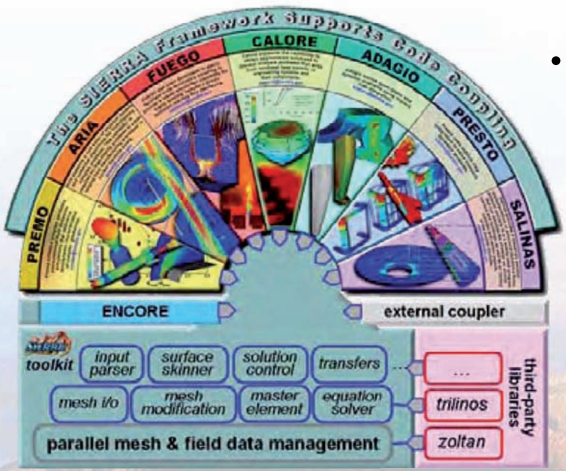
Sandia National Laboratories

September, 2009

SIERRA Mechanics represents enabling capability for repository simulation

Current SOA integrates single physics codes to achieve coarse spatial and time scale simulation…

SIERRA leverages 10 years of ASC development providing:

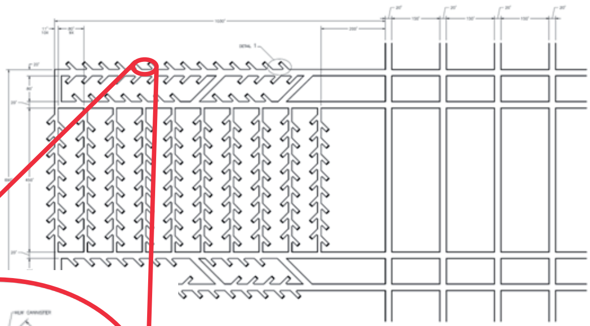


- Framework for coupled multiphysics simulation in a massively parallel environment
- Scalability from 1 to thousands of processors on a variety of platforms
- Launching point for fully integrated THCM with adaptive solution control

Sample Demonstration: Coupled Thermal-Mechanical Simulation of Generic Salt Repository

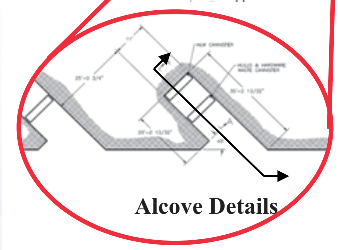
Sample Geometry:

- Configuration based on a 2008 Savannah Rive study
- Vitrified borosilicate glass high level waste canister with output 8.4 kW

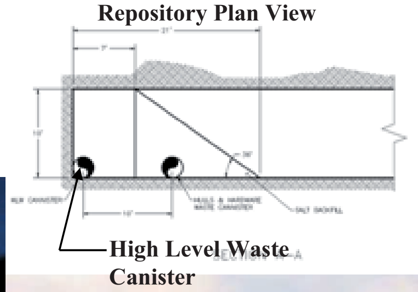


Technical challenges:

- High Thermal Gradients
- Temperature dependent material properties
- Large Deformation Salt Creep behavior
- Contact modeling with heat conduction and load transfer
- Long duration simulation to room closure



Repository Plan View



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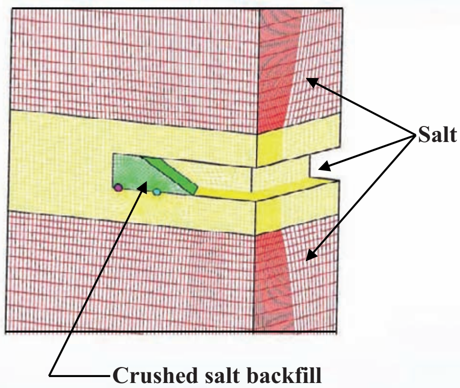
Sierra Mechanics Simulation of Alcove Closure



- Three-dimensional fully coupled thermal/mechanical analysis
- Massively Parallel Calculation - 96 processors
- Dissimilar meshes and domains for thermal and structural mechanics
- Contact surfaces used for both thermal and structural problems

Thermal Analysis Features:

- 904736 nodes / 864927 elements
- Contact surfaces used to accommodate heat conduction between contacting surfaces (alcove and haulage way)
- Re-computation of radiation view factors for deforming heated room surfaces

Structural Analysis Features:

- Quasistatic analysis with 294698 nodes / 279537 elements
- Large deformation, large strain formulation
- Nonlinear power law secondary creep model for salt
- Volumetric compaction model for the crushed salt
- Contact surfaces defined to allow arbitrary roof, rib, and floor contact
- Temperature dependent material properties

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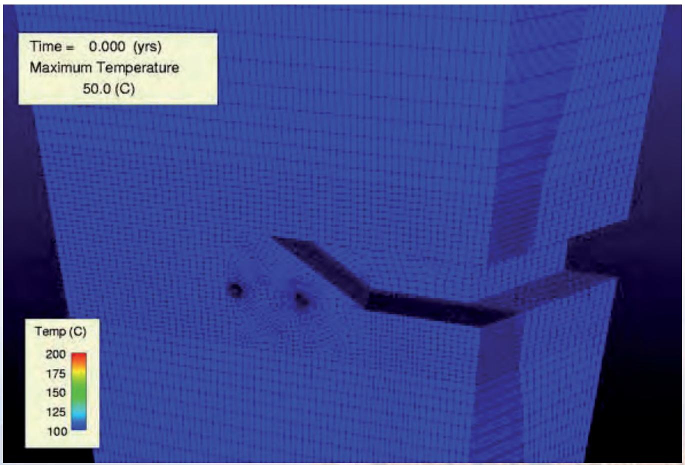
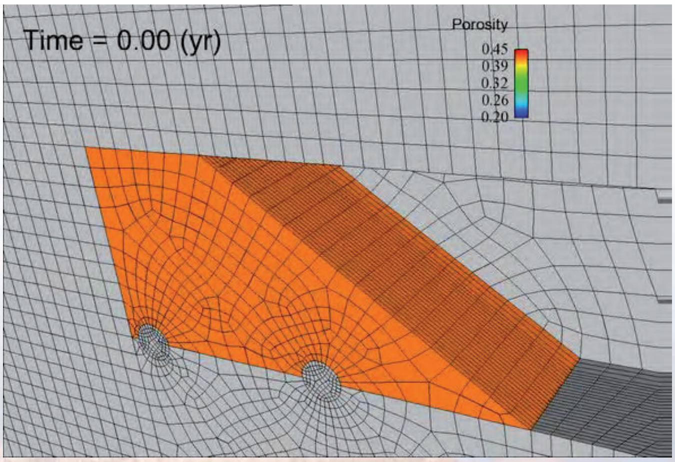
Analysis Results

- Maximum salt temperature 407 C (canister/salt interface)
- Haulage way floor/ceiling contact at 21 years
- Closure modes are different for haulage way and alcove
- Full closure predicted by 27 years
- Minimum crushed salt porosity at 27 years 12.4% (original 42%)



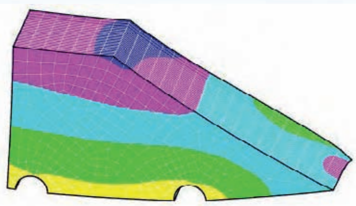
Repository Temperature Contours



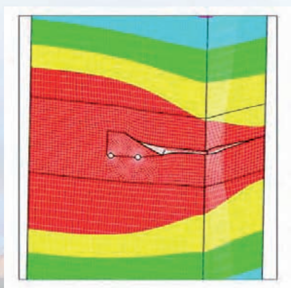
Crushed Salt Backfill Porosity Contours

THCM development needs

Constitutive Models
- Geomaterial constitutive models for multiphysics coupling
- Coupled kinetic and transport descriptions for geochemical-biological activity across relevant length and time scales
- Computational and experimental investigation of repository phenomena



Multi-Physics Coupling Techniques
- Efficient and robust coupling algorithms for subsurface processes across many scales
- Grid transfer technology to allow different physics to use appropriate grids composed of heterogeneous element types
- Integration techniques for disparate time scales



Probabilistic Modeling Techniques
- Geostatistical representation of properties conditioned on available data within SIERRA framework
- Continue to research and develop methods for quantifying uncertainty in flow responses due to uncertainty in geologic properties

RESEARCH ON GEOCHEMICAL ASPECTS OF NUCLEAR WASTE DISPOSAL

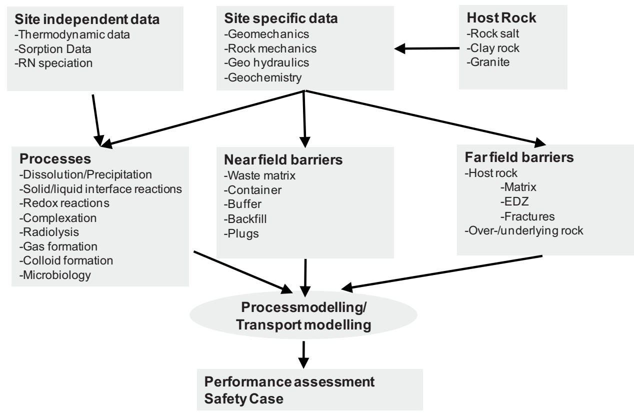
Horst Geckeis
Institut für Nukleare Entsorgung, Karlsruher Institut für Technologie, Postfach 3640,
76021 Karlsruhe, (E-mail: geckeis@ine.fzk.de)

Introduction

The investigation of chemical and geochemical aspects of nuclear waste disposal must be discussed for the performance assessment within the ‚safety case' for any geological nuclear waste disposal project. The importance of 'chemical scenarios', where radionuclide release and retention in repository barriers via aquatic pathways are taken into account, depends on the respective disposal concept and the relevance of water intrusion scenarios. Nuclear waste disposal in rock salt is considered to offer specific advantages. High heat conductivity offers the possibility to construct a compact repository for heat producing waste. High plasticity minimizes the probability of water access to emplacement caverns through factures due to the pronounced self healing capabilities of rock salt. In general, one can deduce that probability of water access to the waste for the ‚expected evolution' of a repository in rock salt formations is low. The challenge of furnishing scientific proof of a nuclear waste repository safety is the long time scales of hundred thousands of years which have to be considered. This requires the examination of even less likely scenarios, which tentatively could lead to radionuclide release by limited water access through residual permeabilities in backfill material, or plugs and sealings or from fluid inclusions present in the host rock. Furthermore, pathways for water access can be created by human intrusion after closure of the repository.

Chemical aspects of the safety case for nuclear waste disposal

Radionuclide release from a repository and the potential radiation dose for the population can be estimated for each considered scenario by applying an appropriate transport model. Chemical and geochemical data represent important input parameters. The implementation of site independent and site specific chemical data and parameters into performance assessment considerations is schematically shown in the figure below. A multitude of chemical and geochemical reactions can lead to both radionuclide mobilization and retention in a repository system. After corrosion of waste container walls corrosion of the waste form starts. Corrosion and radionuclide release rates are then quantified as ‚source term'. Underlying reactions are, however, very complex. Radionuclide dissolution in the repository near field is controlled by radiolysis, coupled redox reactions and secondary phase formation. Notably the long-lived radiotoxic transuranium elements, Pu, Am, Np undergo retention through precipitation of secondary solid phases. Reduction of redox sensitive long-lived radionuclides such as U, Pu, Np, Se and Tc are currently intensely investigated [1]. Container corrosion and the concomitant evolution of hydrogen overpressure creates low redox potentials and thus in general low solubilities for those radionuclides and low spent fuel corrosion rates. Understanding of redox reactions has very much improved during the last years (e.g. [2]) and respective reliable thermodynamic data on solubilities and complexation reactions with groundwater ligands become increasingly available (e.g. [3]).



Chemical and geochemical aspects in performance assessment [4].

Radionuclide retention has been long time almost exclusively considered as surface sorption phenomenon represented by a solid-liquid distribution factor Kd. This view has turned out to be much too simple. Detailed chemical, spectroscopic and modeling studies have demonstrated that various mechanisms are responsible for sorption reactions, which vary depending on the given geochemical milieu. Advanced mechanistic sorption model approaches allow for some systems, e.g. radionuclide sorption in clay rock [5], prediction of so called 'smart Kd-values' as a function of different ground- and porewater chemistries. Furthermore, it has turned out that mineralization reactions such as formation of solid-solutions become active retention mechanisms in various repository barriers (e.g. radionuclide interaction with cementitious phases and calcite as a major constituent of sedimentary rock). In many cases thermodynamic data for such phases are not yet available and their derivation is presently subject of international research projects (e.g. [6]). Structural incorporation into mineral phases is believed to play a major role as a chemical barrier in the near- and far field of a nuclear waste repository. Mobilization of notably the polyvalent actinide ions by colloid formation has also been a focus of recent investigations and still represents a matter of discussion. Obviously polymeric and colloidal species have to be considered as relevant species in solubility studies [7]. They increase the maximum actinide concentration in solution under given chemical conditions. However, stability of colloidal species and their mobility rendering them as possible transport vectors for radionuclides appear to be low under highly saline conditions [8].

Conclusions

Reliable data being appropriate to allow predictions on radionuclide behaviour over long time scales cannot be obtained by simple extrapolation of phenomenological data. A fundamental molecular understanding of processes can be achieved by appling state-of-the-art spectroscopic and theoretical tools and methods. Data have to be in addition validated in up scaling field experiments and if possible by natural analogue investigations. Recent research activities have in general revealed various additional chemical barrier functions in a repository system, which can efficiently hold back radionuclides even if water accesses the waste. Radionuclide interaction with corroding container material, plug and seal constituents, and retention by mineralization reactions are currently investigated and have to be quantified in ongoing research activities.

References

[1] European community research project: Redox phenomena controlling systems (RECOSY), (www.recosy.eu)
[2] Neck V., Altmaier M, Fanghänel Th. (2007), Comptes Rendus Chimie, 10, 959
[3] NEA-OECD, (2003), Update on the chemical thermodynamics of uranium, neptunium, plutonium, americium and technetium, compiled by Guillaumont, R., Fanghänel, Th, Fuger, J., Grenthe, I., Neck., V., Palmer, D.A., Rand, M.H., edited by Mompean, F.J., Illemassene, M., Domenech-Orti, C., Ben Said, K., Elsevier, Amsterdam.
[4] Geochemische Forschungsfelder für den Sicherheitsnachweis zur Endlagerung hochradioaktiver Abfälle, GRS, FZD, FZJ, KIT, October 2008
[5] Bradbury, M.H., Baeyens, B., (2006), A quasi-mechanistic non-electrostatic modeling approach to metal sorption on clay minerals, in Lützenkirchen, J. (ed.), Surface complexation modelling, Interface Science and Technology, Vol. II, Academic Press, Elsevier, Amsterdam, p. 518-538
[6] Helmholtz Virtual institute, “"Advanced Solid-Aqueous RadioGeochemistry", (www.fzk.de/fzk/idcplg?IdcService=FZK&node=2707&document=ID_064225)
[7] Neck, V., Altmaier, M., Seibert, A., Yun, J.I., Marquardt, C.M., Fanghänel, Th. (2007), Solubility and redox reactions of Pu(IV) hydrous oxide : Evidence for the formation of PuO2+x(s, hyd), Radiochim. Acta, 95, 193-207
[8] Schäfer Th., Noseck U. (Eds.), Colloid/ Nanoparticle formation and mobility in the context of deep geological nuclear waste disposal, (Project KOLLORADO; Final report), Karlsruhe Institute of Technology, Scientific reports, FZKA 7515, 2010

KIT
Karlsruhe Institute of Technology

Research on geochemical aspects of nuclear waste disposal

Institute for Nuclear Waste Disposal (INE)

Horst Geckeis

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-28, 2010
Jackson, Mississippi USA

KIT
Karlsruhe Institute of Technology

Chemistry/geochemical aspects in nuclear waste disposal

- are to be discussed in the ‚safety case‘ of any geological nuclear waste disposal project!

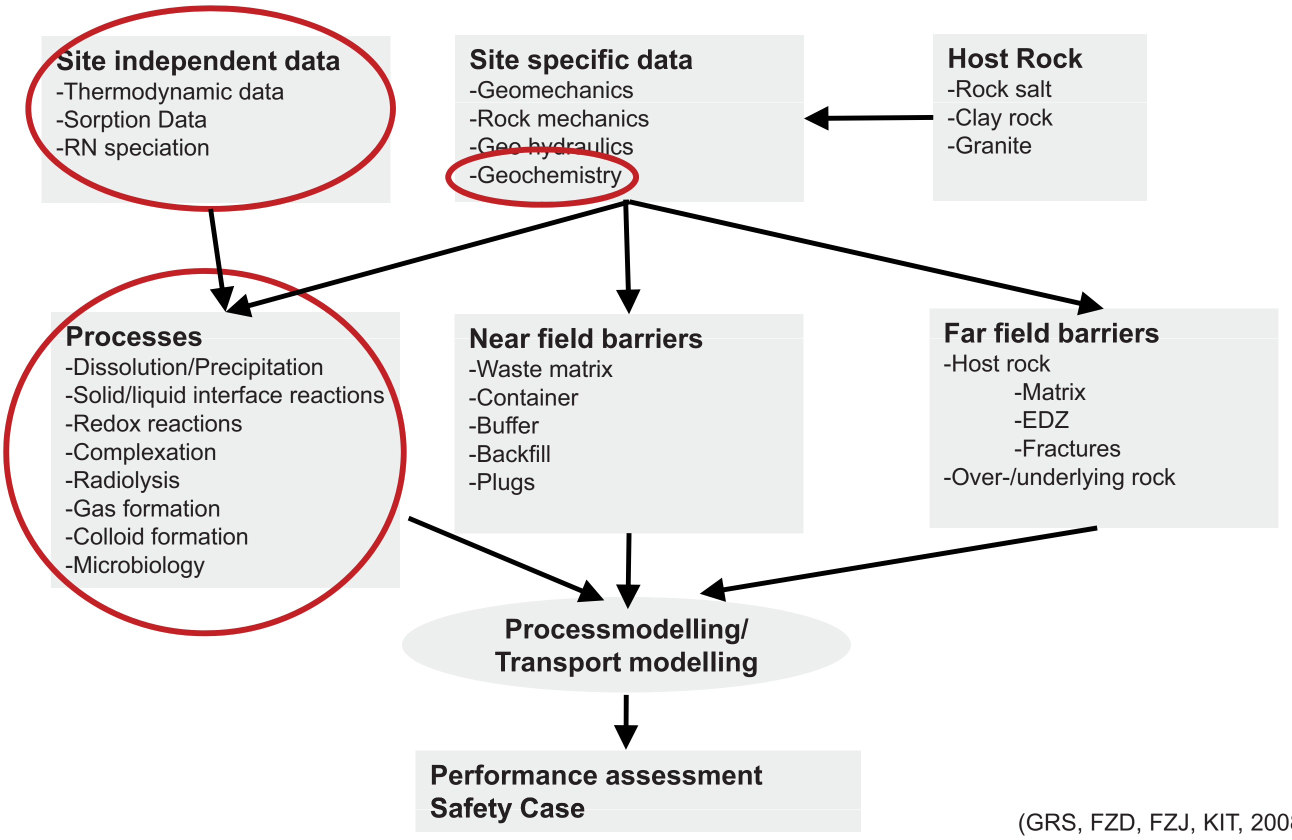
- become relevant, if water comes into the game!

- Water intrusion scenario for the ‚expected evolution‘ of a repository have different relevance depending on the disposal concept

(clay rock~granite >rock salt)

Components of the ‚Safety Case‘

Chemical and geochemical aspects



(GRS, FZD, FZJ, KIT, 2008)

Chemical and geochemical aspects

Dissolution and solubility constraints

Redox reactions: determining geochemical behaviour of actinides and fission products

Colloids: enhancing radionuclide solubility and mobility?

Radionuclide retention in repository barriers

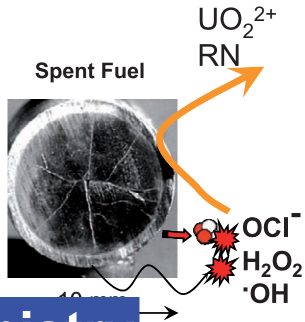
Geochemical research needs and benefits

Geochemistry Research in Nuclear Waste Disposal

KIT Karlsruhe Institute of Technology

$$r = k_0 \times A_{min} \times e^{-E_a/RT} a_{H^+}^{n_{H^+}} \, g(I) \prod_i a_i^{n_i} f(\Delta G_r)$$

Dissolution, RN-Release



Source Term

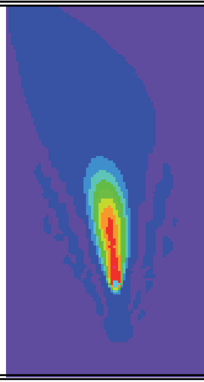
Geochemistry

$$-u\frac{\partial c_i}{\partial t} + D\frac{\partial^2 c_i}{\partial x^2} - \frac{\rho}{\theta}K_d\frac{\partial c_i}{\partial t} = \frac{\partial c_i}{\partial t}$$

$$D_a = \frac{D}{\varepsilon + \rho K_d}$$

Advection dispersion

Diffusion



Migration

419

Dissolution and solubility constraints

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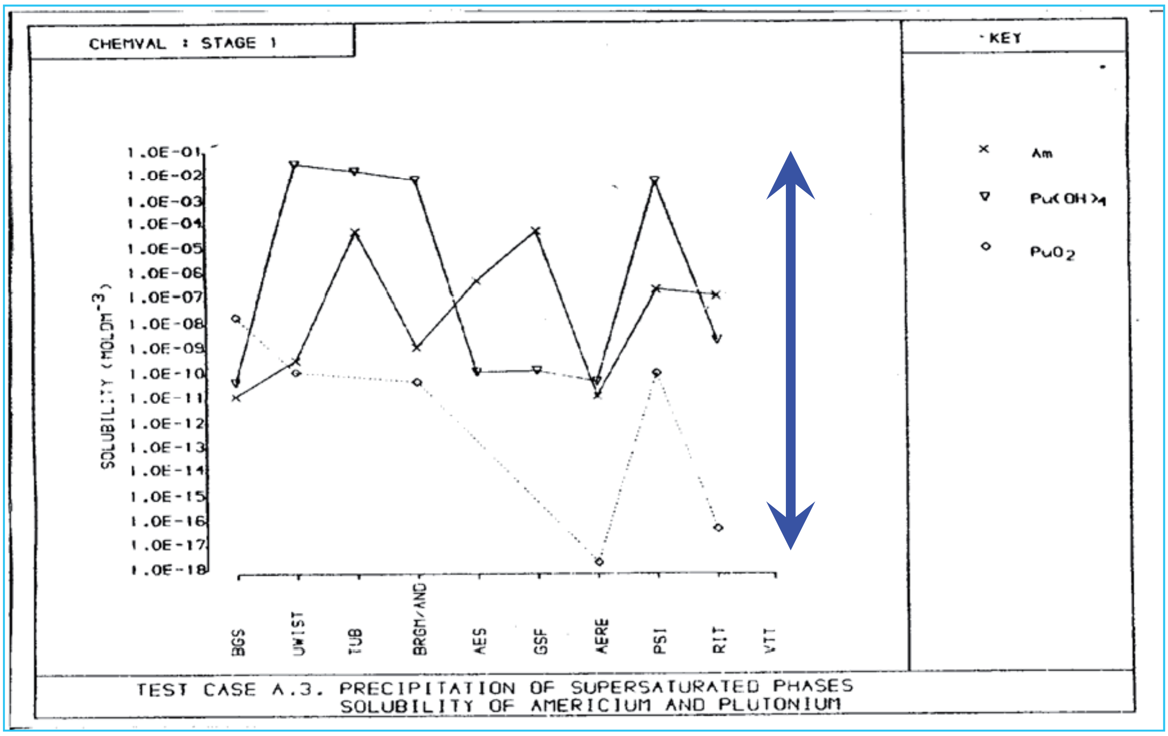
- Solubility of actinides (20 years ago) -

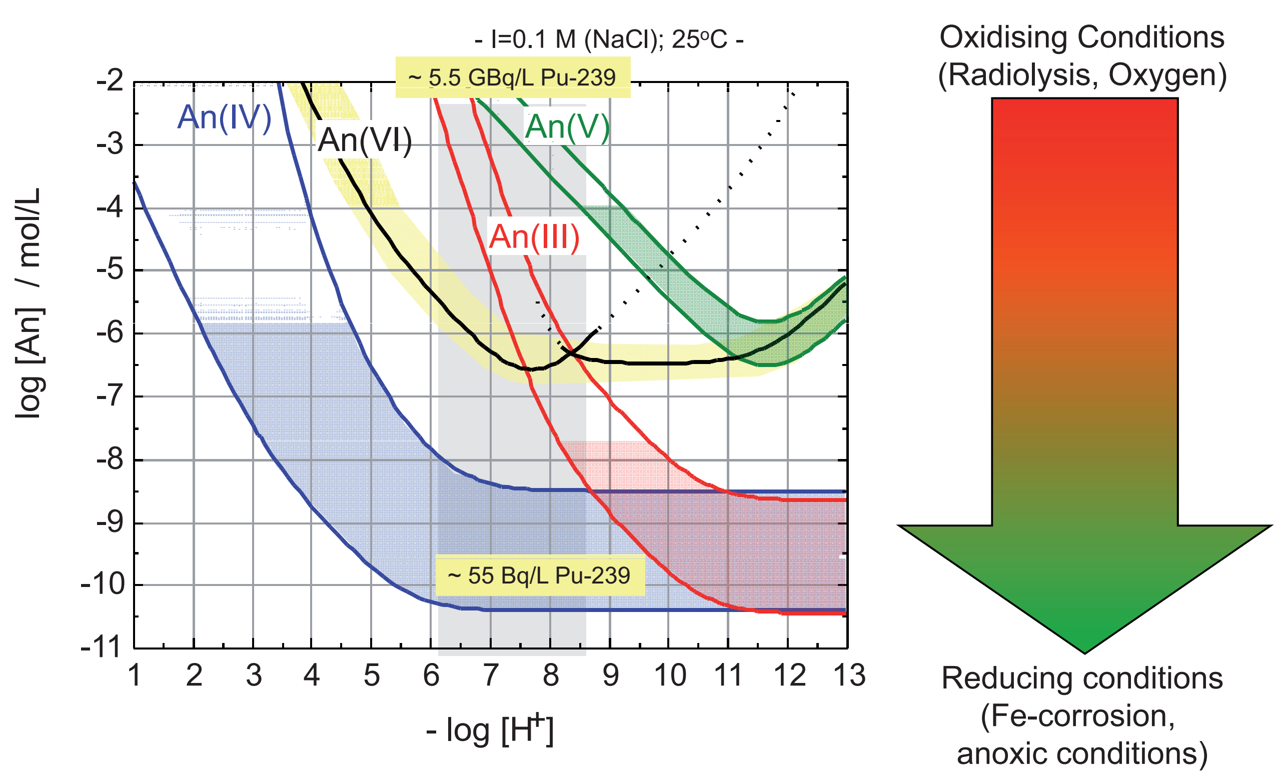


(From CEC Report EUR 12237 en (1989): CHEMVAL Project Stage 1: Verification of speciation models)

420

Dissolution and solubility constraints

- Solubility of Actinides (today) -



Neck, Fanghänel et al. FZK-INE 001/01

Dissolution and solubility constraints

PITZER parameters for An(III) species in the system An(III)-Na-Mg-Ca-Cl-H_2O (from [97KÖN/FAN], [98NEC/FAN] and present work) are based on auxiliary data and parameters for other ions from Harvie, Moller and Weare [84HAR/MOL].

Binary parameters					Ternary parameters			
i	k	$\beta^{(0)}_{ik}$	$\beta^{(1)}_{ik}$	C^{ϕ}_{ik}	j	θ_{ij}	Ψ_{ijk}	
An^{3+}	Cl^-	0.5856	5.60	-0.016	Na^+	0.10	0	
					Ca^{2+} (Mg^{2+})	0.20	0	
$AnCl^{2+}$	Cl^-	0.593	3.15	-0.006	Na^+	0	0	
					Ca^{2+} (Mg^{2+})	- 0.014	0	
$AnCl_2^+$	Cl^-	0.516	1.75	0.010	Na^+	0	0	
					Ca^{2+} (Mg^{2+})	- 0.196	0	
$AnOH^{2+}$	Cl^-	0.055	1.81	0	Na^+	0	0	
					Ca^{2+} (Mg^{2+})	0	0.04	p.w.
$An(OH)_2^+$	Cl^-	*(-0.414)*	0	0	Na^+	0	0	
		- 0.13			Ca^{2+} (Mg^{2+})	0.29	0.07	p.w.
$An(OH)_4^-$	K^+ (Na^+)	0.00	0	0	Cl^-	0	0	p.w.
	Ca^{2+} (Mg^{2+})	0	0	0	Cl^-	0	0	p.w. *
$Ca[An(OH)_3]^{2+}$	Cl^-	0.21	1.6	0	Ca^{2+}	0	0	p.w.
$Ca_2[An(OH)_4]^{3+}$	Cl^-	0.70	4.3	0	Ca^{2+}	0	0	p.w.
$Ca_3[An(OH)_6]^{3+}$	Cl^-	0.37	4.3	0	Ca^{2+}	0	0	p.w.

i	k	λ_{ik}		
$An(OH)_3$(aq)	Cl^-	*(- 0.2)*	0	p.w.
	Na^+	*(- 0.2)*	- 0.17	p.w.
	Ca^{2+} (Mg^{2+})		0 *	p.w. *

* Strong interaction with Ca^{2+} must be expressed in terms of ternary Ca-An(III)-OH complex formation

Chemical and geochemical aspects

Dissolution and solubility constraints

Redox reactions: determining geochemical behaviour of actinides and fission products

Colloids: enhancing radionuclide solubility and mobility?

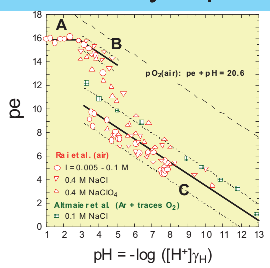
Radionuclide retention in repository barriers

Geochemical research needs and benefits

Redox reactions of radionuclides

- Redox chemistry of Plutonium -

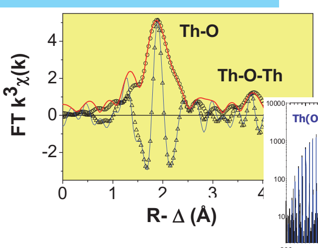
Wet chemistry experiments

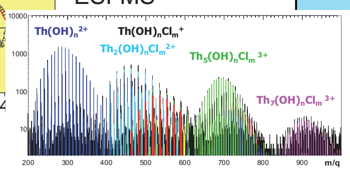


Solubility studies

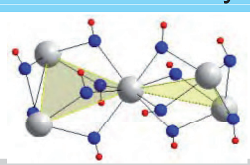
Spectroscopy

UV/VIS
CE-ICP-MS
LIBD
EXAFS/XANES
ESI-MS



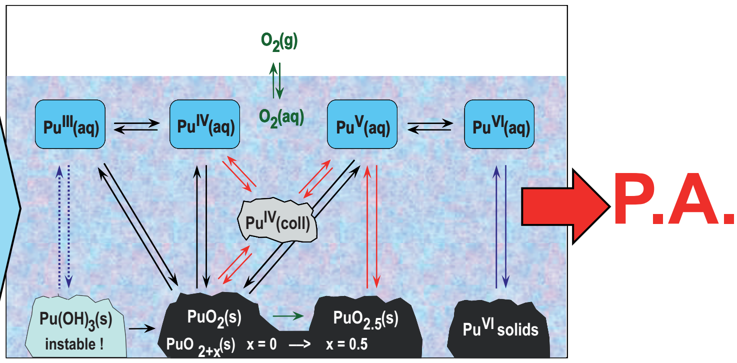


Theoretical chemistry



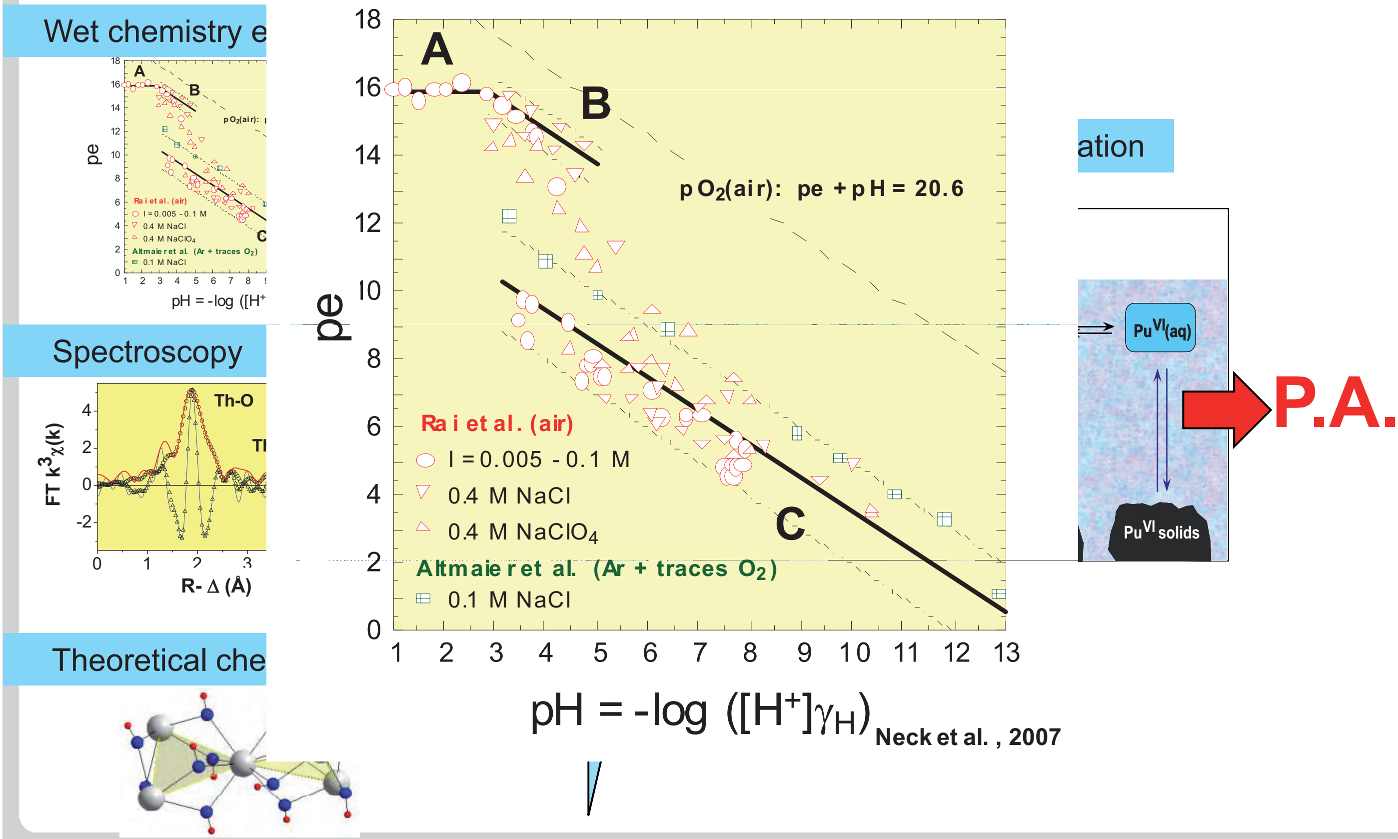
QC

Thermodynamic interpretation



Redox reactions of radionuclides

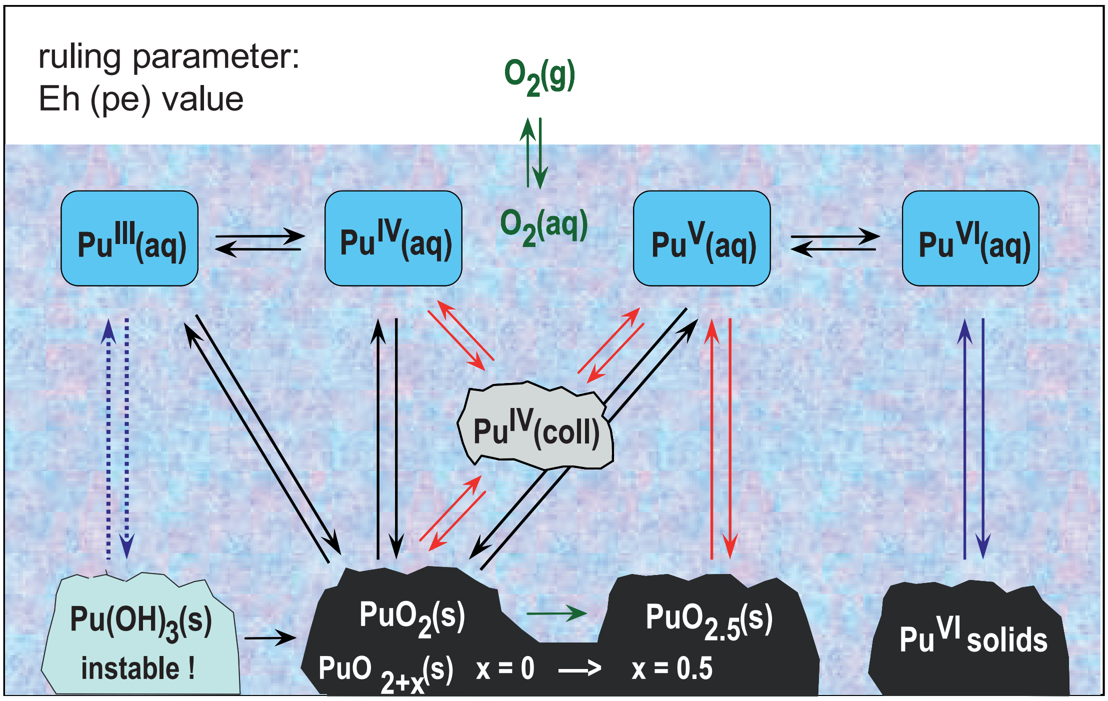
- Redox chemistry of Plutonium -



Neck et al. , 2007

Redox reactions of radionuclides

- Redox chemistry of Plutonium -



Significant improvement in understanding and quantification of Pu-redox chemistry

Neck et al., Comptes Rendu, 2007

Chemical and geochemical aspects

Dissolution and solubility constraints

Redox reactions: determining geochemical behaviour of actinides and fission products

Colloids: enhancing radionuclide solubility and mobility?

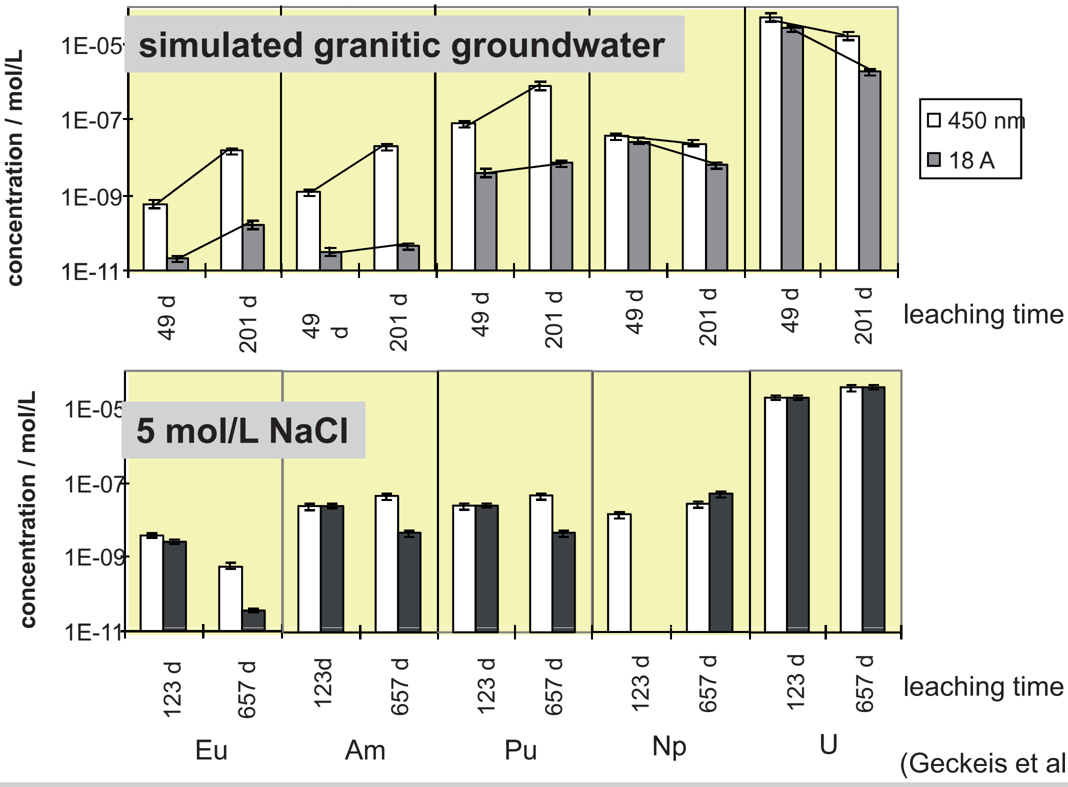
Radionuclide retention in repository barriers

Geochemical research needs and benefits

Colloids: enhancing radionuclide solubility and mobility?

Leaching of powdered spent-fuel

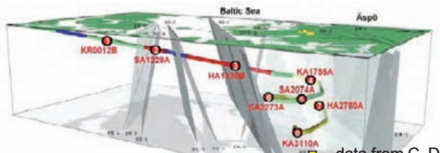
[UO_2; burn-up: 50 MWd/kg U; γ-dose rate: ~ 10 Mrad/h; S/V=1000 m^{-1}) at 25°C]

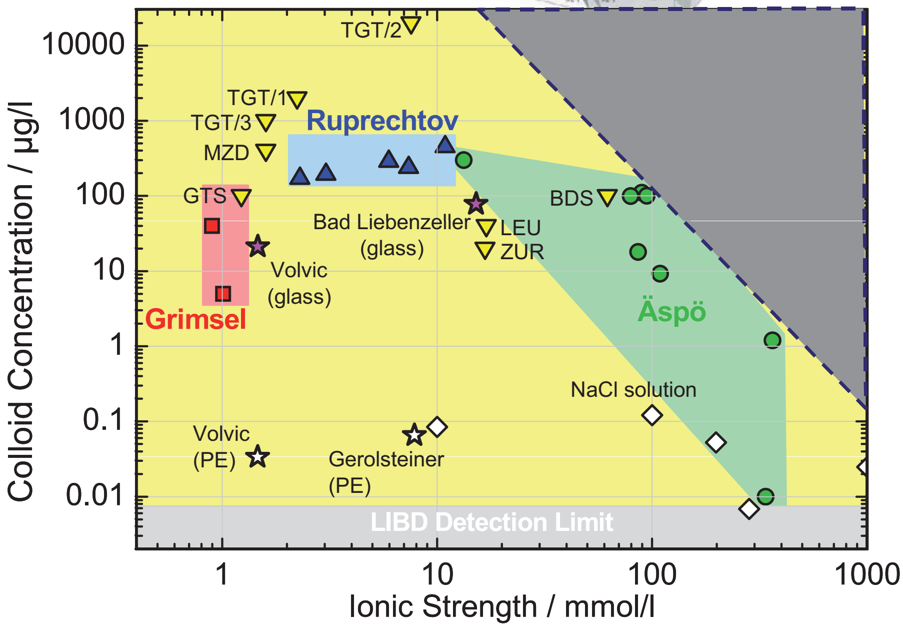


(Geckeis et al. RCA, 1999)

Colloids: enhancing radionuclide solubility and mobility?

- Field studies -





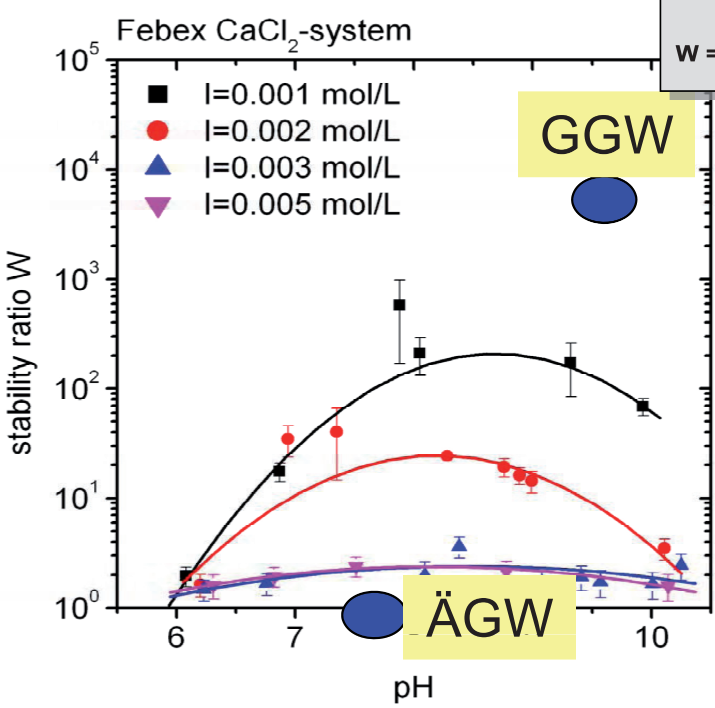
(W.Hauser et al., 2002)

Colloids: enhancing radionuclide solubility and mobility?

- Laboratory studies -

$\alpha = \frac{n_{\text{agglom.}}}{n_{\text{tot.}}}$: "sticking factor"

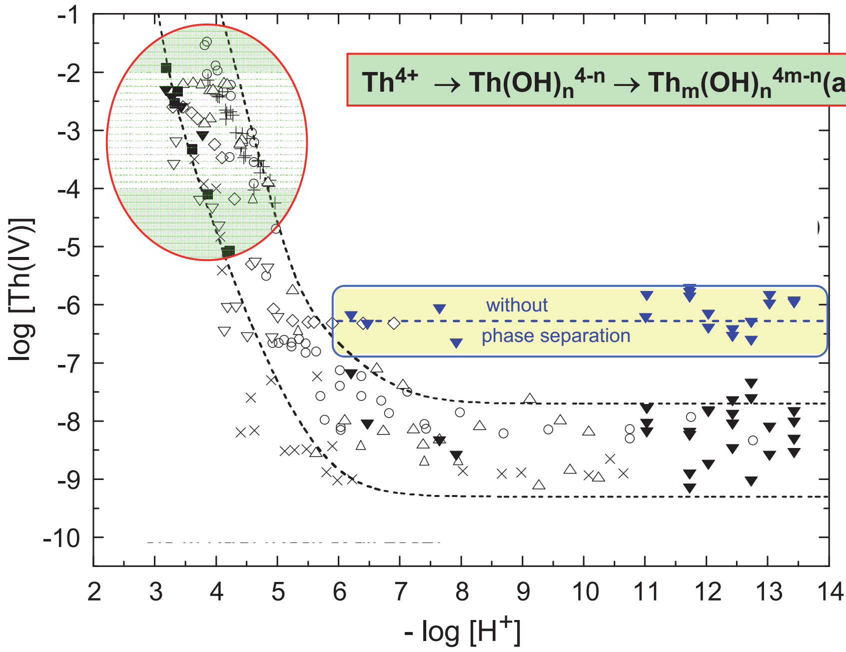
$W = \frac{1}{\alpha}$: "Stability ratio"

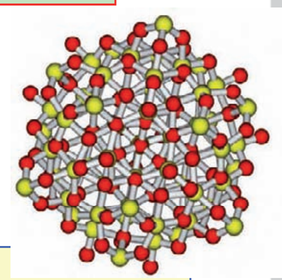


(Schäfer, Noseck et al. KOLLORADO, 2010)

Colloids: enhancing radionuclide solubility and mobility?

Thorium(IV) in 0.5 M NaCl (25 °C)





$Th(OH)_4(aq)$ →

…$Th_m(OH)_{4m}$(coll)

- Charge z = 0
  ($[Th^{IV}]$ independent of pH)
- Colloid size ?

- Studies on Th(IV) solubility and speciation show evidence of colloidal or polymeric species

[Neck et al., RCA, 90 (2002) 485]

Chemical and geochemical aspects

Dissolution and solubility constraints

Redox reactions: determining geochemical behaviour of actinides and fission products

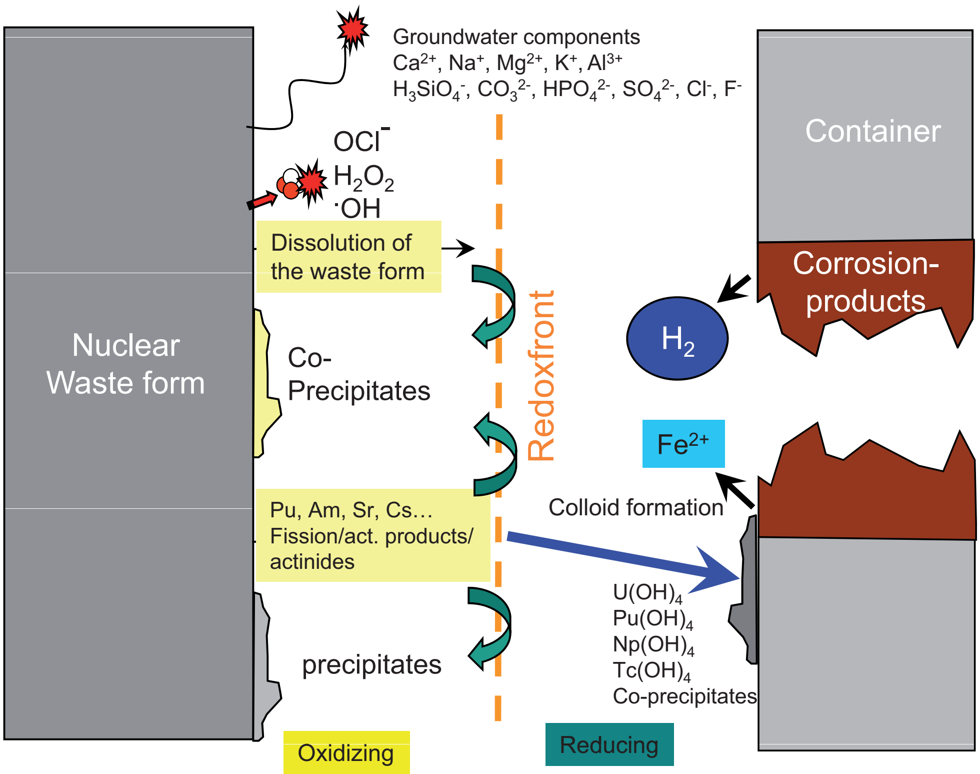
Colloids: enhancing radionuclide solubility and mobility?

Radionuclide retention in repository barriers

Geochemical research needs and benefits

Radionuclide retention in repository barriers

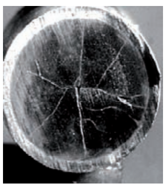
Simplified scheme of chemical processes in the repository near-field



(acc. to Grambow et al. 2000)

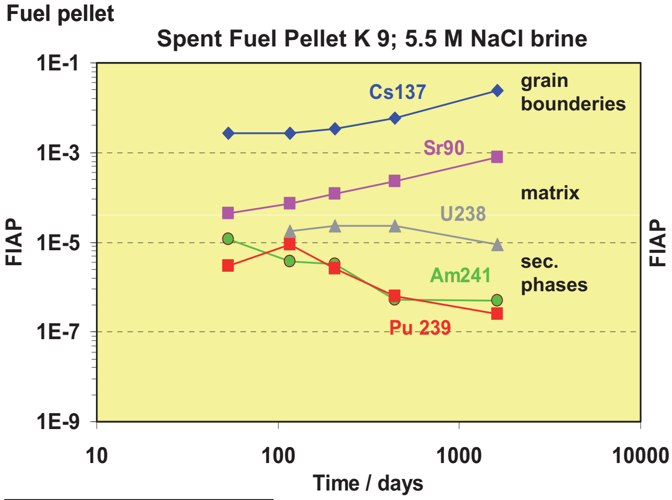
Radionuclide retention in repository barriers

- **Radionuclide release from spent nuclear fuel**

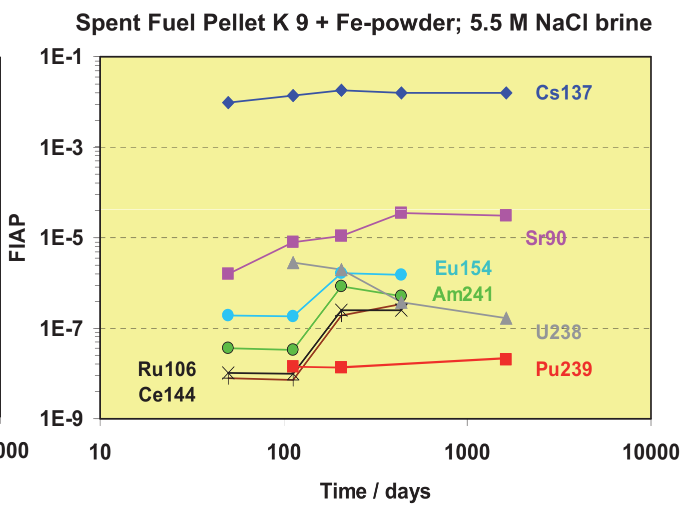


10 mm

Fuel pellet



Influence of corroding Fe

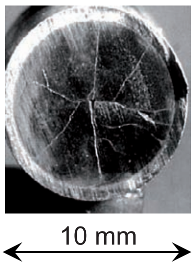


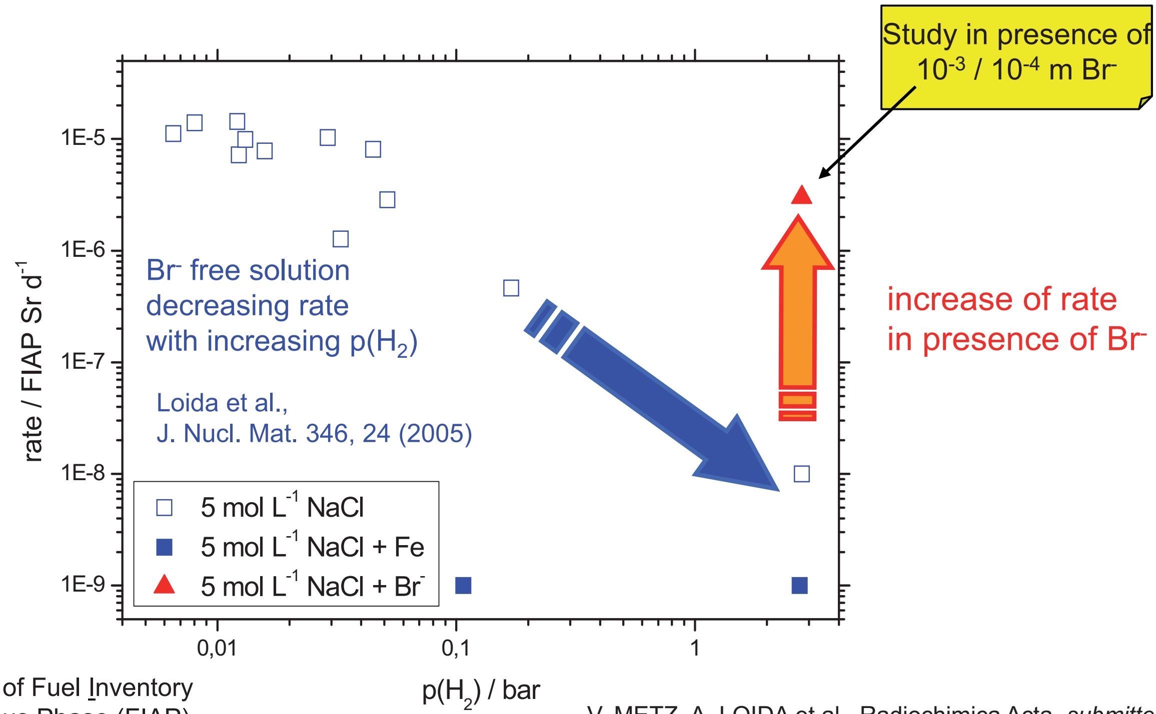
FIAP:
Fraction of inventory in aqueous phase

B. GRAMBOW, A. LOIDA et al., Scientific Reports FZKA 6420 (2000)

Radionuclide retention in repository barriers

• Effect of Br^- on Sr release rate in presence of H_2



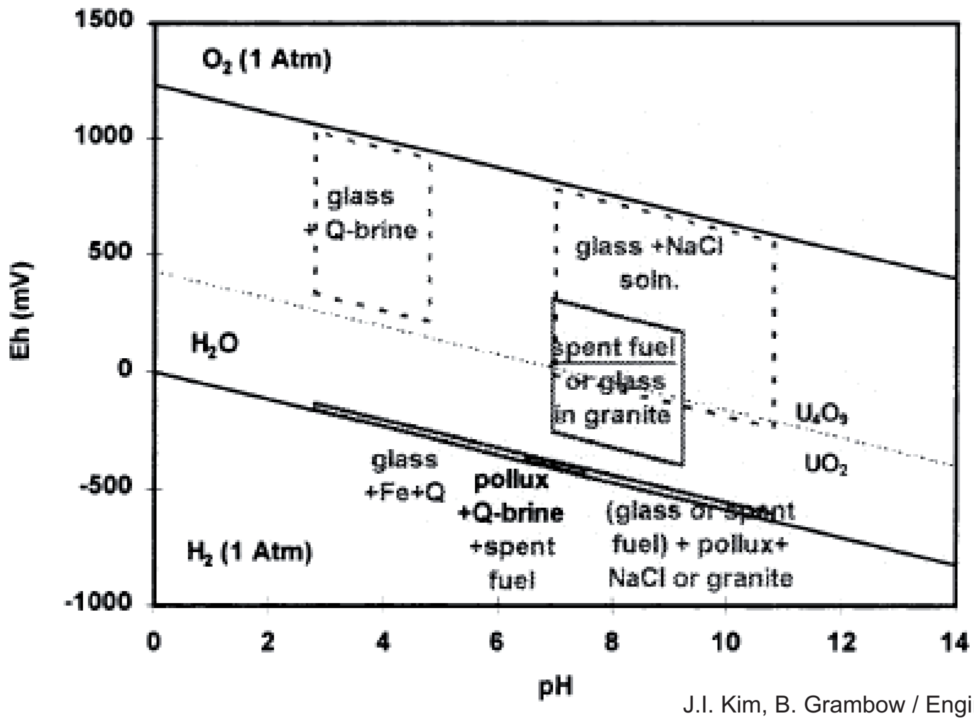


Fraction of Fuel Inventory in Aqueous Phase (FIAP)

V. METZ, A. LOIDA et al., Radiochimica Acta, *submitted*

Radionuclide retention in repository barriers

Effect of container corrosion on redox in the near field

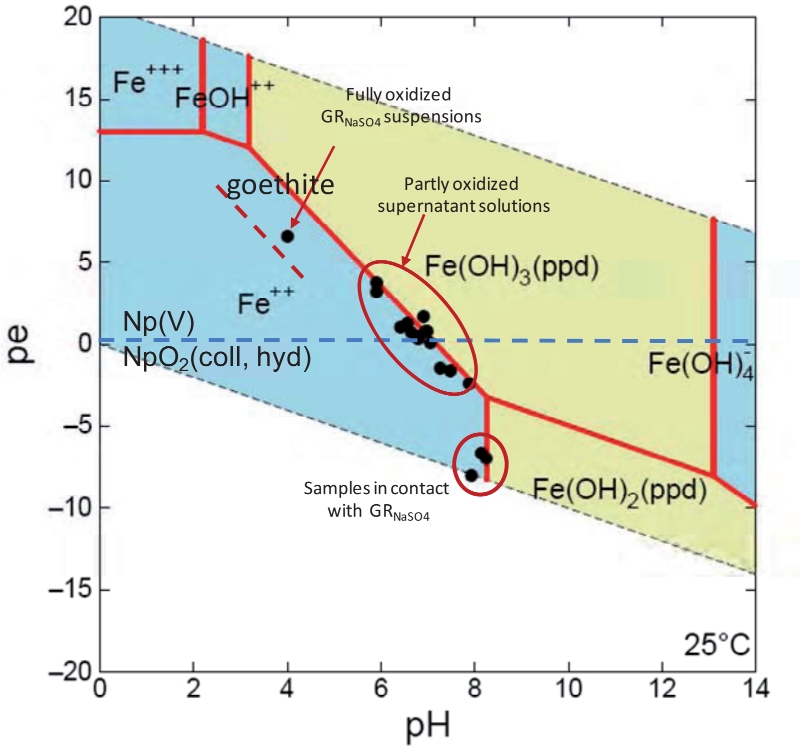


J.I. Kim, B. Grambow / Engineering Geology 52 (1999) 221–230

Radionuclide retention in repository barriers

Corroding Fe-container as chemical barrier

- Formation of Green Rust: $[Fe(II)_4Fe(III)_2(OH)_{12}].[CO_3/SO_4/OH \cdot X\ H_2O]$ -



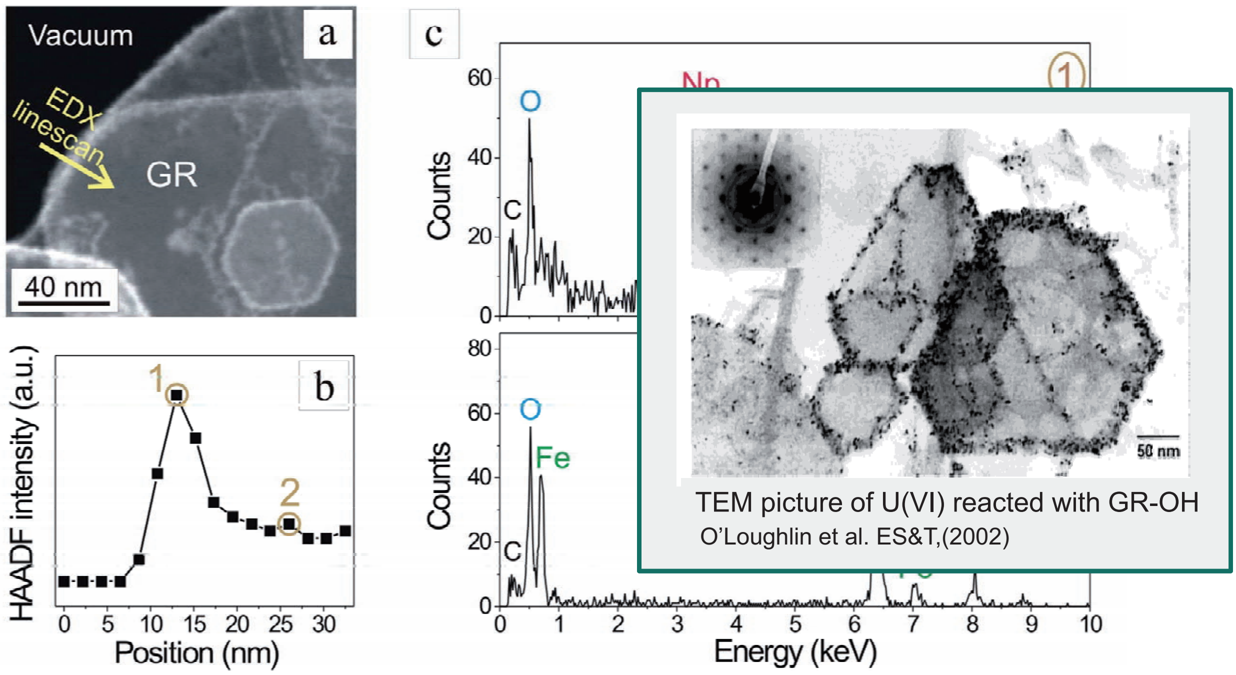
Np(V/IV) redox borderline acc. to Neck, Altmaier

B. Christiansen et al. (2010)
D. Bach et al. (2010)

Radionuclide retention in repository barriers

Corroding Fe-container as chemical barrier

- Formation of Green Rust: $[Fe(II)_4Fe(III)_2(OH)_{12}].[CO_3/SO_4/OH \cdot X\ H_2O]$ -

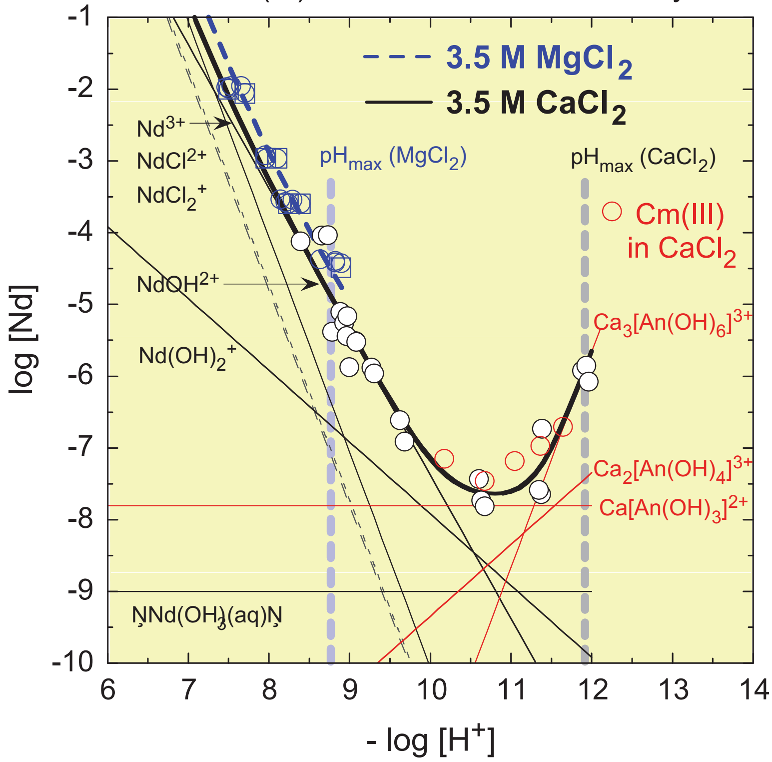


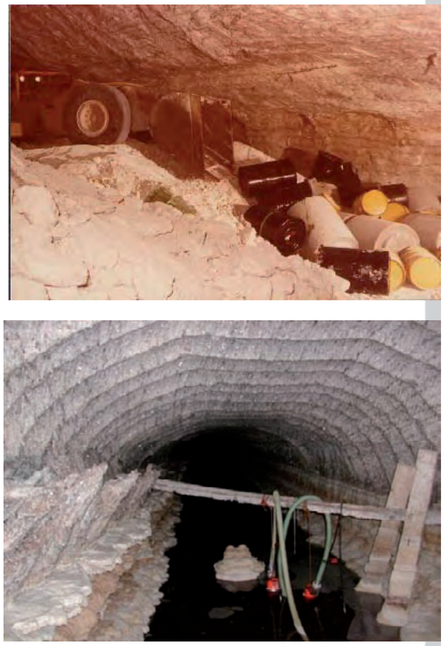
GR-SO_4 reacted with Np(V)

B. Christiansen et al. (2010)
D. Bach et al. (2010)

Radionuclide retention in repository barriers

Retention of An(III) in cement/brine solution systems



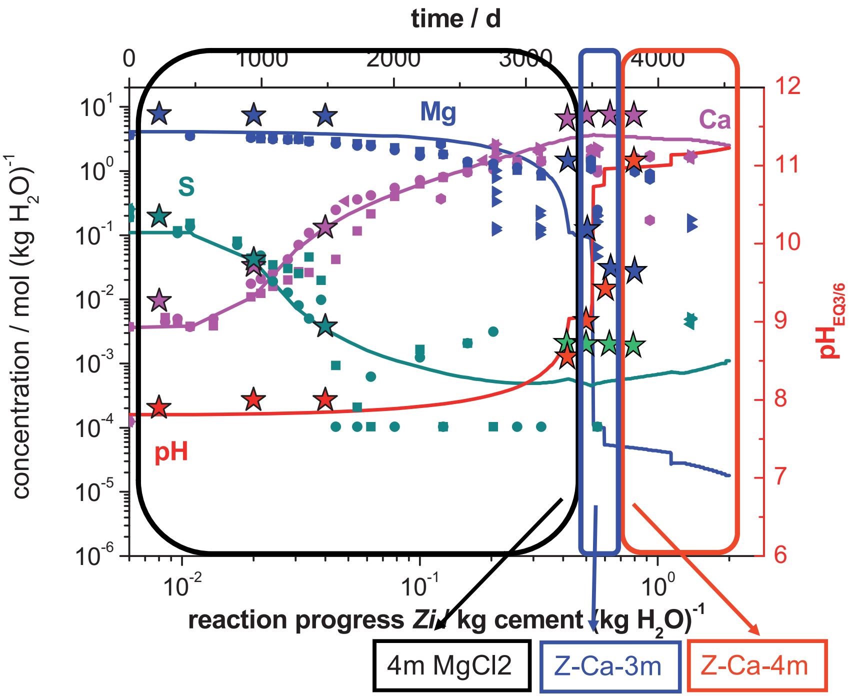


Asse salt mine

Neck, Altmaier et al., Pure and Appl. Chem. 2009
Rabung et al., RCA, 2009

Radionuclide retention in repository barriers

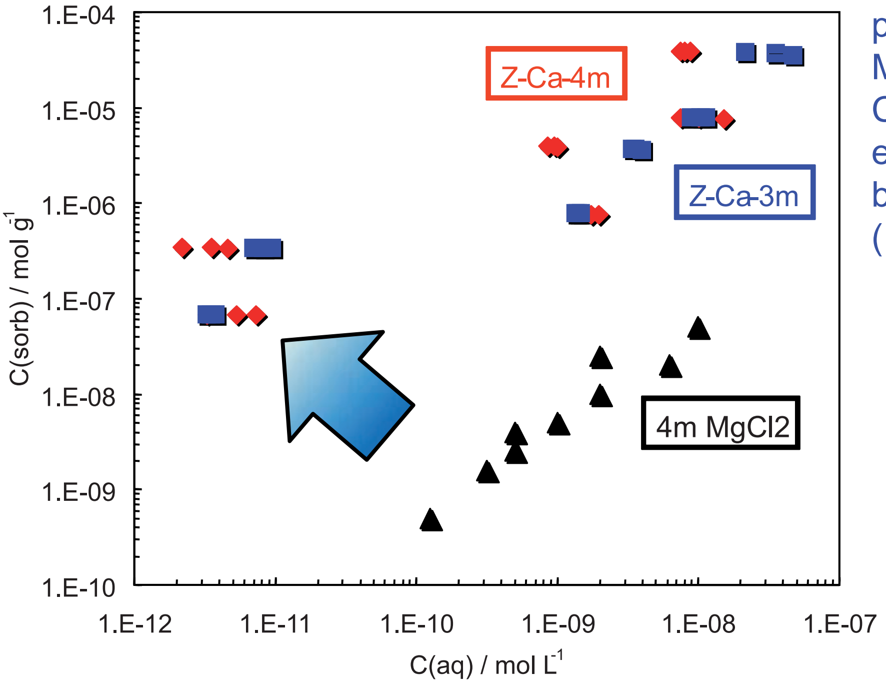
Retention of An(III) in cement/brine solution systems



Kienzler et al., J. Nucl. Sci. & Technology, 2007

Radionuclide retention in repository barriers

Retention of An(III) in cement/brine solution systems



pH_m ~ 9 - >11
Mg-Ca-Na-Cl-solution / $CaCl_2$ rich brine in equilibrium with brucite, gypsum, hydrotalcite (…)

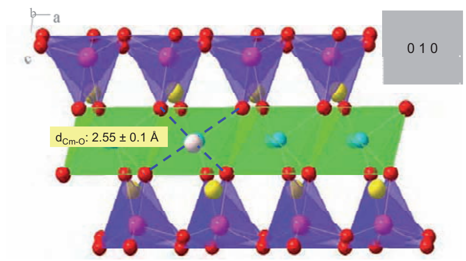
pH_m ~ 8.5
$MgCl_2$ rich solution in equilibrium with Mg-oxychloride, gypsum (…)

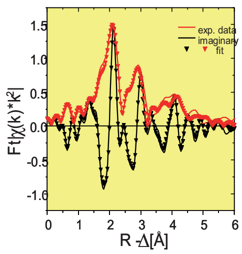
(Lützenkirchen et al., 9th Int'l Conf. Radioactive Waste Management and Environmental Remediation, 4621,pp. 1-7)

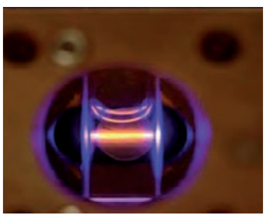
441

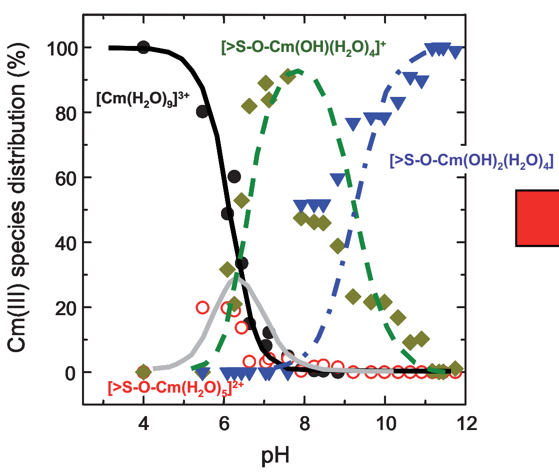
Radionuclide retention in repository barriers

spectroscopy – theory – batch experiments – sorption modelling → P.A









,smart'-K_d

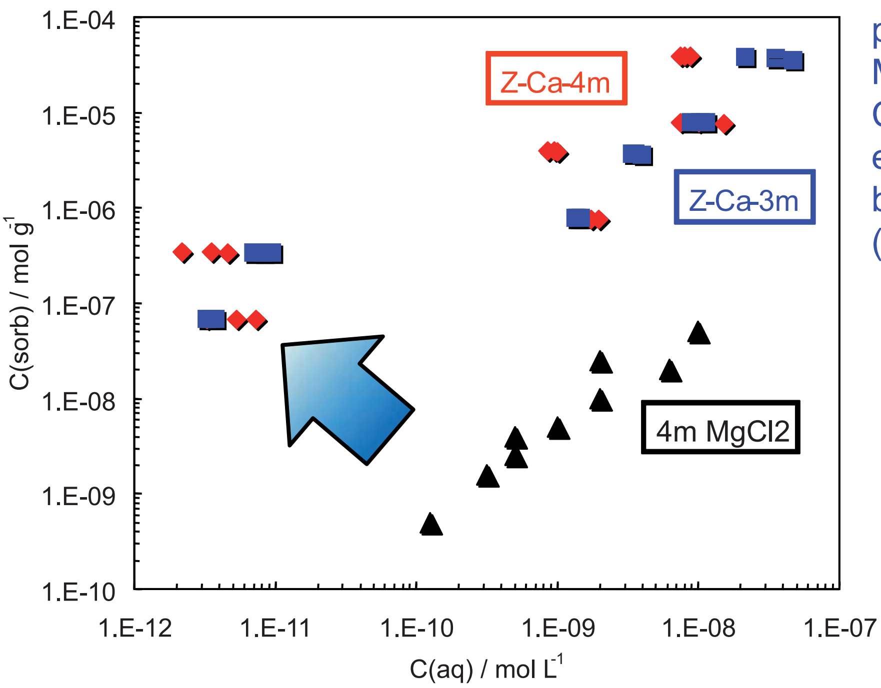
T. Stumpf et al. RCA, 2004
T. Rabung et al. GCA, 2005
H. Geckeis, J. Cont. Hydrol. 2008

Bradbury, et al. GCA (2005)
Rabung et al. GCA (2005)

442

Radionuclide retention in repository barriers

Retention of An(III) in cement/brine solution systems



pH_m ~ 9 - >11
Mg-Ca-Na-Cl-solution /
$CaCl_2$ rich brine in
equilibrium with
brucite, gypsum, hydrotalcite
(…)

pH_m ~ 8.5
$MgCl_2$ rich solution in
equilibrium with
Mg-oxychloride, gypsum
(…)

(Lützenkirchen et al., 9th Int'l Conf. Radioactive Waste Management and Environmental Remediation, 4621,pp. 1-7)

Research benefits and needs

- Knowledge on geochemical processes in nuclear waste disposal has significantly evolved.

- Thermodynamic data for many relevant radionuclides available (also for high ionic strength conditions)

- Significant progress in understanding surface sorption processes (molecular understanding of processes and sorption data availability)

- Chemical/geochemical research has proven that retention mechanisms other than solubility and surface sorption are active in repository systems (e.g. redox, solid solution formation).

Research benefits and needs

- Filling gaps in thermodynamic data (e.g. complexation with borate see Borkowski, Reed, 2009)

-‚Mobile' fission and activation products: ^{129}I, ^{14}C, ^{36}Cl, ^{79}Se, ^{99}Tc

- Impact of microbial activities ?

- How to treat high temperatures ?
  (only for the case of the unlikely case of early container failure)

- Mechanistic description of sorption in highly saline solutions

- Quantification of solid solution formation

- Improving tools for coupled reactive transport modelling

AN ENGINEERING APPROACH FOR A SAFETY CONCEPT FOR THE DISPOSAL OF HLW IN SALT

N. Müller-Hoeppe
DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany

INTRODUCTION

When closing a final repository in rock salt, geotechnical barriers are installed to supplement the tight geological barrier in order to seal the access routes into the repository mine. These geotechnical barriers – shaft and drift seals – play a significant role in long-term repository safety. Shaft and drift seals are considered to be geotechnical structures. Therefore, they have to be designed in accordance with the technical guidelines in force. Technical guidelines usually describe the state of the art in technology and may be looked at as the minimum requirements in the case of an HLW repository. Additional requirements may go beyond the scope of technical standards as an HLW final repository is considered to be a structure with a high hazard potential. As a common European Standard (Eurocodes) in civil engineering has been implemented recently, it must be taken into account when designing the shaft and drift seals of a final repository in rock salt. The results of this engineering approach for a safety concept are discussed in this paper.

OVERVIEW OF EUROPEAN STANDARDS (STRUCTURAL EUROCODES)

In May 2010, the European Standard (EN) in civil engineering (Structural Eurocodes) replaced national guidelines in the member states of the European Union as well as in Iceland, Norway, and Switzerland. Due to this, EN plays a significant role in the licensing of construction works even of an HLW repository. The Structural Eurocodes presently comprise the following standards:

EN 1990	Eurocode:	Basis of structural design
EN 1991	Eurocode 1:	Actions on structures
EN 1992	Eurocode 2:	Design of concrete structures
EN 1993	Eurocode 3:	Design of steel structures
EN 1994	Eurocode 4:	Design of composite steel and concrete structures
EN 1995	Eurocode 5:	Design of timber structures
EN 1996	Eurocode 6:	Design of masonry structures
EN 1997	Eurocode 7:	Geotechnical design
EN 1998	Eurocode 8:	Design of structures for earthquake resistance
EN 1999	Eurocode 9:	Design of aluminium structures

In the context of an HLW repository in a deep geological formation, EN 1990 /1/ and EN 1997 are of special interest. EN 1990 establishes principles and requirements for the safety, serviceability, and durability of structures, describes the basis for their design and verification and gives guidelines for related aspects of structural reliability. It is intended to be used in conjunction with EN 1991 to EN 1999 for the structural design of buildings and civil engineering works including geotechnical aspects, structural fire design, situations involving earthquakes, execution, and temporary structures. A fundamental advantage

of EN 1990 is its applicability for the design of structures where other materials or other actions outside the scope of EN 1991 to EN 1999 are involved. Some basic requirements of EN 1990 are listed below:

A structure shall be designed to have adequate structural resistance, serviceability, and durability during its intended working life and – with an appropriate degree of reliability – sustain all actions and influences likely to occur and remain fit for the use for which it is required. Considering national German guidelines as well, tightness and hydraulic resistivity are also required when designing structures which are installed to serve as a barrier. In the context of EN, the term reliability is related to the probability of failure whereas different levels of reliability are required in case a safety function or a serviceability function fails. Quantitatively, the probability to loose a safety function is required to be below
10^{-4}/working life and 10^{-6}/a. The failure probability related to the loss of a serviceability function, however, begins at 10^{-1}/working life and 10^{-3}/a depending on the expected amount of economical loss.

The degree of reliability required for safety functions is related to the individual residual risk RI < 10^{-6}/a that is quantitatively defined in some countries (e.g. Sweden and the United Kingdom) and implies qualitatively that the individual risk to be killed by failure of a structure (loss of a safety function) is small compared to the common individual risk of death.

In general, the reliability methods described in EN rely on a risk-based approach using (semi)probabilistic methods to prove safety and serviceability functions. When designing structures in practice, the partial factor method is applied which leads to procedures that are very similar to those of the former deterministic approach (providing continuity to successive versions of standards). Within the scope of EN 1990, adequate reliability required for structures is achieved by design based on reliable data, by suitable execution, and by quality management measures.

APPLICATION OF RELIABILITY METHODS TO THE DESIGN GEOTECHNICAL BARRIERS OF AN HLW REPOSITORY

When designing a geotechnical barrier (e.g. a shaft seal) in agreement with EN and the level of reliability defined therein, the probability that the geotechnical barrier does not fulfil its safety function is below 10^{-4}/ working life. Thus, a system of two independent geotechnical barriers installed in series (e.g. shaft and drift seal) shows a failure probability p_f of < 10^{-8}/working lives. Applying the EN approach to geotechnical barriers installed in series forms a sound basis for scenario classification of an HLW repository in rock salt. Assuming a tight geological barrier, two effective geotechnical barriers describe the undisturbed repository evolution, one effective geotechnical barrier is related to disturbed repository evolution and zero effective geotechnical barriers is excluded because of low probability.

METHODS TO PROVE STRUCTURAL RELIABILITY OF AN INDIVIDUAL BARRIER

When designing a structure in civil engineering, structural safety and reliability is usually demonstrated by calculation. This approach is applied if generally accepted design criteria, verified modelling tools, validated models, and a method to manage uncertainties are available. Alternatively, the design-assisted-by-testing method may be used, e.g. if modelling tools or validated models are not available. In some cases, design may be based on a combination of tests and calculations /2/.

The latter procedure was applied to all examples of geotechnical barriers constructed so far. In the case of the ERAM drift seals, for instance, structural resistivity was demonstrated by calculation and flow resistance was demonstrated based on principle by testing a comparable structure – the so-called Asse seal – which is also made of salt concrete /3/. The Asse flow barriers are made of magnesium oxychloride concrete. Again, structural resistivity was demonstrated by calculation and flow resistance by a combination of calculation and testing (prototype testing and geotechnical measurements in situ) /4//5/. In the case of the Salzdetfurth Shaft II Seal, structural resistivity was demonstrated by testing as well as by using flow resistance. The validation of the models was a by-product /6/.

Looking in more detail at the demonstration of the integrity of a geotechnical barrier, it has to be stated first that a shaft or drift seal in rock salt consists of three hydraulically effective elements that act in parallel and may have different hydraulic properties, i.e. the sealing body, the interface between the sealing body and the EDZ, and the EDZ itself. Regarding structural resistivity, several elements have different safety functions but act together as a unit, e.g. abutment (limiting deformations) and a separate sealing element (limiting flow rate). Adequate safety function has to be demonstrated for every individual component. To illustrate this issue, the individual assessments necessary to demonstrated adequate safety functions of the shaft seal elements, including gravel abutments and a bentonite sealing element in the center, (Fig. 1) are shown in Fig. 2. The design requirements (design criteria) of the shaft seal (Salzdetfurth Shaft II Seal) are listed below:

- Hydraulic conductivity (average): $k_f \leq 5 \cdot 10^{-10}$ m/s
- Swelling Pressure (NaCl brine): $p_{q0} \geq 1$ MPa
- Long-term durability

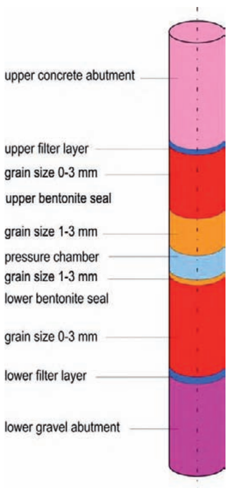


Figure 1: Schematic test arrangement of the experimental shaft in-situ experiment

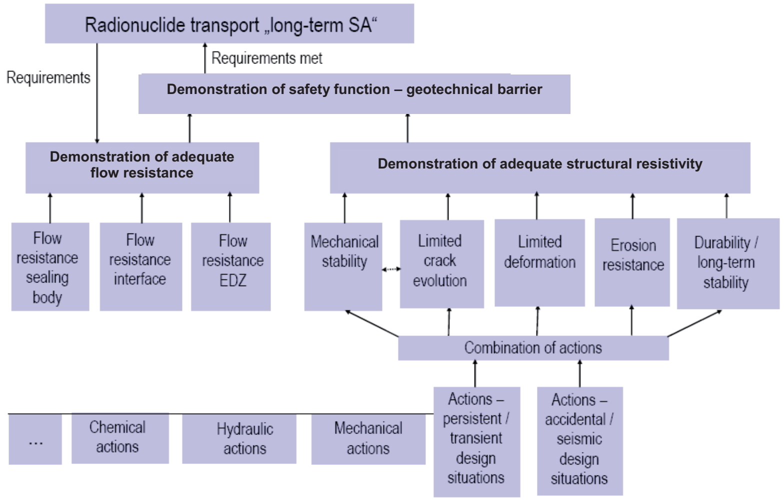


Figure 2: Components of the assessment to demonstrate adequate safety function of the shaft seals

Exemplarily, an assessment for the bentonite sealing body to demonstrate its safety function is described below. Hydraulic conductivity and permeability depends significantly on the dry density of the bentonite achieved when installing the sealing element. Using a mixture of bentonite powder and pellets, a dry density of 1.60 – 1.75 t/m³ is obtained during the construction process and verified by quality control measures. When calculating the hydraulic conductivity in accordance with EN 1990 using experimental laboratory data, $k_f = 3.7 \cdot 10^{-13}$ m/s is proven when using the 5% fractile for the characteristic value X_k and $k_f = 1.3 \cdot 10^{-13}$ m/s when using the 95% level of confidence for X_k. Calculating the design value directly yields $k_f = 1.5 \cdot 10^{-12}$ m/s ($p_f \leq 0.1\%$), see annex D in /1//7/. All these values meet the design criterion of $k_f \leq 5 \cdot 10^{-10}$ m/s.

The experimental shaft in situ experiment showed an average hydraulic conductivity of $k_f = 4.4 \cdot 10^{-11}$ m/s. The swelling pressure p_{q0} was measured in the range of 1 – 1.2 MPa and long-term durability was shown by the natural analogue of salt clay. Comparison of calculation results and findings from the dismantled seal showed good agreement of the saturation front in the bentonite sealing body. Close to the interface to the host rock, however, it looks like saturation originates from the interface or the EDZ. This effect might be a result of an increased hydraulic conductivity of the EDZ /6//7/.

Nevertheless, it can be concluded that in the case of the Salzdetfurth Shaft II Seal, the demonstration of structural reliability is at an advanced state, however, due to the design-assisted-by-testing method, the validity is limited due to the initial, boundary, and load conditions of testing. The main uncertainty at present is assessing the state of the EDZ because the healing process of the EDZ is uncertain and high pore pressure may increase permeability (again). Thus, meeting the fluid pressure criterion $p_{fluid} \leq p_{tot}$ in the EDZ is important because $p_{fluid} \approx p_{tot}$ may initiate the widening of grain boundaries /8/ as well as cracks and micro-fissures. In addition, the need for a partial safety factor Δp is still an open question.

CONCLUDING REMARKS

If the geological barrier is tight and the safety function of two independent seals installed in series is successfully demonstrated in accordance with the EN, scenario classification becomes simple and transparent. Furthermore, when comparing safety case and EN procedures it becomes evident that they are very similar (Tab. 3). The demonstration of adequate safety function of a geotechnical barrier is more or less an inner loop of the safety case for an HLW-repository.

Table 3: Comparison of safety case and EN procedures

FEP, system concept	Identification of structural system*), actions and design situations
Safety concept, assessment cases	Combination of actions considering different design situations
Safety assessment	Determining state variables (effect of actions) considering relevant combinations and design situations
Analysis of consequences	Comparison of state variables (effect of actions) and design criteria, statement on safety function
Analysis of what-if cases, robust safety statement	Reliability analysis**)

*) Safety concept is included **) Not considered explicitly

Thus, applying EN to an HLW repository in rock salt helps to link "long-term safety assessment" and the demonstration of adequate safety function of geotechnical barriers, to derive and apply suitable technical specifications and procedures and indicates issues that cannot reliably be proven at present. Additionally, meeting the EN requirements is fundamental for licensing civil engineering works in Europe and the EN are an excellent tool to identify the most urgent R&D in geotechnical barrier design. In this respect, studies focusing on different working lives of geotechnical barriers according to EN (several decades at the maximum) and working lives required in long-term safety assessment are fundamental as well as coupling the risk-based engineering approach to demonstrate adequate safety function with the dose-based approach to demonstrate radiological safety.

ACKNOWLEDGMENTS

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REFERENCES

/1/ DIN EN 1990: Eurocode: Basis of structural design, English version of DIN EN 1990, October 2002

/2/ Müller-Hoeppe, N.; Jobmann, M.; Polster, M; Schmidt, H.: The Role of Structural Reliability of Geotechnical Barriers of an HLW/SF Repository in Salt Rock within the Safety Case, Proc. Symp. On Safety Cases for Deep Disposal of Radioactive Waste: Where Do We Stand?, Paris, France, 23-25 Jan 2007

/3/ Mauke, R.; Müller-Hoeppe, N.; Wollrath, J.: Planning Assessment, and Construction of a Drift Seal in a Salt Repository – Overview of Investigations, Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case: Design Confirmation and Demonstration, Workshop Proc. Tokyo, Japan, 12-15 September 2006, OECD/NEA 2007

/4/ Kappei, G.: 100 Jahre Schachtanlage Asse II, Stationen eines Bergwerks, Kali und Steinsalz, Heft 1, 2007 (in German)

/5/ Meyer, T.; Teichmann, L.; Heydorn, M.: Geotechnische Messungen an einer Pilotströmungsbarriere, Messen in der Geotechnik 2008, Mitteilung des Instituts für Grundbau und Bodenmechanik, TU Braunschweig, Heft Nr. 87, 2008 (in German)

/6/ K+S AG: Forschungsprojekt Schachtverschluss Salzdetfurth Schacht II, BMBF-Forschungsvorhaben 02C0516, Kassel, 2002 (in German)

/7/ Eberth, S.; Müller-Hoeppe, N.: Übertragung des Sicherheitsnachweiskonzeptes für ein Endlager im Salz auf andere Wirtsgesteine, ÜBERSICHT, Abschlussbericht (FKZ 02 E 9521), DBE TECHNOLGY GmbH, 2009 (in German)

/8/ Popp, T.; Minkley, W.: Integrity of a Salt Barrier during Gas Pressure Build-up in a Radioactive Waste Repository – Implications from Laboratory Investigations and Field Studies - , Proc. Int. Conf. Radioactive Waste Disposal in Geological Formations, Braunschweig, November, 2-9, 2007.

AN ENGINEERING APPROACH FOR A SAFETY CONCEPT FOR DISPOSING OFF HLW IN SALT

Nina Müller-Hoeppe

DBE TECHNOLOGY GmbH

US-GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH; DESIGN, AND OPERATION
MAY 25 - 28, 2010
JACKSON, MISSISSIPI, USA

Introduction and History

1975: CEC decided on an action programme in the field of construction, based on article 95 of the Treaty. The objective was the elimination of technical obstacles to trade and harmonisation of technical specifications.

1980: First generation of European codes for the design of construction works, which in a first stage served as alternative to the national rules in the Member States and (→ to replace them ultimately)

1989: Preparation and publication of the Eurocodes was transferred to CEN in order to provide them with the future status of European Standard (EN).

2002: The European Standard was given the status of a national standard at latest.

2010: Conflicting national standards must be withdrawn at latest.

EN play a signifcant role in licensing construction works of an HLW-repository

Scope

EN 1990 establishes principles and requirements for the safety, serviceability, and durability of structures, describes the basis for their design and verification and gives guidelines for related aspects of structural reliability.

EN 1990 is intended to be used in conjunction with EN 1991 to 1999 for the structural design of buildings and civil engineering works, including geotechnical aspects, …

→ E.g. EN 1997: Geotechnical design

EN 1990 is applicable for the design of where other materials or other actions outside the scope of EN 1991 to EN 1999 are involved.

Note:

For the design of special construction works (e.g. nuclear installations, dams, etc.), other provisions than those in EN 1990 to EN 1999 might be necessary.

Basic Requirements

Target:

A structure shall be designed to guarantee

⇨ structural resistance

⇨ serviceabiliy

⇨ durability

⇨ tightness (national German guideline, not EN)

during its intended working life with an adequate level of reliability.

Rating reliability quantatively:

safety function: 10^{-04} → 10^{-07}

Probability of failure p_f	10^{-01}	10^{-02}	10^{-03}	10^{-04}	10^{-05}	10^{-06}	10^{-07}
Reliability index β	1,28	2,32	3,09	3,72	4,27	4,75	5,20

serviceability function: 10^{-01} → 10^{-05}

For Comparison: Occupational Risk

Occupational risk	*Mean value of deaths per year*
Logger, logging	$1{,}0\cdot10^{-03}$
Forest enterprises	$9{,}0\cdot10^{-04}$
Construction worker	$5{,}0\cdot10^{-04}$
Chemical industry	$1{,}5\cdot10^{-04}$
Mechanical industry	$1{,}0\cdot10^{-04}$
Miner in Germany	*$1{,}0\cdot10^{-04}$*
Office work	$5{,}0\cdot10^{-05}$

The data are restricted to Western Europe and North America

Residual risk: RI $\leq 10^{-06}$ /a (e. g. Schweden, Great Britain,…)

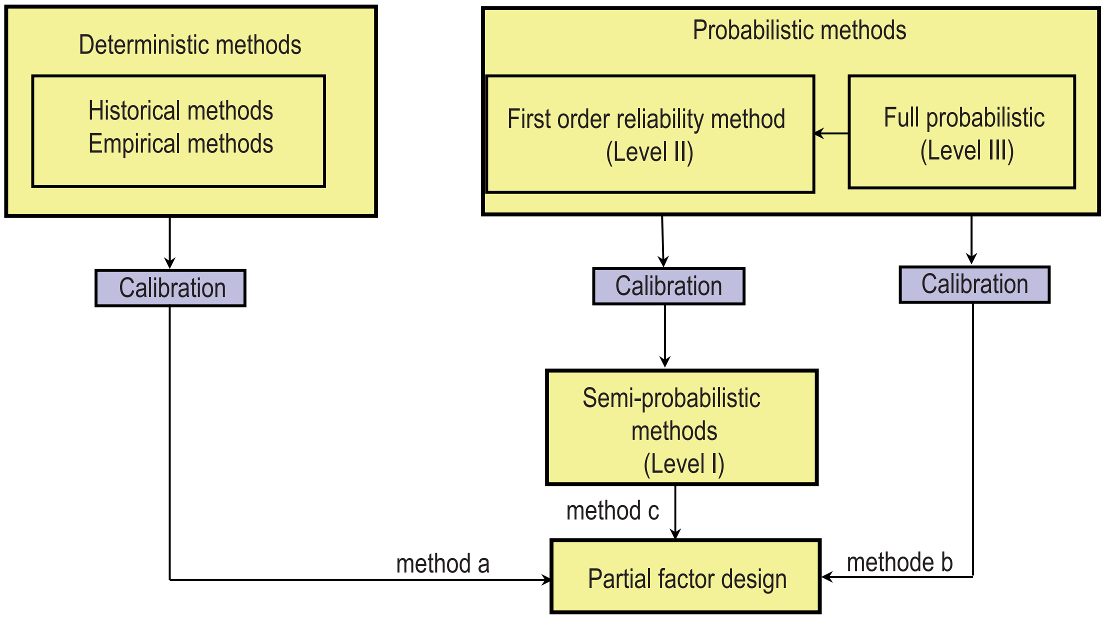
Reliability Methods

1. Risk based approach
2. (Semi)probabilistic concept to prove safety function
3. In practice: Partial factor method
4. Procedures are very similar to the former deterministic concept to prove safety function

provided that

1. Based on data (not on expert judgement!)
2. Quality management: Organisational and technical measures
3. Assignment of qualified and experienced personnel

Reliability Methods



Application to Geotechnical Barriers of an HLW-Repository

One geotechnical barrier

- Failure probability: $p_f \leq 10^{-4}$ / working life

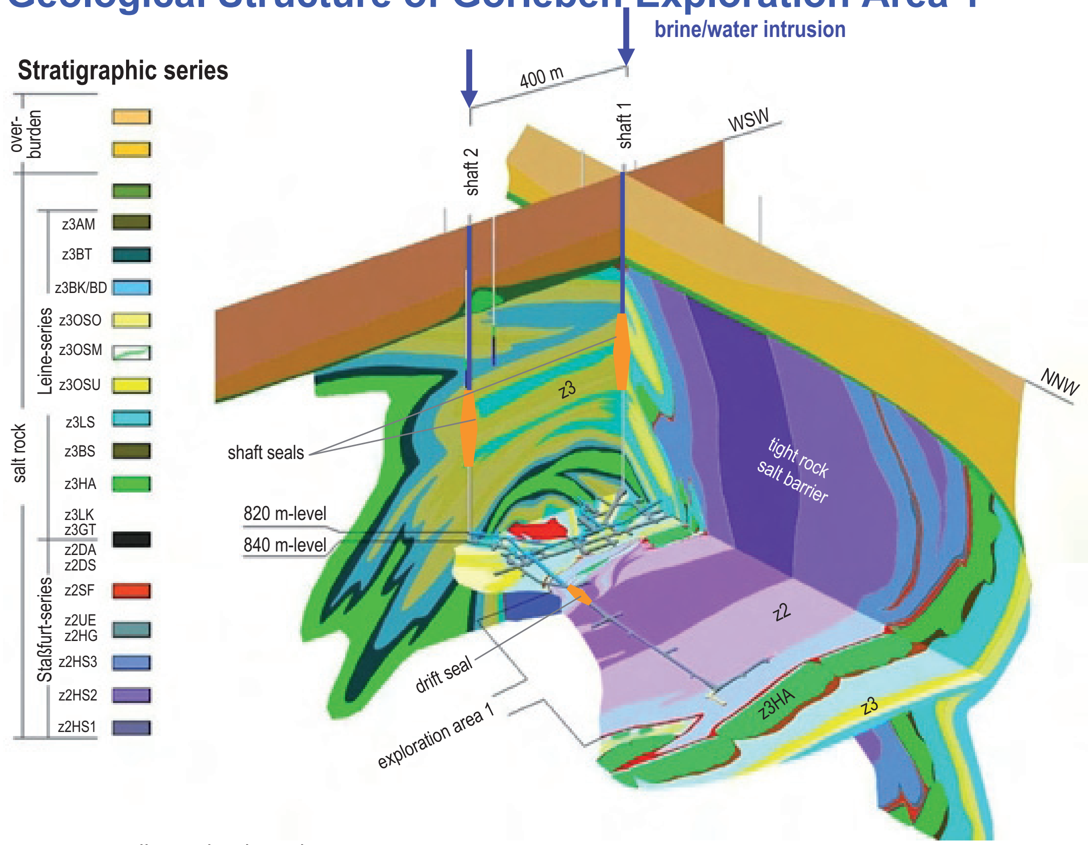
A system of two independent geotechnical barriers

- Failure probability: $p_f \leq 10^{-8}$ / working lives

→ 2 effective geotechnical barriers – undisturbed evolution
→ 1 effective geotechnical barrier – disturbed evolution
→ 0 effective geotechnical barrier – excluded, because of low probability

Application of EN to geotechnical barriers of an HLW-repository forms a sound basis for scenario classification.

Geological Structure of Gorleben Exploration Area 1



www.dbe-technology.de

Müller-Hoeppe,
US-German Workshop, Jackson, MS, 2010

DBETEC DBE TECHNOLOGY GmbH

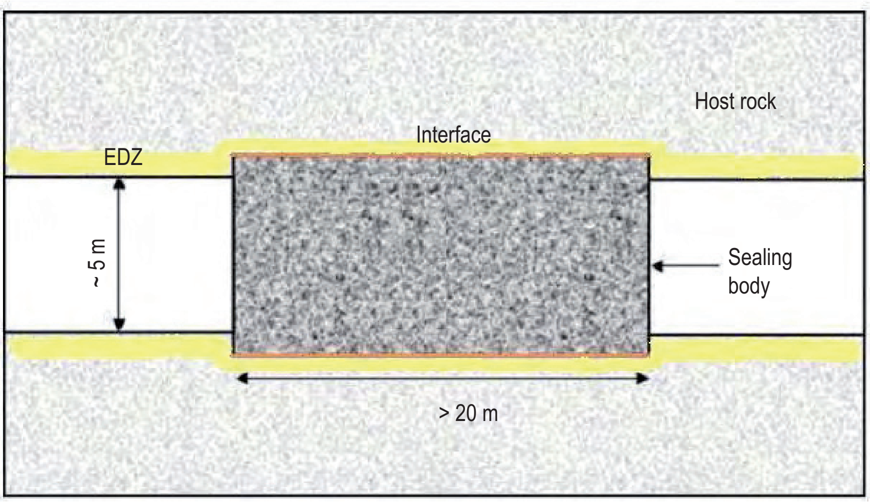
Methods to Prove Structural Reliability

- **By calculation**

→ Design criteria, modeling tools, validated models, and a method to manage uncertainty are available

- **Design assisted by testing**

→ If modeling tools resp. validated models are not available



Hydraulically effective elements of seal acting in parallel

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Examples

ERAM drift seals:

- Structural resistivity is proven by calculation
- Flow resistance is proven by testing (in principle)

ASSE flow barriers:

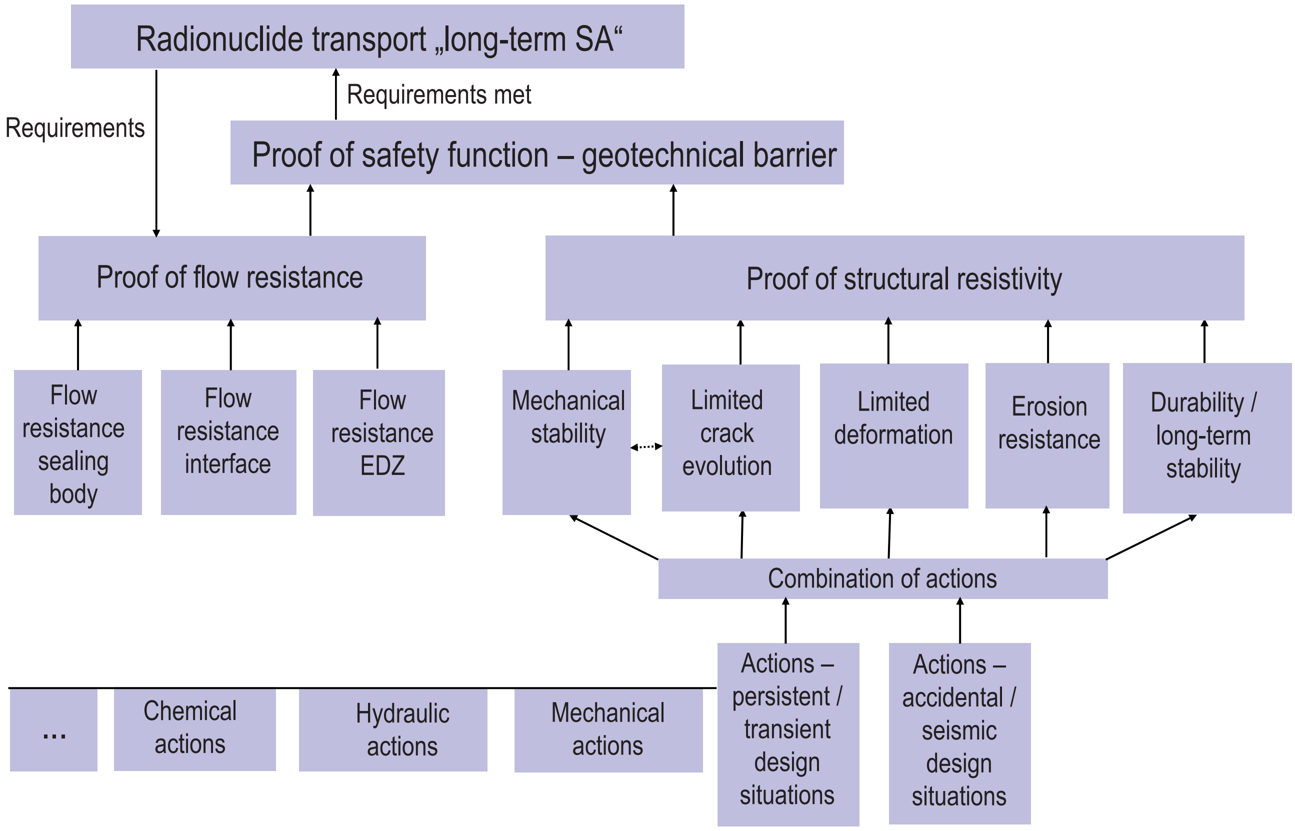
- Structural resistivity is proven by calculation
- Flow resistance is proven by a combination of calculation and testing (in situ-tests, prototype, geotechnical measurements)

Salzdetfurth Shaft II seal:

- Structural resistivity is proven by testing
- Flow resistance is proven by testing

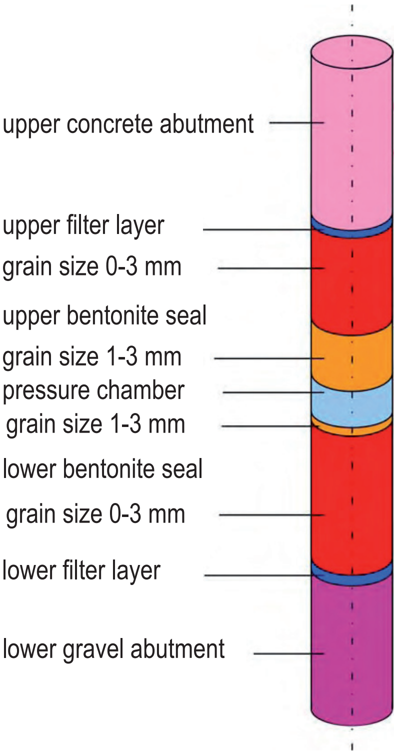
  → Validation of models as a by-product

Shaft Seal – Proof of Safety Function



Example: Experimental Shaft Salzdetfurth

Schematic test arrangement

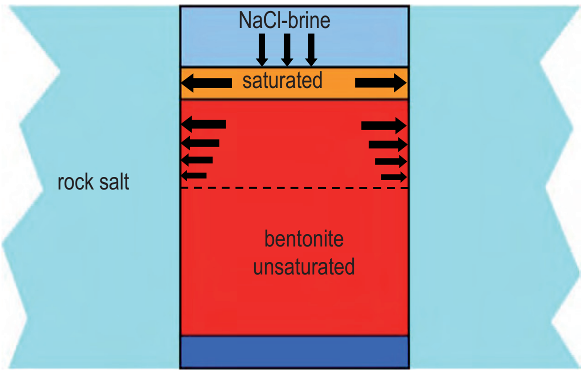


Design requirements (design criteria)

$k_f \leq 5 \cdot 10^{-10}$ m/s

$p_{qo} \geq 1$ MPa (NaCl-brine)

Long-term durability



Sealing Body of Shaft Seal

- Mixture of bentonite powder and pellets
- Dry density reliably achieved during construction process

1,60 – 1,75 t/m³

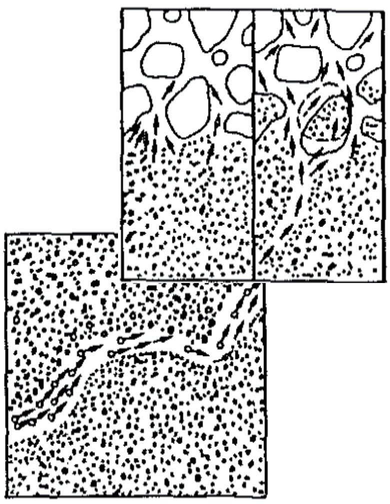
- Quality control by technical measures

powder

pellets

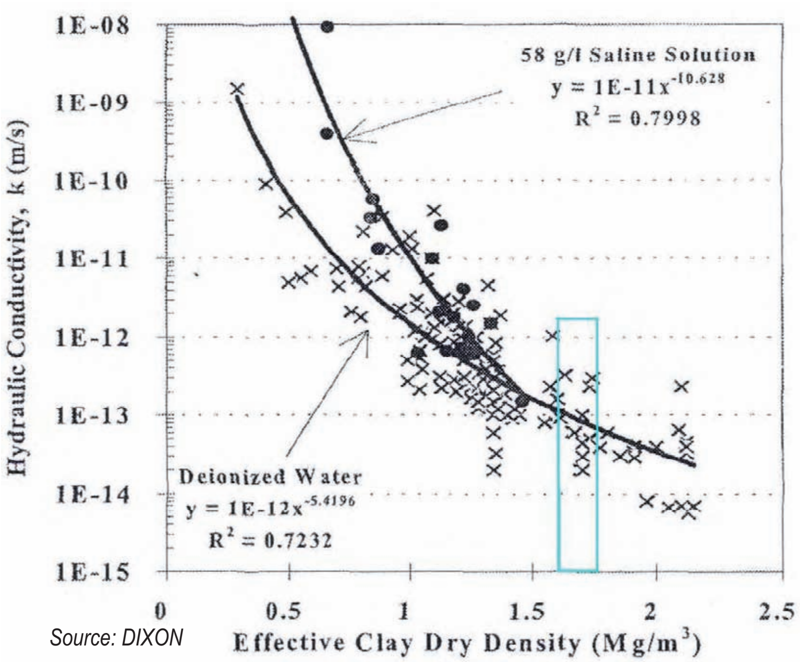
after installation

Source: K+S



erosion processes

Sealing Body - Bentonite



Source: DIXON

Experimental data k_f [m/s]	*Expermintal data $\ln k_f$ (normalized)*
$3 \cdot 10^{-13}$	-28,83
$3 \cdot 10^{-13}$	-28,83
$2 \cdot 10^{-13}$	-29,24
$1 \cdot 10^{-13}$	-29,93
$9 \cdot 10^{-14}$	-30,04
$6 \cdot 10^{-14}$	-30,44
$5 \cdot 10^{-14}$	-30,63
$4 \cdot 10^{-14}$	-30,85
$4 \cdot 10^{-14}$	-30,85
$3 \cdot 10^{-14}$	-31,14
$2 \cdot 10^{-14}$	31,54
Mean value $m_x = 7{,}6 \cdot 10^{-14}$	***-30,21***
Standard deviation, s_x	***0,9226***
Variation coefficient, v_x	***0,0305***

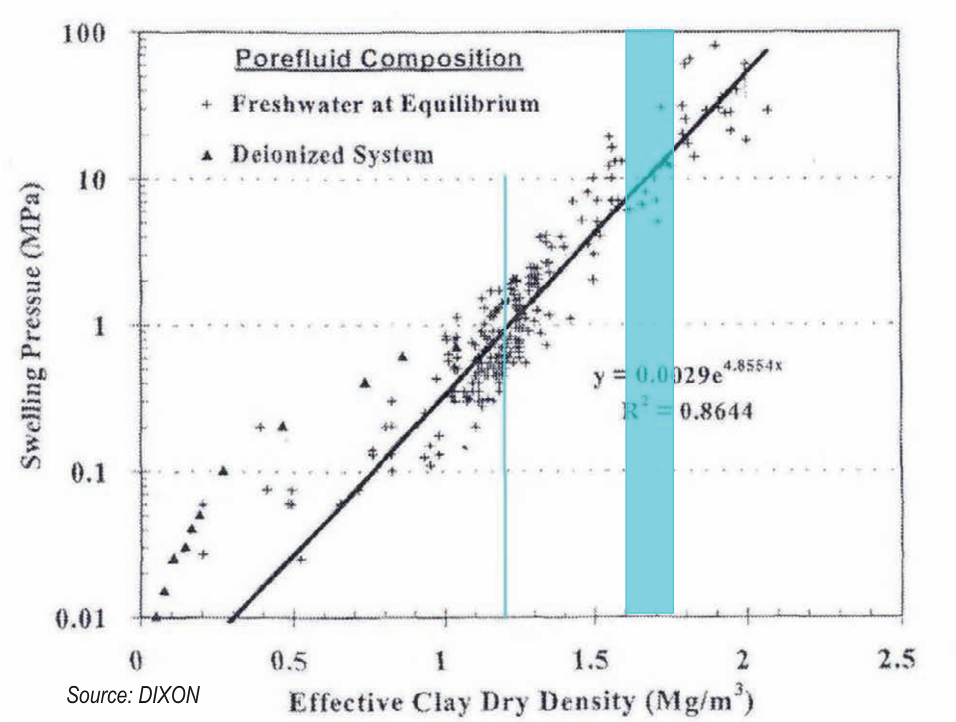
Experimental data in the range of 1,60 g/cm³ < ρ_{tr} < 1,75 g/cm³

X_k 5%-fractile	$k_f = 3{,}7 \cdot 10^{-13}$ m/s
X_k 95%-level of confidence	$k_f = 1{,}3 \cdot 10^{-13}$ m/s
X_d ULS design value (p_f< 0,1%)	$k_f = 1{,}5 \cdot 10^{-12}$ m/s

Characteristic resp. design values of hydraulic conductivity

design criterion: $5 \cdot 10^{-11}$ m/s

Interface: Sealing Body – Rock Salt

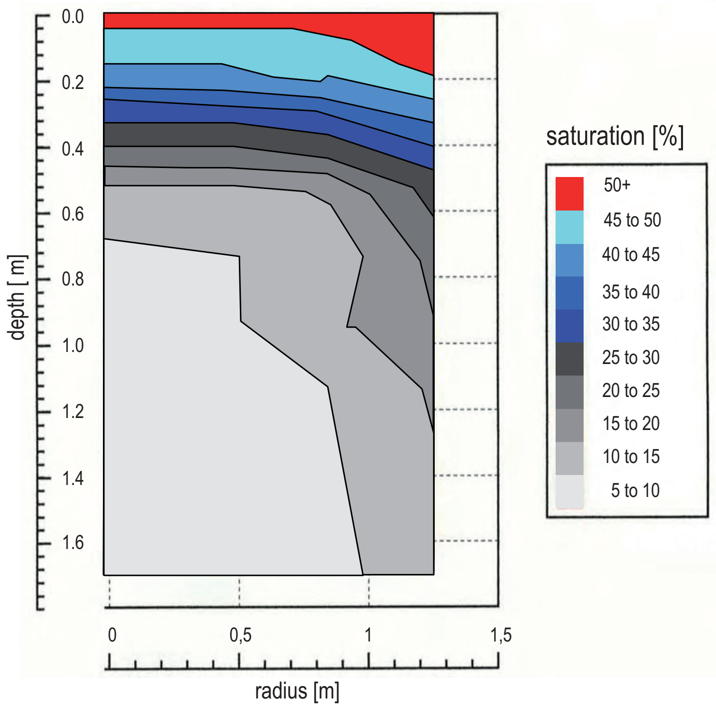


Source: DIXON

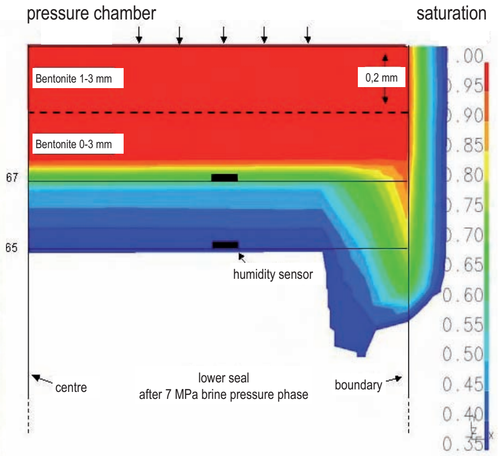
Design criterion: $p_q \geq 1$ MPa → plausibility check

Experimental Shaft – Saturation of Bentonite Seal

Dismantled seal



Calculation results



Results of in situ-test

$k_f = 4{,}4 \cdot 10^{-11}$ m/s < $5 \cdot 10^{-10}$ m/s

p_{qo} ~ 1-1.2 MPa ≥ 1 MPa

Long-term durability: natural analogue

Safety Function of Geotechnical Barriers – Status of Proof

Salzdetfurth Shaft II seal:

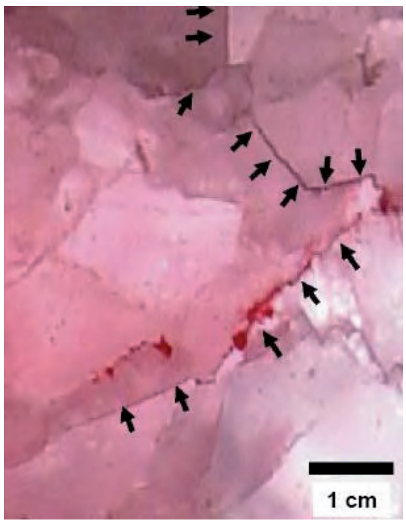
- Advanced state of proof of structural reliability
- Validity is restricted due to initial, boundary, and loading conditions of testing
- Initial, boundary, and loading conditions might be comparable to Gorleben shaft seals
- Main uncertainty: Assessing state of EDZ

- Healing of EDZ is uncertain
  → High pore pressure may increase permeability (again)
  → Meeting the fluid pressure criterion in the EDZ is important

Widening of grain boundaries →

$p_{fluid} \approx p_{tot}$

Partial safety factor Δp?



Source: IfG

Safety Function of Geotechnical Barriers –Conclusion

Application of EN shows

- Proof of safety function is well developed for several seal designs
- Considering sealing body and interface common mode failure is excluded by using different seal designs
- Performance of EDZ is uncertain (= not sufficiently reliable)
- Uncertainty is mainly coupled to the stress state of the EDZ
- Common mode “failure” cannot be excluded reliably at present
- EDZ is the weakest spot of a shaft or tunnel seal

Consequence: Better understanding of EDZ is decisive to show and to improve safety function of a shaft or tunnel seal. If safety function of 2 independent seals is successfully proved scenario classification becomes simple and transparent.

Comparison: Safety Case and EN Procedures

FEP, system concept ↓	Identifcation of structural system*), actions and design situations ↓
Safety concept, assessment cases ↓	Combination of actions considering different design situations ↓
Safety assessment ↓	Determining state variables (effect of actions) considering relevant combinations and design situations ↓
Analysis of consequences ↓	Comparison of state variables (effect of actions) and design criteria, statement on safety function ↓
Analysis of what-if cases, robust safety statement	Reliability analysis**)

*) Safety concept is included **) Not considered explicitly

Applying EN to an HLW – repository in rock salt helps

- to link “long-term SA” and the proof of safety function of geotechnical barriers
- to derive and apply adequate technical specifications and procedures
- to indicate issues that cannot reliably be proven at present

Agreeing with EN is fundamental for licensing

EN is an excellent tool to identify the most urgent R&D

Next steps

- Investigations to check to consequences of different working lives for geotechnical barriers required in “long-term SA” and EN
- Coupling of the risk based engineering approach to prove safety function and the dose based approach to prove radiological safety

DBE TECHNOLOGY GmbH

Thank you for your attention!

BACKFILL COMPACTION AND EDZ RECOVERY

Tilmann Rothfuchs, Klaus Wieczorek
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany

Abstract

Most concepts for the disposal of radioactive waste in geological salt formations consider backfilling with crushed salt as a suitable measure to stabilize the underground repository and to provide long-term sealing of the waste from the biosphere by compaction of the backfill in consequence of room convergence.

In Germany, two emplacement concepts have been developed for the disposal of heat generating waste in a salt repository: First, ***the drift disposal concept*** for the direct disposal of spent nuclear fuel elements which considers the emplacement of self-shielding Pollux-disposal casks in underground drifts. Immediately after deposition of the casks the empty drift volume is backfilled with crushed salt. Second, ***the borehole disposal concept*** which considers the disposal of cut spent fuel rods in BSK-3-canisters or vitrified high-level waste from reprocessing of spent fuel in Cogéma steel canisters in up to 300-m-deep vertical boreholes. To provide for distribution of the canister weight load into the rock mass, the annulus between waste canisters and borehole wall is backfilled with crushed salt in case of the borehole disposal concept. In addition, to isolate the waste canisters from the drift, the remaining empty space of about 30 to 40 m between the top of the canister stack in the borehole and the drift may also be backfilled.

In contrast to the consideration of altered scenarios in the past, a new approach focusing on the proof of the safe containment of the waste within an Isolating Rock Zone (IRZ) is currently pursued in Germany. The radioactive waste is contained inside the IRZ in such a way that it essentially remains at the site of emplacement and that not more than minimal defined quantities of material are able/allowed to leave the IRZ [1]. The proper function of the IRZ is jointly guaranteed by the host rock in this zone and the engineered barrier system (EBS) consisting of technical seals and salt backfill.

Within the IRZ, the engineered barrier system plays an important role in the proof of long-term safety of the repository system. The seals in the shafts and connecting drifts are essential features to avoid an intrusion of brine from the overburden into the mine and especially into the disposal cell. In case of failure of a seal, another seal takes charge of the safety function within a multi barrier series arrangement. In the long term, the seal function of the EBS is taken over by the compacted backfill in the entire mine because a technical seal may fail due to its limited long term stability.

The assessment of the seal function of both the technical seal and the backfill in addition to that of the geological barrier represents an important task in long-term safety analyses. The credibility of the used models is significantly increased if the modeling results are in reasonable agreement with measuring results from large-scale field experiments performed under representative conditions. The TSDE experiment (Thermal Simulation of Drift Emplacement) and the DEBORA experiments (Development of Borehole Seals for Radioactive Waste) performed at the Asse mine/Germany within the BAMBUS project [2] were such large-scale simulation experiments.

In the TSDE experiment representing the direct drift disposal of spent fuel, six simulated Pollux casks were deposited in two test drifts backfilled with crushed salt. The decay heat of the spent fuel was simulated by electric heaters in the casks. Heating was kept up with a constant power over almost nine years from September 1990 until February 1999. The maximum temperature of 210 °C decreased to 170 °C at the termination in consequence of backfill compaction and increasing thermal conductivity. Until the end of the heating period, drift convergence led to a reduction of backfill porosity from initially 35 % to 20 % in the heated area. For the final confirmation of the achieved backfill compaction the drifts were uncovered after

termination of the experiment. A detailed determination of the remaining porosity and permeability distribution in the backfill material was performed during a post-test analysis program [3].

The DEBORA experiment consisted of two single tests simulating different conditions in a backfilled HLW disposal borehole. Both experiments were performed at the 800-m level of the Asse mine in 15 m deep boreholes with a diameter of 0.6 m. In DEBORA 1 the situation in the annulus between the waste canister stack and the borehole wall was investigated. In DEBORA 2 a non-lined borehole was used to simulate the seal region above the waste canister stack. The heat production of the waste canisters was simulated by four peripheral heaters located at a radius of 1.1 m from the borehole. The lower third of both boreholes was backfilled with crushed salt. Backfill temperature, borehole closure, and resulting backfill pressure were measured at three levels in the backfilled boreholes. Maximum backfill compaction to a remaining porosity of about 7% was achieved within a two years lasting test period.

Reduction of porosity close to that of the sound rock salt was not reached within the experimental period in both experiments, but are expected in a repository in the long term. However, data of both tests together with data from accelerated laboratory tests have been used for the calibration of constitutive models used by different institutions. It is important to mention that larger model uncertainties still exist in the porosity range below 1% due to limitations regarding the determination of very small porosity which is of special importance in long term safety assessments. Respective investigations will therefore be initiated in a new project named REPOPERM.

Evolution and especially re-compaction of the EDZ was and is still a further important issue within the German research program because of the above-mentioned new approach of the safe containment.

Three related projects were performed in the Asse salt mine during the recent 20 years. The first was the ALOHA project in which the extent and hydraulic properties of an EDZ under the floor of a drift were investigated [4]. The second was the EC-funded BAMBUS II project [3] which concentrated on EDZ anisotropy and self-sealing; the third project ADDIGAS [5] within the EC-funded NF-PRO project was completed in 2007 and investigated the effectiveness of EDZ removal and the subsequent evolution of a new EDZ.

Finally, the EC project THERESA (2007 - 2009) was performed to extend the geo-scientific data bases for an in-depth understanding of THM coupled processes and to provide advanced modeling capabilities for assessing the evolution of the EDZ before and after closure of the repository.

In situ investigations performed at Asse revealed that, depending on stress conditions and history, the EDZ can extend one to two metres into the rock salt. Permeability can increase by several orders of magnitude up to the range of 10^{-14} to 10^{-13} m^2, with the permeability of the undisturbed salt being below 10^{-20} m^2. EDZ removal by additional excavation is effective in the sense that it takes years for a new EDZ to evolve. The long-term evolution of the EDZ, particularly its re-compaction, however, is to be assessed by numerical simulations on the basis of models adequately validated with experimental data.

Hence, the focus of the salt group in the THERESA project has been on modeling of rock salt dilatancy and on re-compaction or healing effects. Since reliable data on these phenomena are scarce, laboratory experiments with different objectives were performed to produce data for further model calibration. A benchmark simulation of a laboratory test case was defined and performed using the calibrated models. Finally, one of the models was used to predict EDZ evolution and re-compaction around a sealed drift and the results were used as input for the analysis with GRS's Total System Performance Analysis (TSPA) code module LOPOS.

A special benefit of THERESA was that practically all European institutions that work in the field of radioactive waste disposal in rock salt were joined in the THERESA project. The THERESA project partners were BGR, CIMNE, DBE-TEC, FZK, GRS, IfG, NRG and TUC [6].

The shortcomings of characterization and modeling of the EDZ in rock salt, as they present themselves after THERESA, can be summarized as follows:

- The database for calibration of the models, i.e., the number of available well-defined and documented experiments, was not sufficient, even though additional laboratory tests for

THERESA were performed outside the EC funding. Additional experiments will be indispensable for sound model calibration.

- As a consequence, the calibration had to be carried out on a weak database and is therefore incomplete.
- Some models showed weaknesses during test case simulation and need further improvement.
- TSPA modeling was based on only one process-level model, which itself is not sufficiently calibrated and validated.

On the whole, however, THERESA was a success, as it provides a sound and complete basis for further investigations, especially with regard to the EDZ in rock salt. This future work, which is considered indispensable for completion of the EDZ complex, should comprise

- Further experimental investigation with well-defined objectives and boundary conditions to complete the database on dilatancy and recompaction, including investigation of brine influence on EDZ recompaction,
- Further development of some and extended calibration of all of the process-level models, including validation of their suitability for in-situ application,
- Implementation of time-dependent EDZ permeability functions derived from comprehensively calibrated models in the TSPA codes, and
- Performing reliable predictions of the impact of brine inflow into a repository with realistic assumptions.

References

[1] BMU (2009): Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste.- Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Berlin, July 2009 (Source: Homepage of BMU).

[2] Bechthold, W., Rothfuchs, T., Poley, A., Ghoreychi, M., Heusermann, S., Gens, A., Olivella, S., 1999: Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS Project), Final Report, European Commission, EUR19124 EN

[3] Bechthold, W., Smailos, E., Heusermann, S., Bollingerfehr, W., Bazargan Sabet, B., Rothfuchs, T., Kamlot, P., Grupa, L, Olivella, S., Hansen, F.D. (2004): Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS-II Project), EUR 20621, Commission of the European Communities

[4] Wieczorek, K., and Zimmer, U. (1998): Untersuchungen zur Auflockerungszone um Hohlräume im Steinsalzgebirge, Final Report, GRS-A-2651, Braunschweig, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH.

[5] Jockwer, N. and Wieczorek, K. (2007): Excavation Damaged Zones in Rock Salt Formations, 6th Conference on the Mechanical Behaviour of Salt (SaltMech6) -Understanding of THMC Processes in Salt Rocks, Hannover, May 22 - 25, 2007.

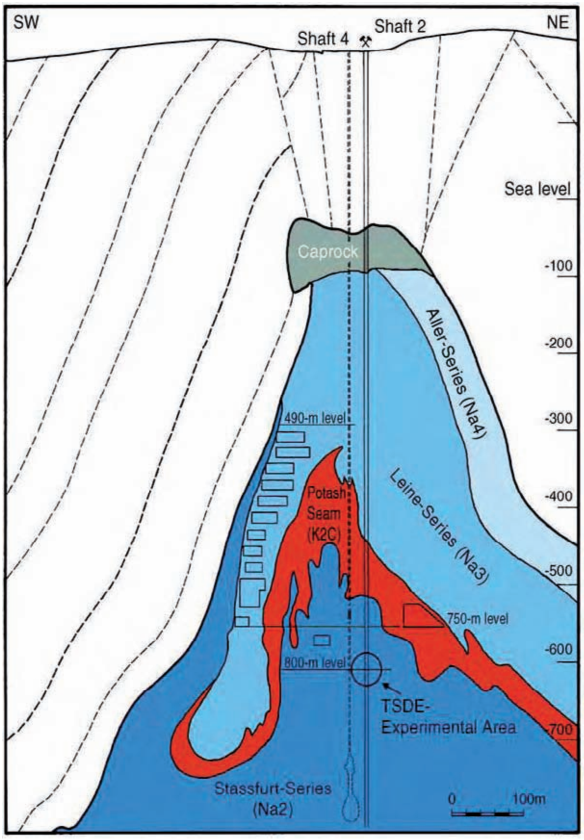
[6] Wieczorek, K., Rothfuchs, T., Förster, B., Heemann, U., Olivella, S., Lerch, C., Pudewills, A., Kamlot, P., Grupa, J., Herchen, K., 2009: Coupled Processes in Salt Host-Rock Repositories, Final Report of Work Package 3, THERESA project, Deliverable D9, Commission of the European Communities, Brussels

Backfill Compaction and EDZ Recovery

Tilmann Rothfuchs, Klaus Wieczorek
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
D 38011 Braunschweig, Germany
P.O. Box 2126

Overview of Presentation

- Status of Research on Backfill Compaction
  - Results of the TSDE Experiment
  - Results of the DEBORA Experiment
  - Plans for ongoing Research: the REPOPERM Project
- Status of Research on EDZ Evolution/Recovery
  - Results of the ALOHA Project
  - Results of the THERESA Project
  - Plans for ongoing Research
- Conclusions and Outlook



Asse salt mine

- Shaft sinking 1906 -1908
- Salt mining 1908 – 1964
- Testing of radioactive waste disposal 1967 – 1978

- Underground research laboratory 1978 – 1995 (2003)
- Backfilling and closure 1994 – 2020?

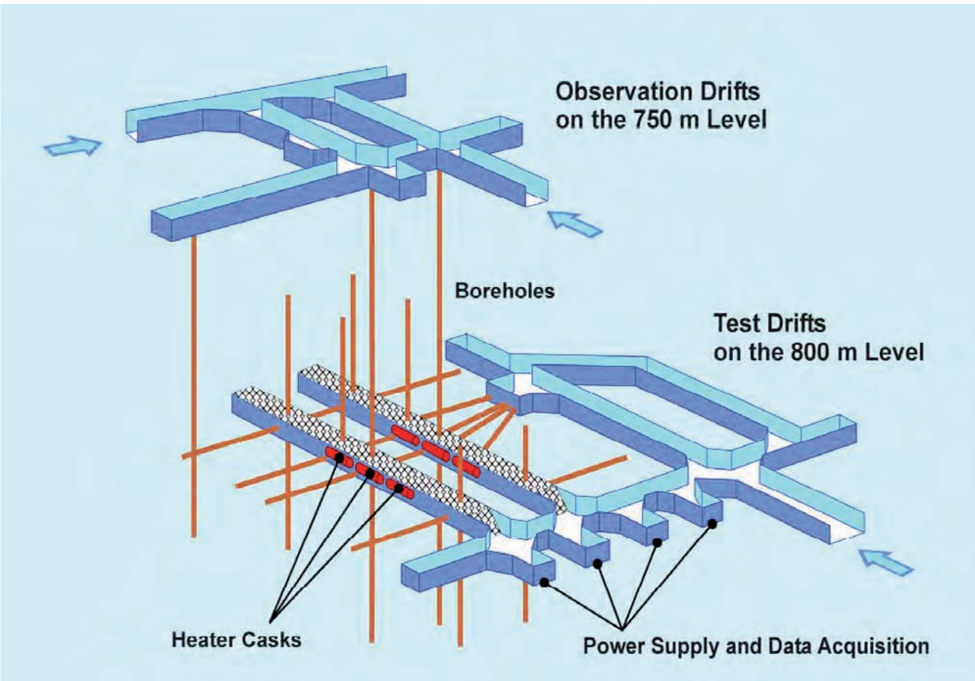
Underground Testing at the Asse Mine

Test/Experiment	Period
Thermal Simulation of Drift Emplacement (TSDE) Post Test Analysis of the TSDE experiment	1990 – 2000 2000 – 2004
DEBORA-Project (Development of Seals for HLW disposal boreholes)	1991 – 1995 (Phase I) 1996 – 1999 (Phase II)
Investigation of the Excavation Damaged Zone (ALOHA) ALOHA 2 / BAMBUS II	1995 – 1998 1998 – 2003
Advective and Diffusive Gas Transport in Rock Salt Formations (ADDIGAS)	2004 – 2007

Backfill Compaction

GRS

TSDE Test Field at 800-m Level at the Asse Mine / Germany



Heating Phase
Sept. 1990 – Jan. 1999
8 years 4 months

Uncovering Phase
Aug. 2000 – May 2001

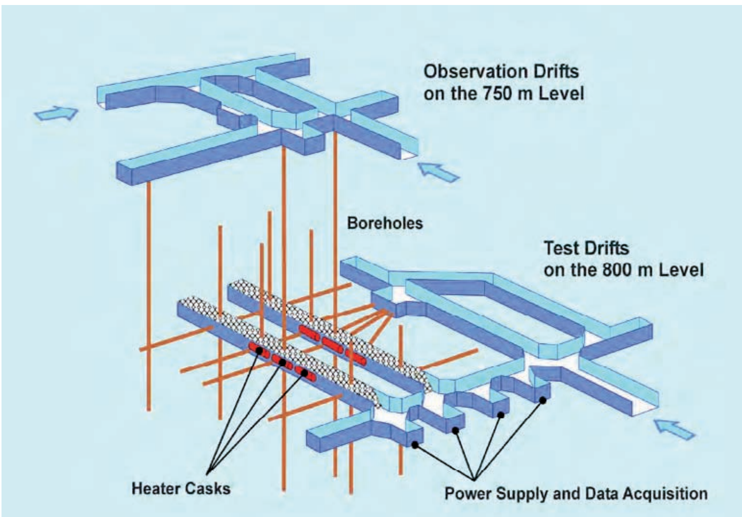
Post-Test Investigations
Aug. 2000 – Dec. 2002

Final Report Available
Summer 2003

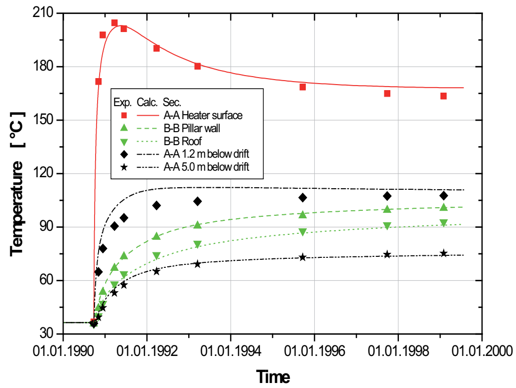
Overview of Codes and Constitutive Models Used in BAMBUS

Institution	Code	Const. Model	Remarks
BGR	DJIFE (3D)	Heemann (2003)	full 3D
DBETEC	$FLAC^{3D}$	Hein (1991)	full 3D
GRS	Ansys	Zhang (1993)	2D
NRG	MARC	Hein (1991)	full 3D
UPC	Code_Bright	Olivella-Gens	full 3D
FZK	FAST-BEST ADINA, MAUS	Hein (1991)	3D Temperature 2D Stress-Strain
G.3S	ANTHYC	G.3S	3D Temperature 2D Stress-Strain
IfG	$FLAC^{2D}$	IfG	2D

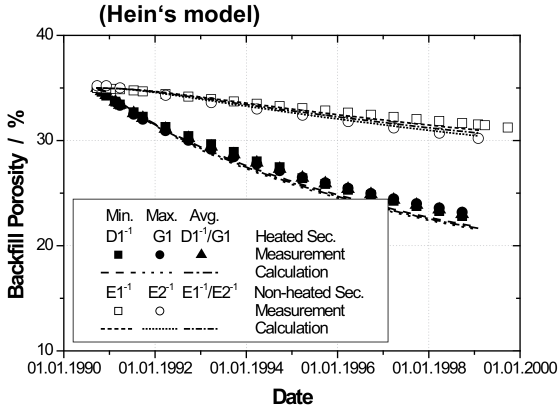
TSDE:
Comparison of Measured and Predicted Data (Improved 3D-Modelling in 2003, Final Report)



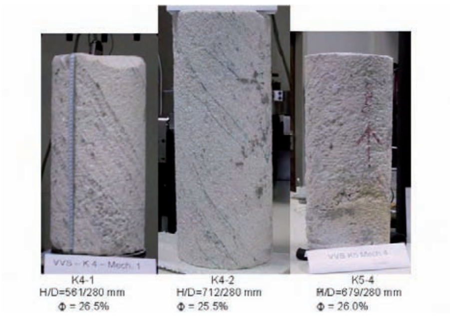
Temperature Evolution (DBETEC)

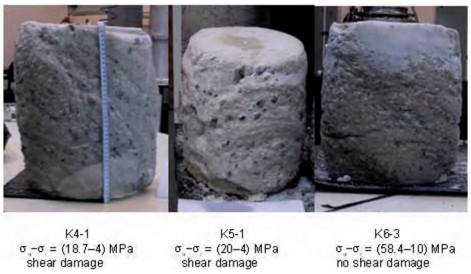


Backfill Compaction (DBETEC)
(Hein's model)



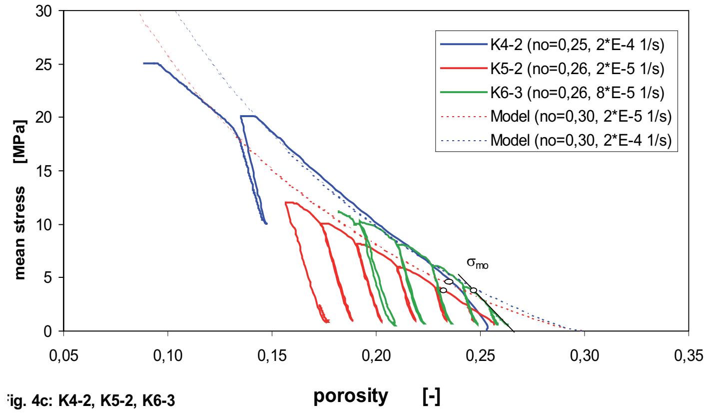
Post Test Investigation of TSDE Samples





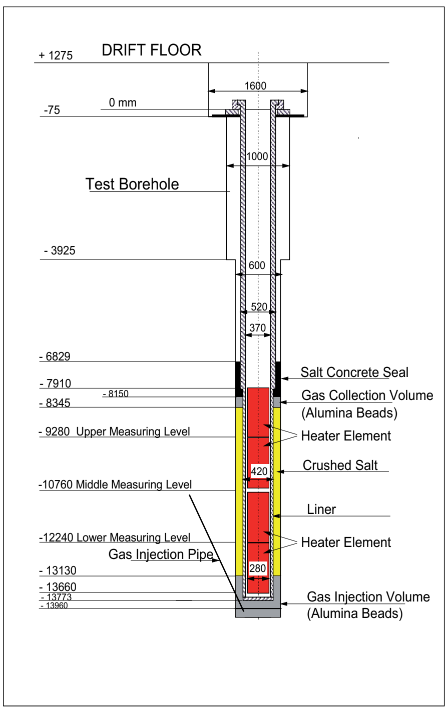
Zhang's model (1993)

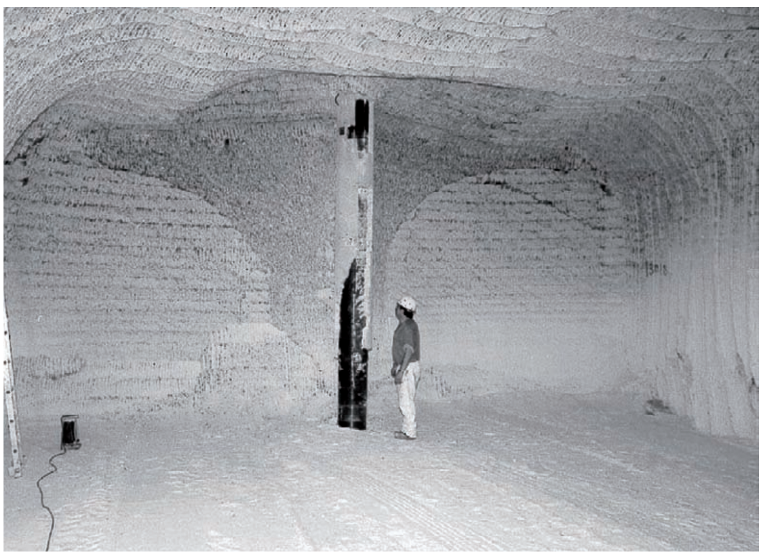
$$\dot{\varepsilon}^V = A \cdot \exp(-\frac{Q}{R \cdot T}) \cdot S^n \cdot (\ln(\frac{\varepsilon^{VE}}{\varepsilon^{VE} - \varepsilon^V}))^{-m}$$



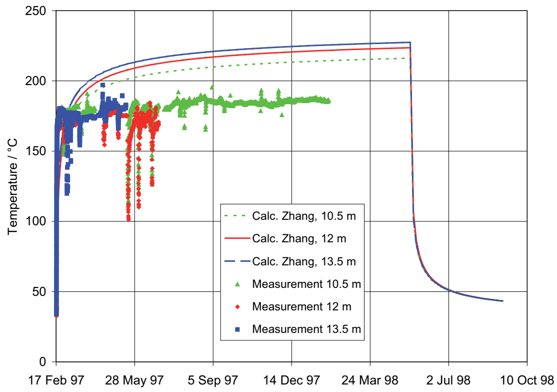
ïg. 4c: K4-2, K5-2, K6-3

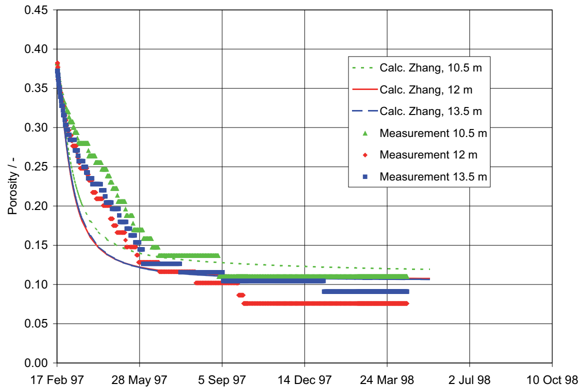
Post-Test Investigations in the DEBORA Borehole Experiment





Results of DEBORA





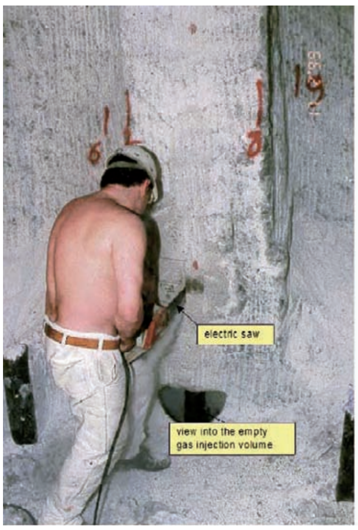
Temperature development Porosity development

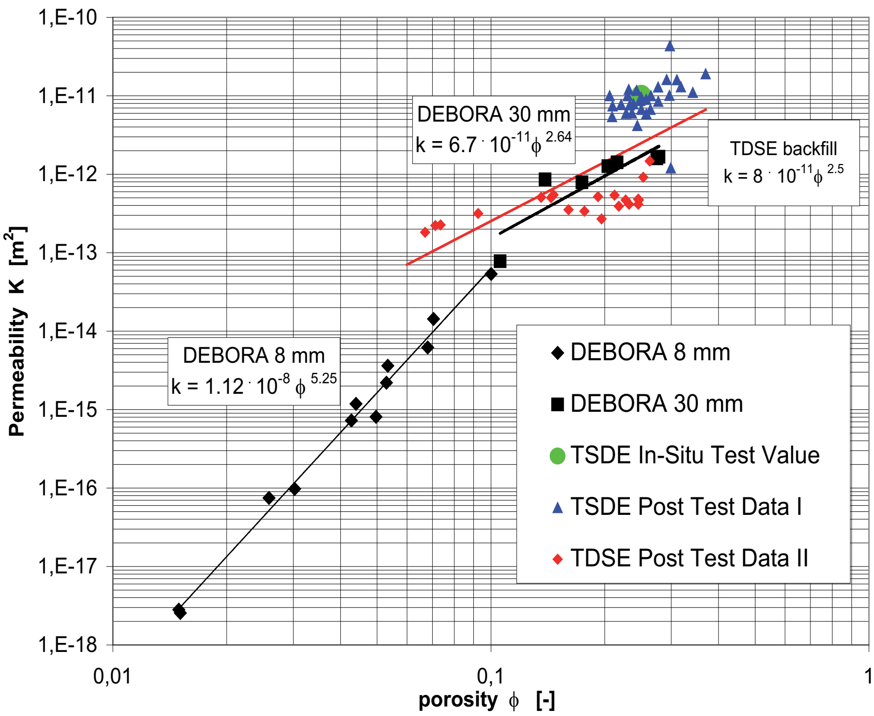
in the backfilled borehole annulus

Zhang's model confirmed by adequate agreement of measurements and predictions in the investigated porosity range

Results of DEBORA

Porosity/permeability relation obtained from DEBORA confirms older laboratory results of various investigators reported in Müller-Lyda et al. (1999)



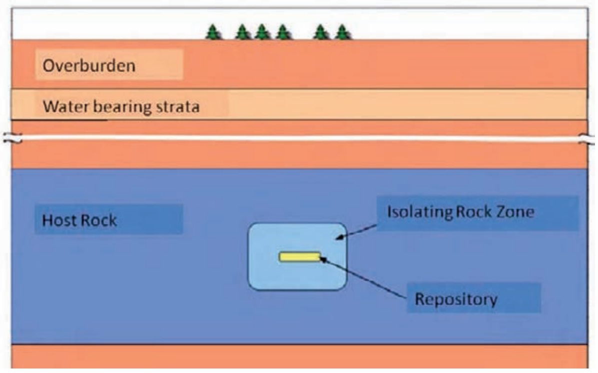


Conclusions Backfill Compaction

- Compaction of dry crushed salt has been investigated in the laboratory and *in situ* down to about 1%.
- Models available to date allow reasonable simulation in the range down to about 3%
- Data below 1% are scarce and suffer of uncertainties regarding reliable determination of material density/porosities
- Only little data from very few experiments at differing test conditions are available for wet crushed salt

Project REPOPERM

- Assessment of needs to further investigate the porosity range below 1% with a view to compliance with safety criteria for the **safe containment within the Isolating Rock Zone**
- Complete characterization of DEBORA reference material with focus on varying water content
- Reliable coupled THM-modeling for assessing the possible brine inflow into a repository (including two-phase flow)



EDZ Evolution/Recovery

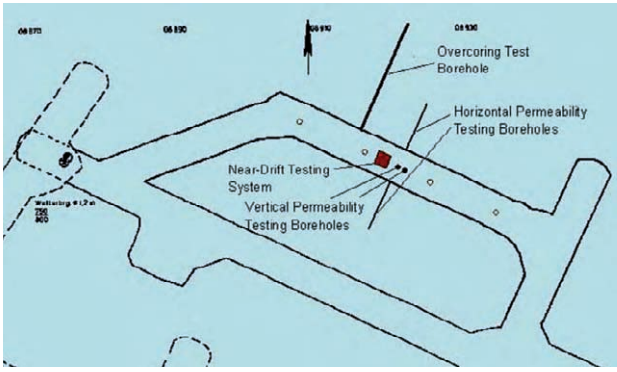
ALOHA / ALOHA 2 1995 - 2003

Objectives

- Determine extent and hydraulic properties of the EDZ around different openings at Asse
- Compare hydraulic properties (permeability) to mechanical state (stress state)
- Investigate hints to EDZ recovery in situ

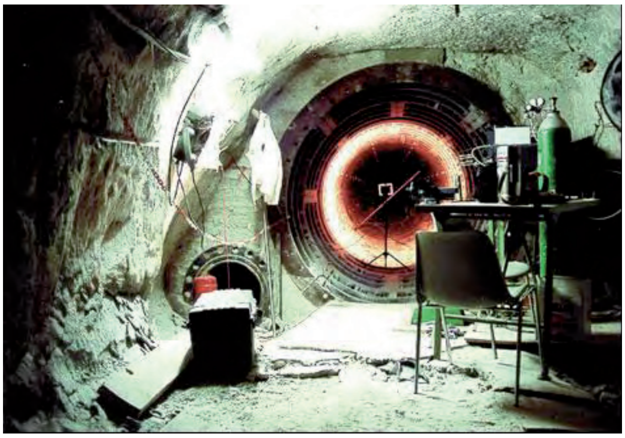
ALOHA / ALOHA 2 Test Sites

ALOHA Test Field on the 875-m level



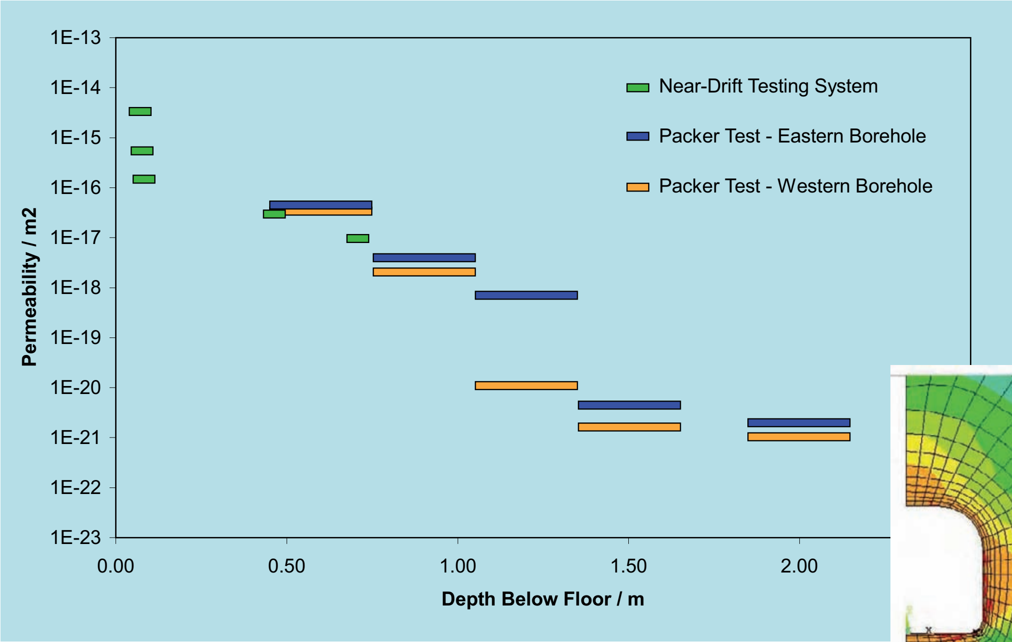
ALOHA 2: AHE drift on the 800-m level

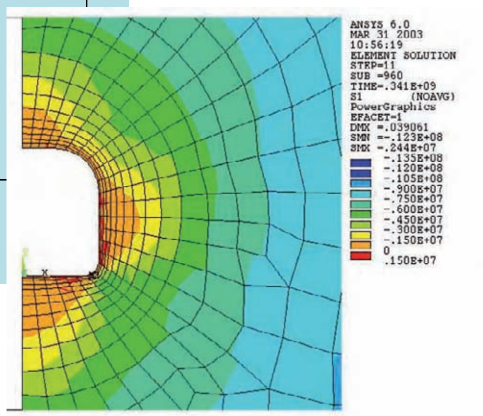
ALOHA 2: Old chamber on the 532-m level



ALOHA 2: Bulkhead drift on the 700-m level

ALOHA / ALOHA 2 Results: Permeability Distribution in the Drift Floor

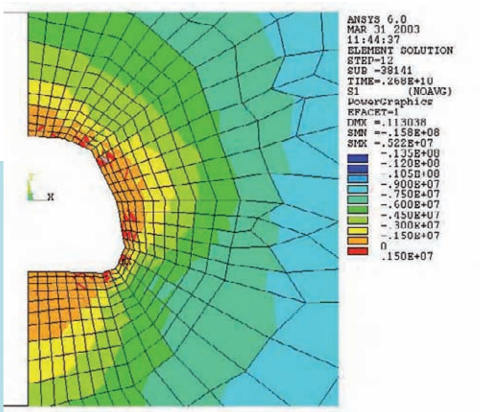


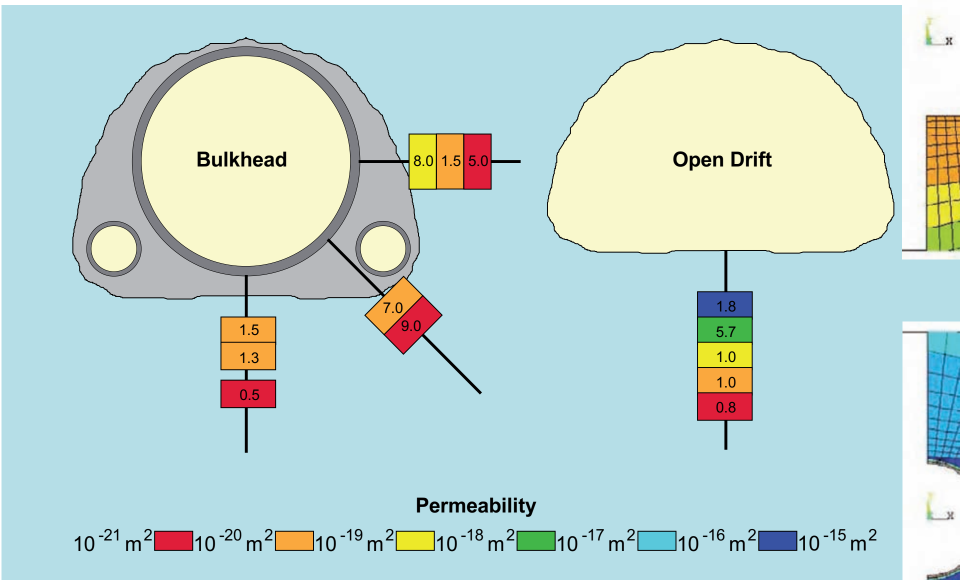


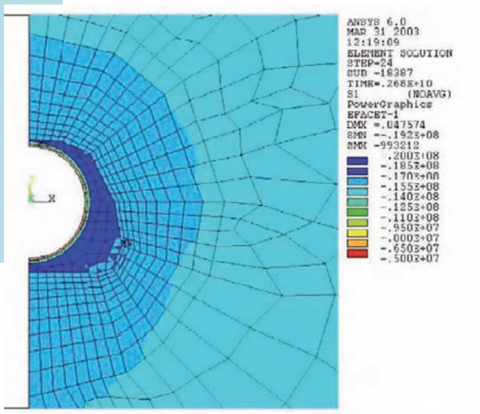
Modelled Minimum Principal Stress around the AHE drift

ALOHA / ALOHA 2 Results: Permeability Reduction around a Cast Steel Bulkhead emplaced 90 years ago

Modelled Minimum Principal Stress around the open Drift





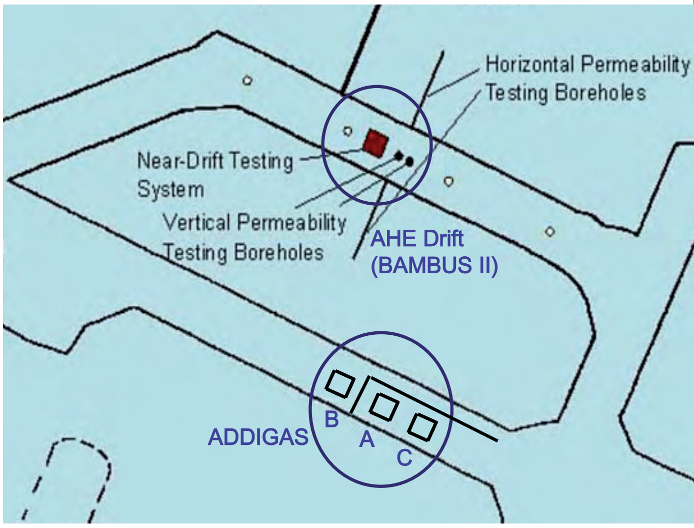


Modelled Minimum Principal Stress around the Bulkhead

ADDIGAS 2004 - 2007

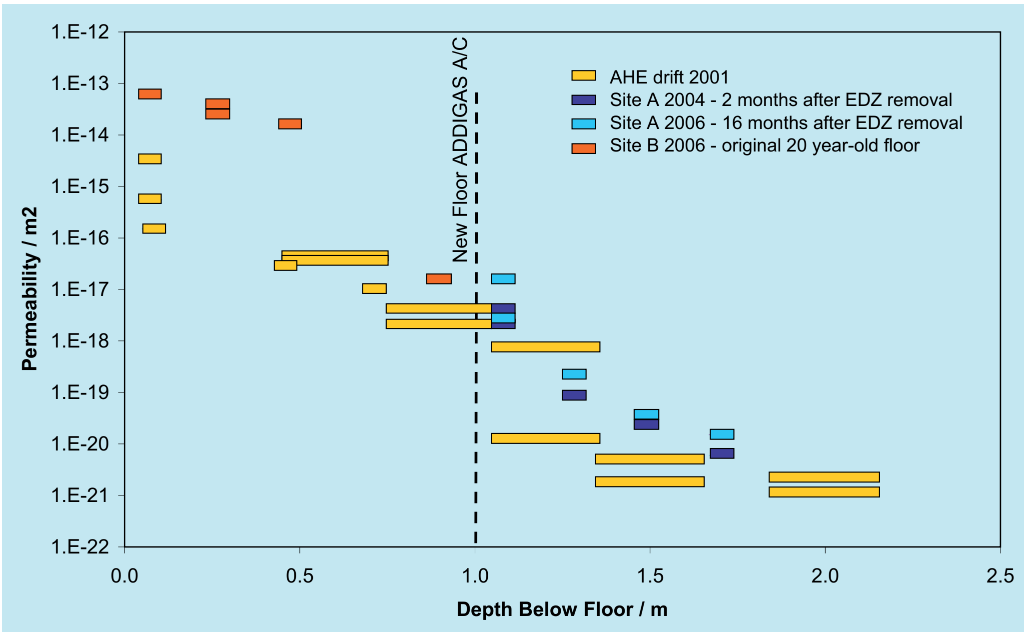
Objectives

- Investigate gas diffusion close to an excavation
- Investigate Gas and brine permeability close to the excavation as function of distance to excavation and time since excavation/EDZ removal
- Investigate anisotropy of permeability close to the excavation



ADDIGAS Conclusions (1)

- Both the permeability and the diffusivity of the salt below the floor are considerably higher if the EDZ is not removed
- After removal of the EDZ the hydraulic properties of the salt below do not change significantly within months, meaning EDZ removal is effective for improving seal performance



THERESA 2007 – 2009

Overall Objective:

Develop, verify and improve the modeling capabilities of constitutive models and computer codes for analysis of coupled THMC processes in geological and engineered barriers for use in Performance Assessment (PA) of the long-term safety of nuclear waste repositories

Work Package 3 (WP3) dealing with rock salt:

Evaluation and improvement of numerical modeling capabilities for assessing the performance and safety of nuclear waste repositories in rock salt, with particular regard to the long-term evolution of the EDZ, considering thermal-hydraulic-mechanical (THM) processes.

WP3 partners:

- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) as work package coordinator,
- Bundesanstalt für Geowissenschaften und Rohstoffe (BGR),
- DBE TECHNOLOGY GmbH (DBE TEC),
- Forschungszentrum Karlsruhe (FZK), Institut für Gebirgsmechanik (IfG),
- Technische Universität Clausthal (TUC),
- Centre International de Métodes Numèrics en Enginyeria (CIMNE),
- Nuclear Research and consultancy Group (NRG) with University of Utrecht (UU) as contractor.

THERESA WP3 Work Program

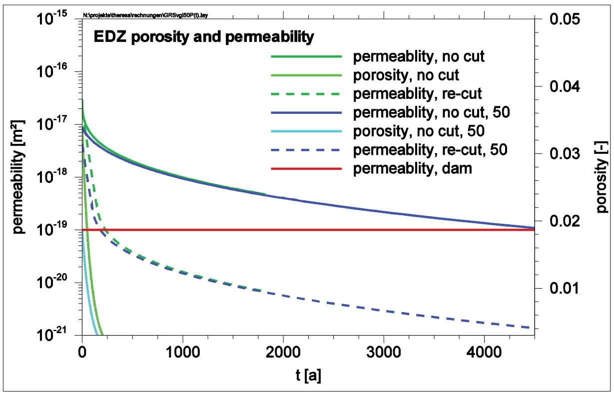
- Evaluation of the capabilities and/or development needs of the numerical modeling codes used by the participating teams and compilation of data relevant for model calibration/improvement
- Implementation of constitutive models in the computer codes and testing of the calibrated models
- Definition and benchmark simulation of a test case with measured data from a laboratory test involving coupled THM processes
- **Integration of the results of the process-level codes in a TSPA code and calculation of a repository reference case**

Involved codes

- Continuous medium and dilatancy concept: JIFE, CODE_BRIGHT, ADINA, FLAC^{3D}, FLAC
- Microphysical model for crack healing implemented in MARC
- Discrete element method: PFC^{3D}
- TSPA code module: LOPOS

THERESA WP3: Main Results

- Several approaches for modeling the THM behavior of rock salt were documented, improved, calibrated and tested successfully
- The **database** for the THM behavior of rock salt was **(slightly) broadened**
- **Time-dependent EDZ permeability was implemented in a TSPA code for the first time**, and first calculations concerning the significance of the EDZ around a drift seal in case of a brine intrusion via the shaft were performed



Conclusions Regarding EDZ Evolution

- The database for calibration of the models, i.e., the number of available well-defined and documented experimentsnot sufficient, so far
- As a consequence, model calibration had to be carried out on a weak database and is therefore incomplete
- Some models showed still weaknesses during test case simulation and need further improvement

Outlook

- Further experimental investigation with well-defined objectives and boundary conditions to complete the database on dilatancy and recompaction, including investigation of brine influence and pore pressure on EDZ recompaction
- Extended calibration of the process-level model implemented in CODE_BRIGHT
- Implementation of time-dependent EDZ permeability functions (“dry” and “wet” case) derived from comprehensively calibrated models in the TSPA code module LOPOS
- Perform reliable predictions of the impact of brine inflow into a repository with realistic assumptions

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

SCIENCE AND ENGINEERING OF SEAL DESIGN

Leo L. Van Sambeek
RESPEC
Rapid City, South Dakota

Science and Engineering of Seal Design

Leo L. Van Sambeek
RESPEC
Rapid City, South Dakota

Seal Purposes

- Mining
  - *Prevent water from entering*
  - *Prevent flood waters from exiting*
  - *Gas containment (abandoned areas)*
- Repositories
  - *Prevent water from entering*
  - *Prevent waste-contaminated water from exiting*
  - *Gas containment (waste panels)*

Seals in Mines

- Operating Mines
  - *Shaft liners and keys*
  - *Ventilation stopings*
  - *Panel bulkheads*
  - *Water dams and bulkheads*
  - *Borehole pillars*
- Closed Mines
  - *Shaft seals*

Seal Design

- Objective:
  - *"an engineered system in a mined opening that plugs the opening and restores near-ambient permeability within the surrounding rock"*
    - In other words – something that both plugs a hole and makes the rock around the hole nearly as tight as it was before mining
  - *Engineered systems (waste casks, backfills, and drift and shaft seals) are required until the geological-salt barrier encloses the waste material over time.*

PILLAR SHORTLY AFTER MINING (3 m Tall)

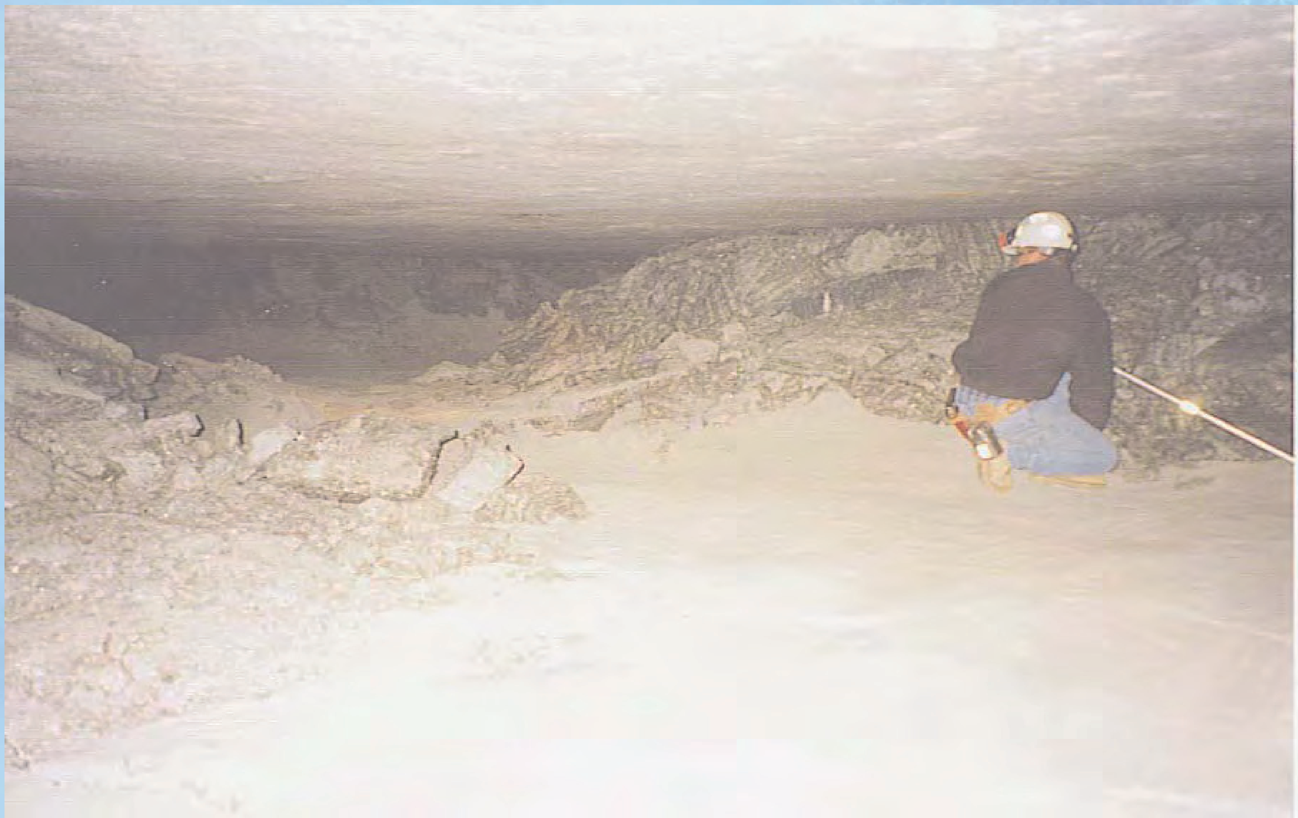
AFTER 10 INCHES (0.25 M) OF CLOSURE

15 INCHES (0.35 m) OF CLOSURE

511

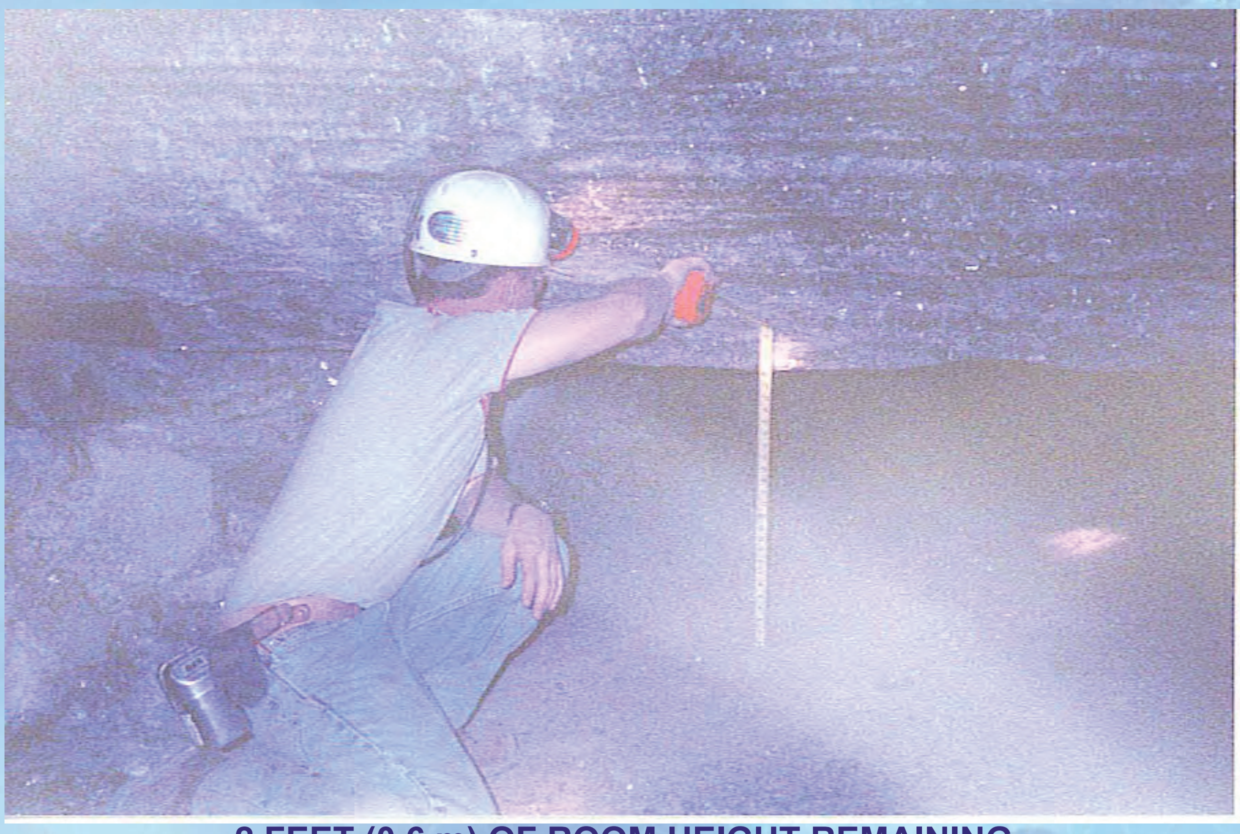
~36 INCHES (~1 m) OF CLOSURE

512



80 INCHES (2 m) OF CLOSURE

513



2 FEET (0.6 m) OF ROOM HEIGHT REMAINING

STARTED AT 9 FEET (3 m)

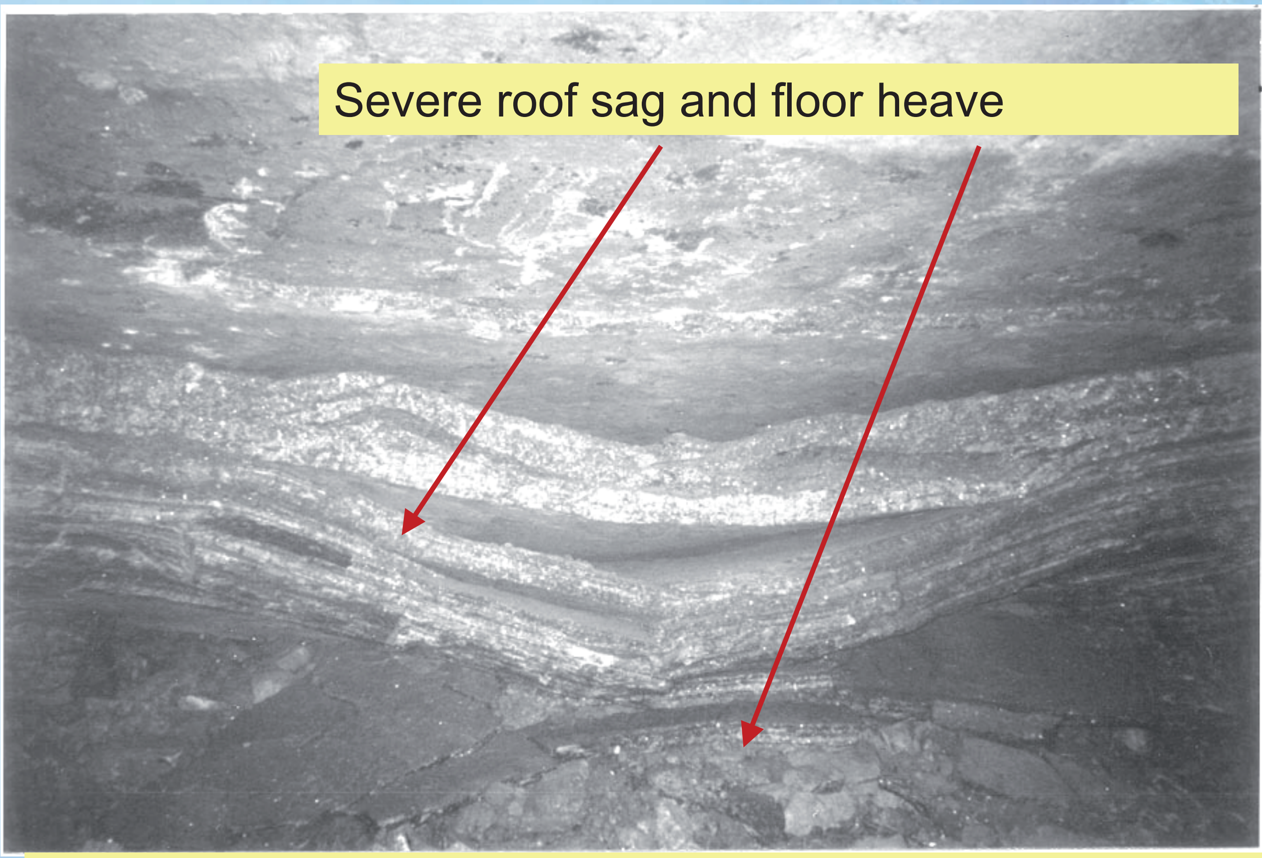
514

Total Closure

515

Roof Sag over 35-foot wide room (11 m wide)

516



Originally a 9-foot (3 m) tall opening

Seal Materials

- Engineering Specification
  - *Sufficient strength*
    - Creep loading
    - Non-uniform deformation
  - *Adequate permeability*
  - *Constructability*
  - *Redundancy*
    - Number of seals
    - Combinations of seal materials
- Science Expectation
  - *Age-related deterioration of strength or tightness*
  - *Geochemical compatibility*
    - Host rock
    - Waste and brine
  - *Sorbtive or buffering capacity*

Disturbed Rock Zone (DRZ)

- Definition –
  - *Rock around a mined opening whose properties were altered as a consequence of mining the opening*
  - *Primarily "permeability enhancement related to damage-induced porosity increases"*
- Examples
  - *Cracks and fissures*
  - *Slabs and separations*
  - *Grain-boundary loosening*
  - *Microfracturing*

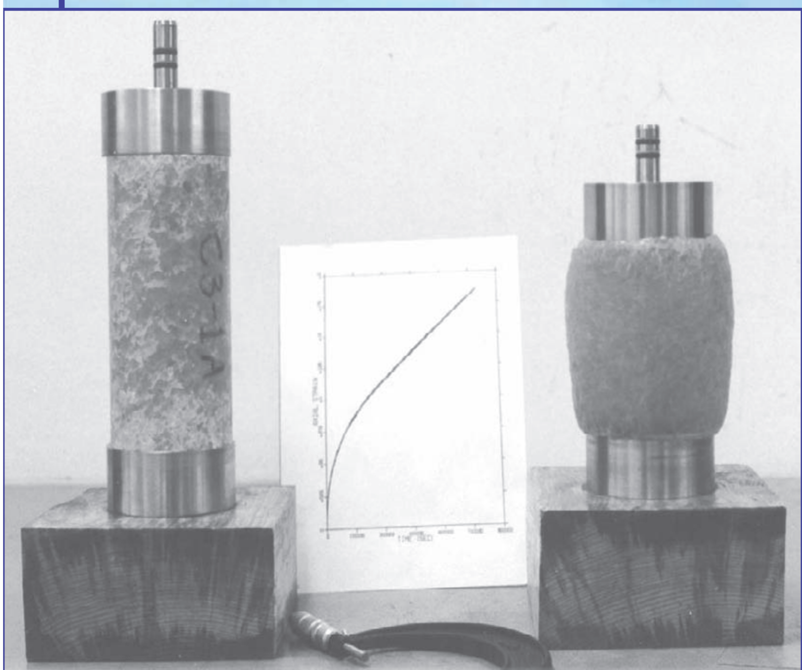
Options for Fixing the DRZ

- Remove damaged rock at seal location
- Use stiff liner to avoid DRZ; installed soon after mining
- Grout DRZ porosity; permeability reduction
- Delay seal's function until DRZ heals

Seal Materials

- Geochemically compatible cement-based
  - *Class H cement and Class C fly ash*
  - *Silica and calcium sulfate additives*
  - *Low salt-water to cementitious solids (w/c = 0.32)*
  - *Slightly expansive and lower heat-of-hydration to reduce thermal cracking*
- Re-compacted or re-consolidated crushed salt

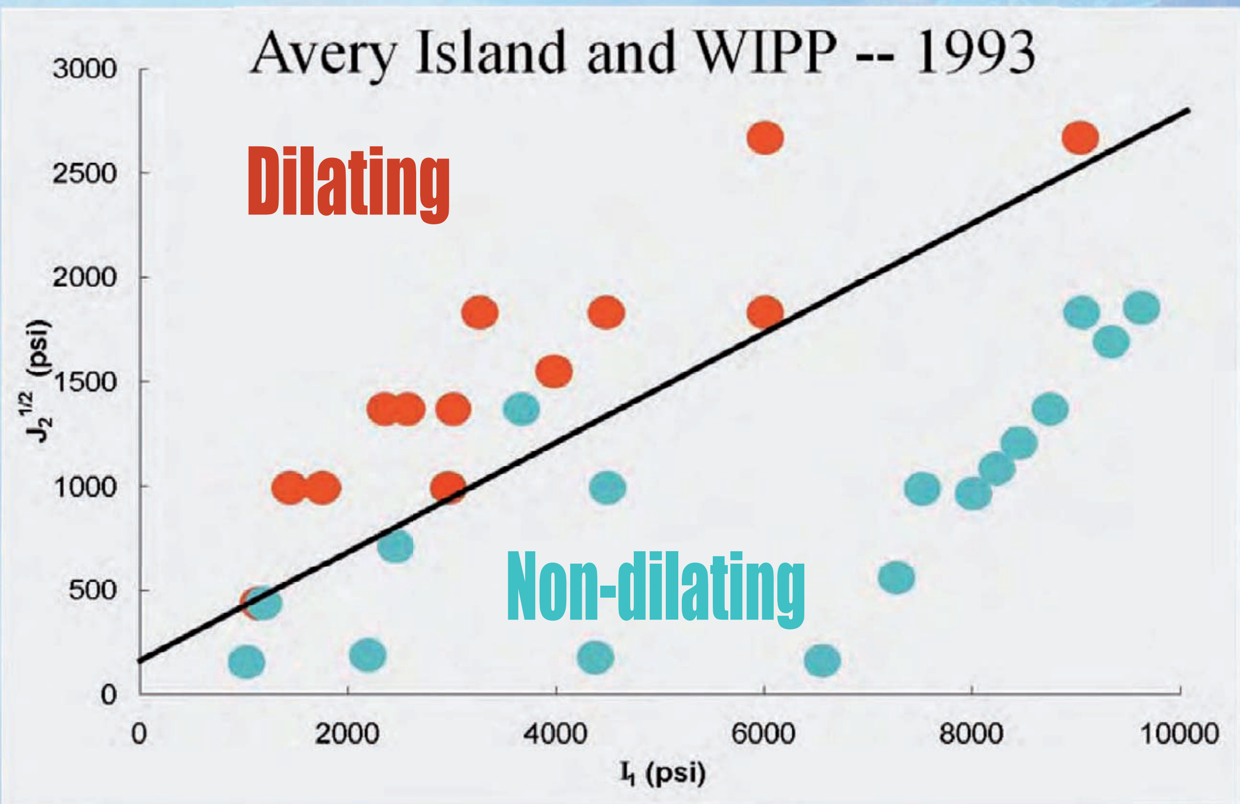
Deformation of Salt



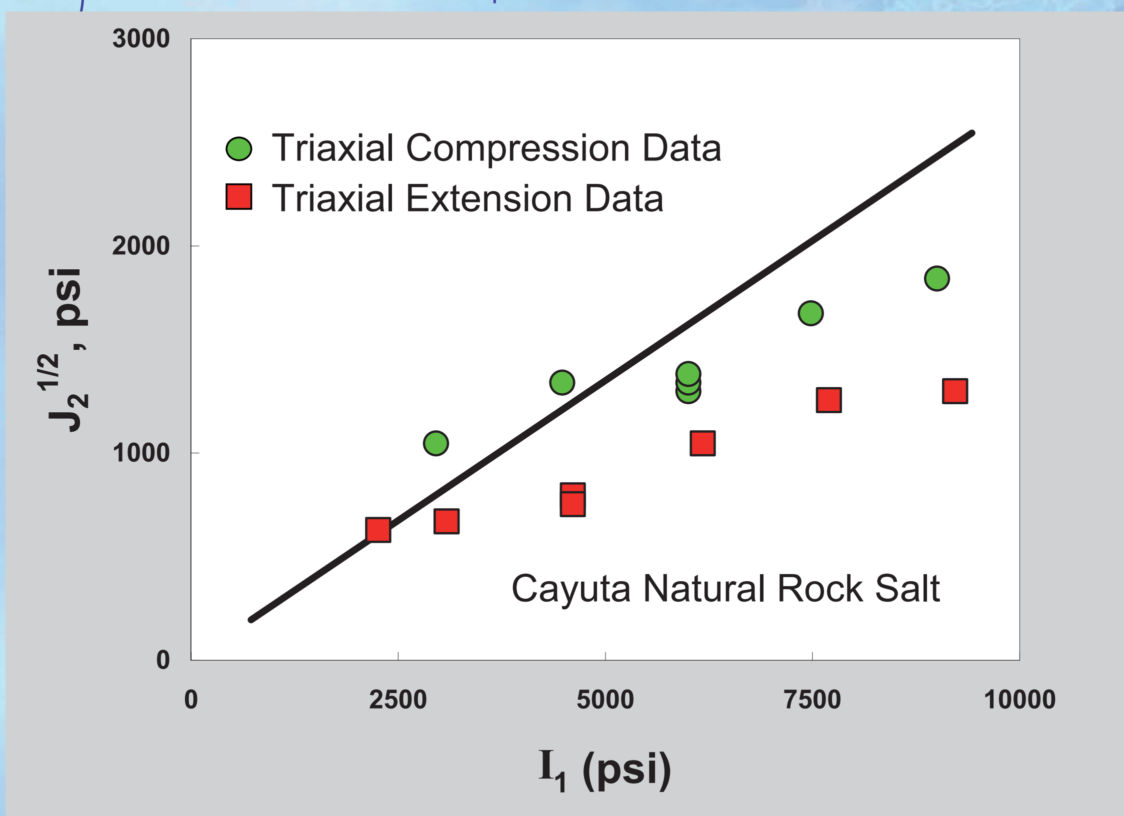
Pre-test **Post-test**

- **Creep is Isochoric**
  - ***Specimen shape changes but <u>volume remains constant</u>***
  - ***Creep is Unavoidable***
- **Damage is Dilatant**
  - ***Microfracturing causes <u>volume increase</u>***
  - ***Damage is Preventable***
- **Both Processes are Time-Dependent**

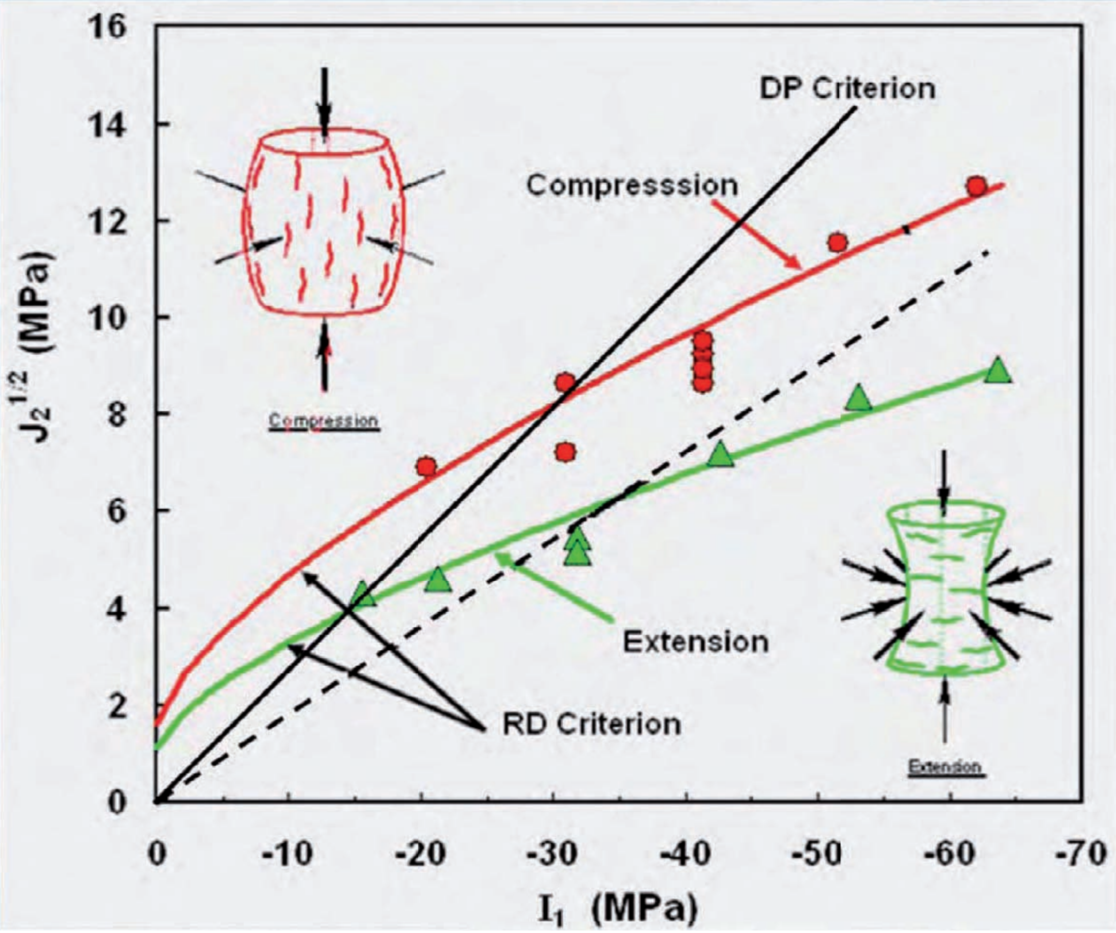
Engineering Approach Dilation



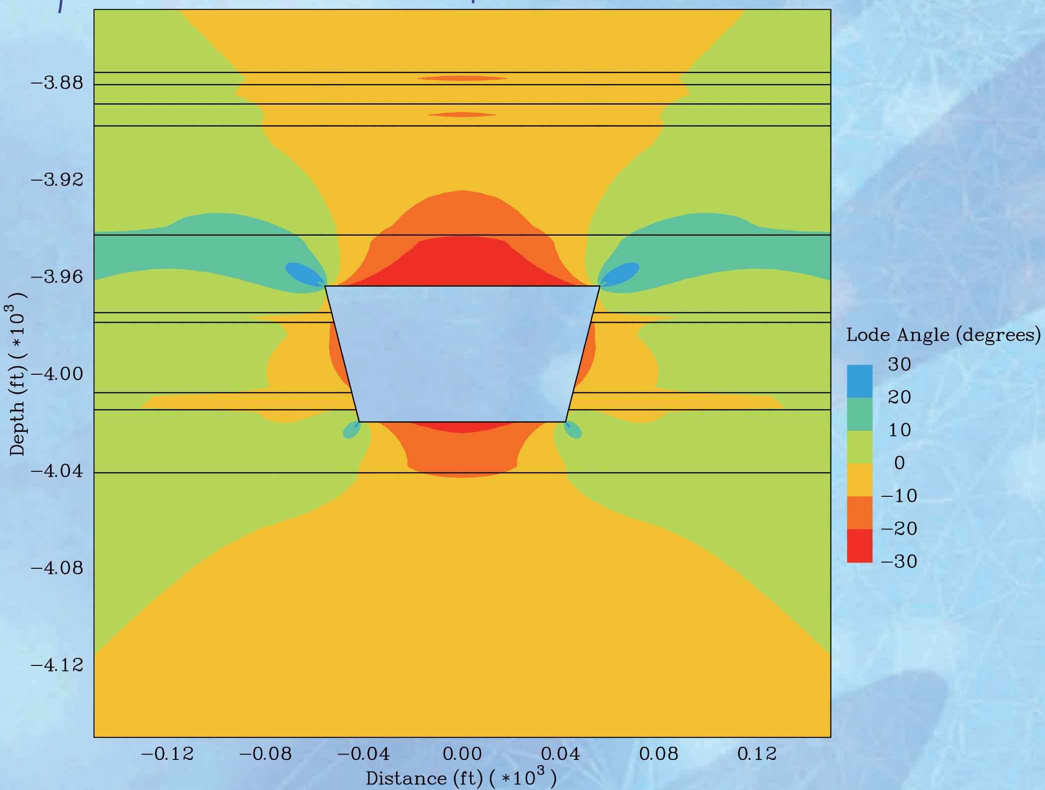
Science Suggests Something Else



Revised Criterion

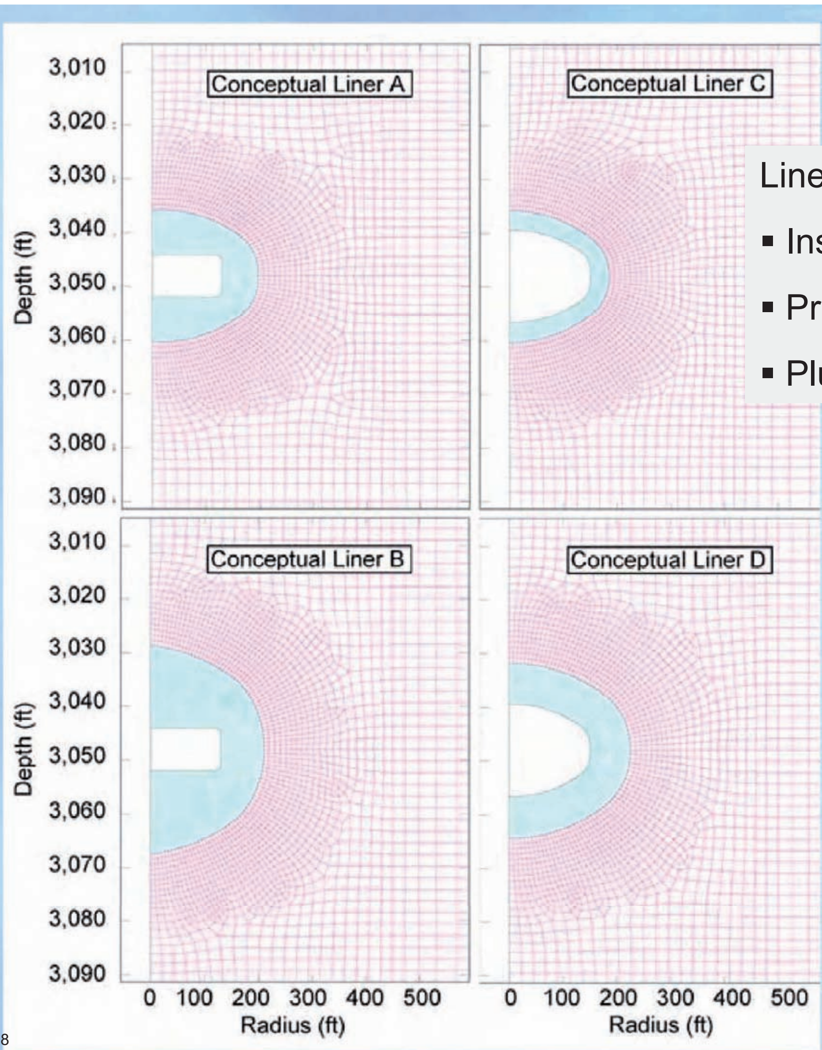


Triaxial Extension Dominates



RESPEC DILATION (RD) CRITERION

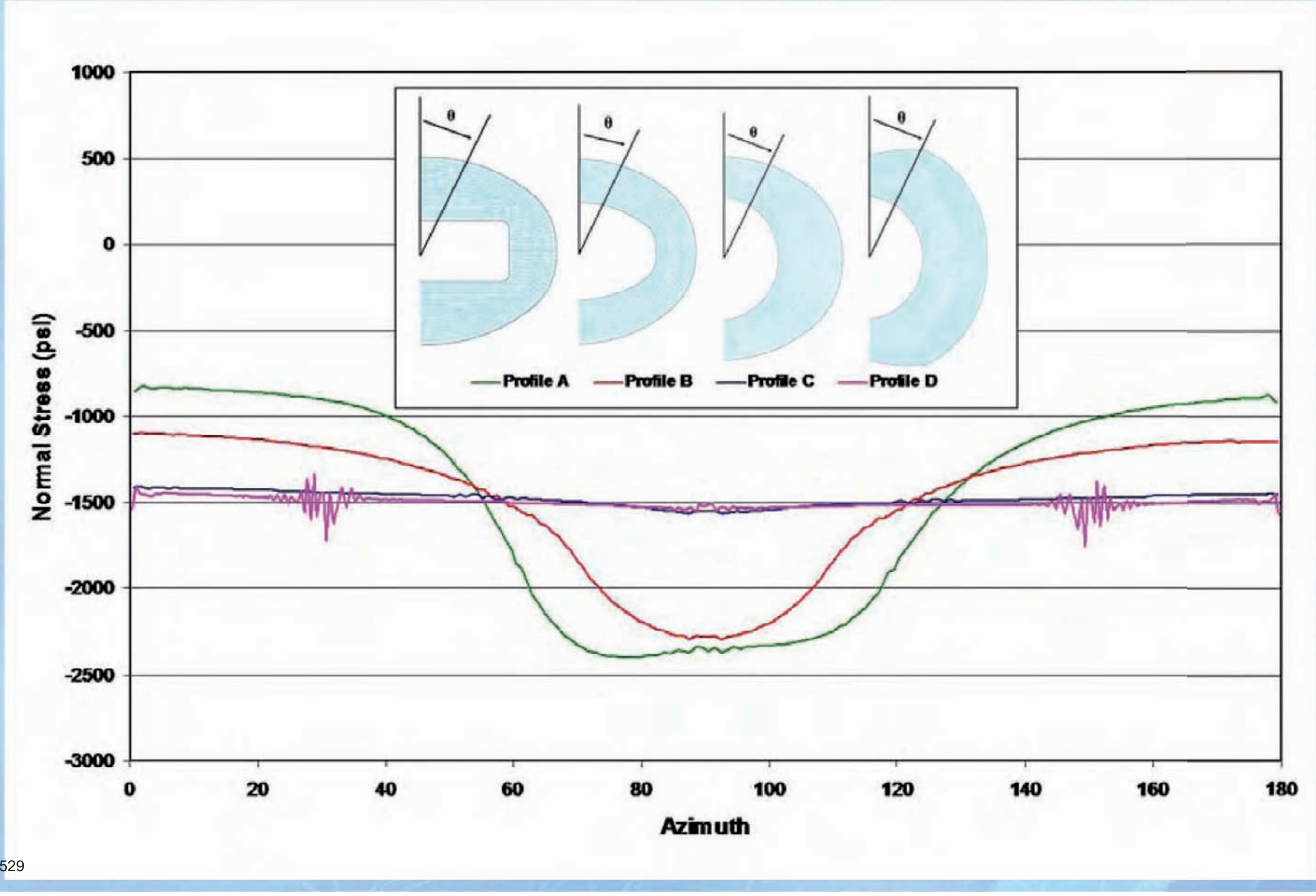
$$\sqrt{J_{2,dil}} = \frac{D_1\left(\frac{-I_1}{\sigma_0}\right)^n + T_0}{\sqrt{3}\cos(\psi) - D_2\sin(\psi)}$$



Liner Concept:

- Install stiff liner soon after mining
- Prevent DRZ from forming
- Plug the liner for permanent seal

Confining Stress on Liner (15 years)



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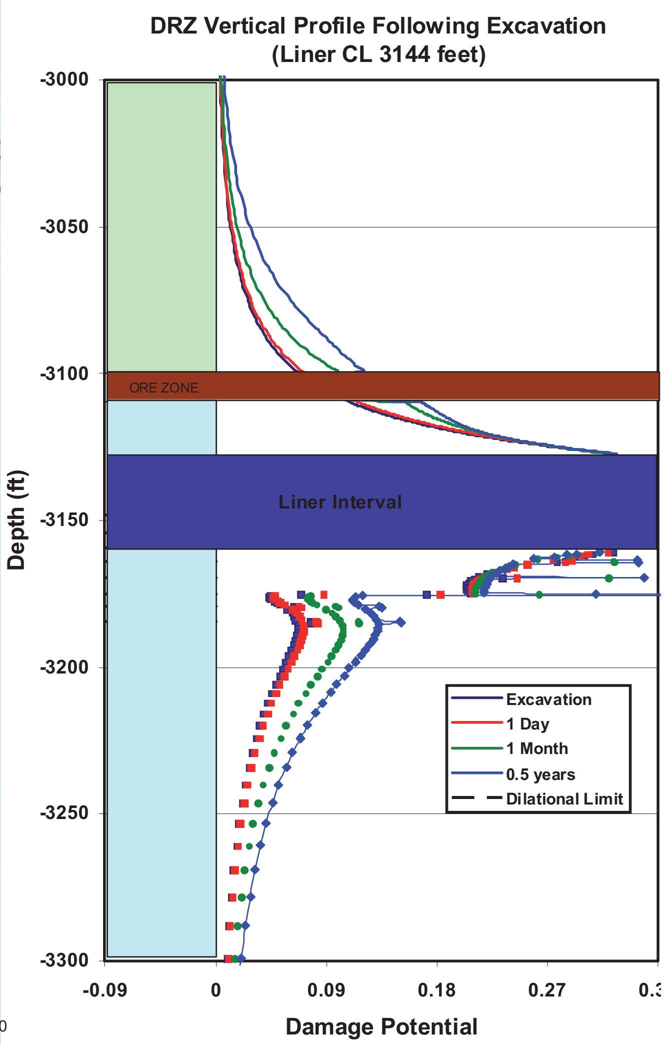

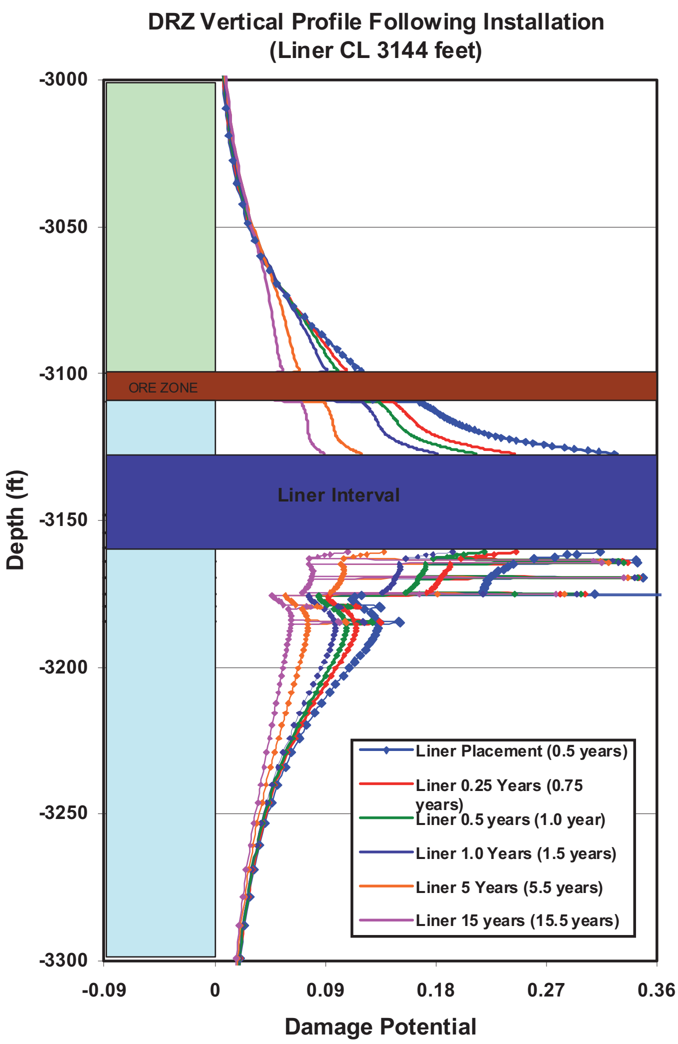

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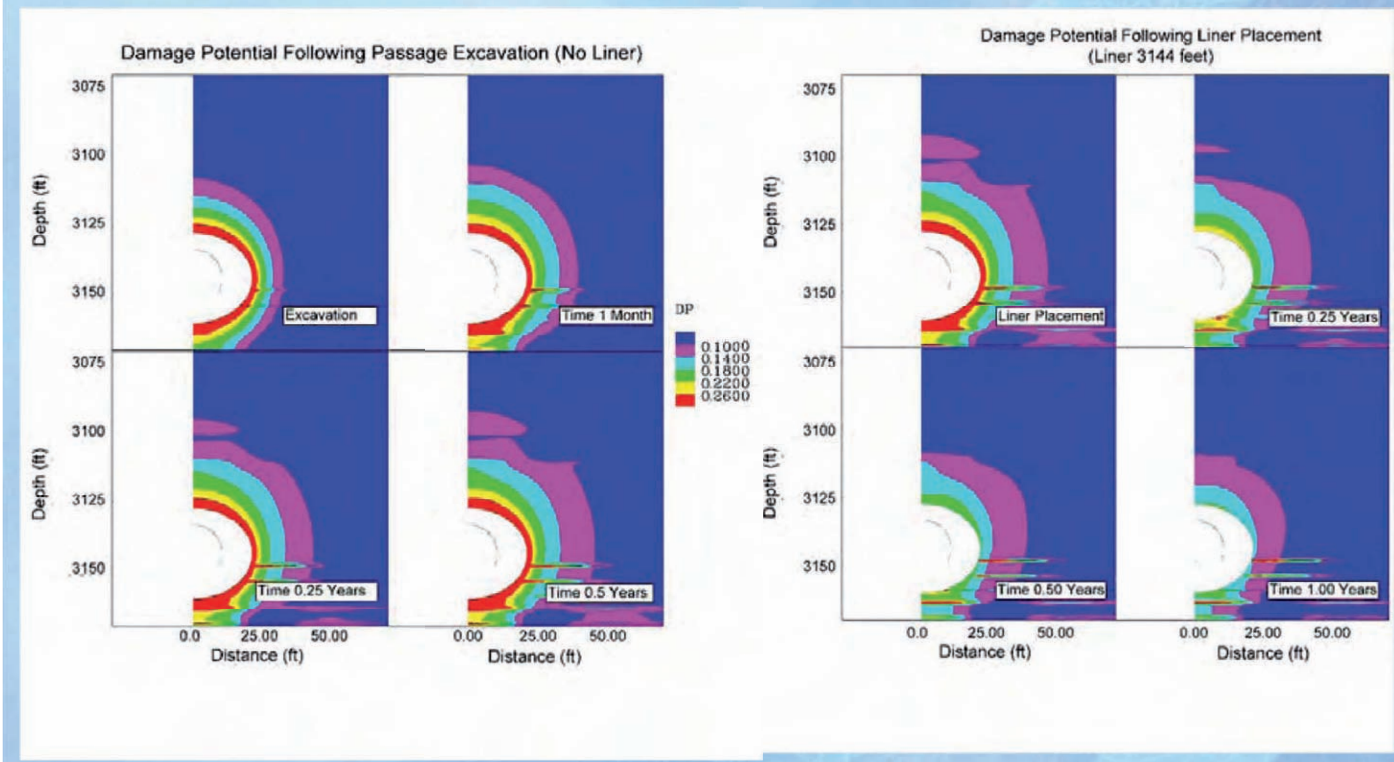
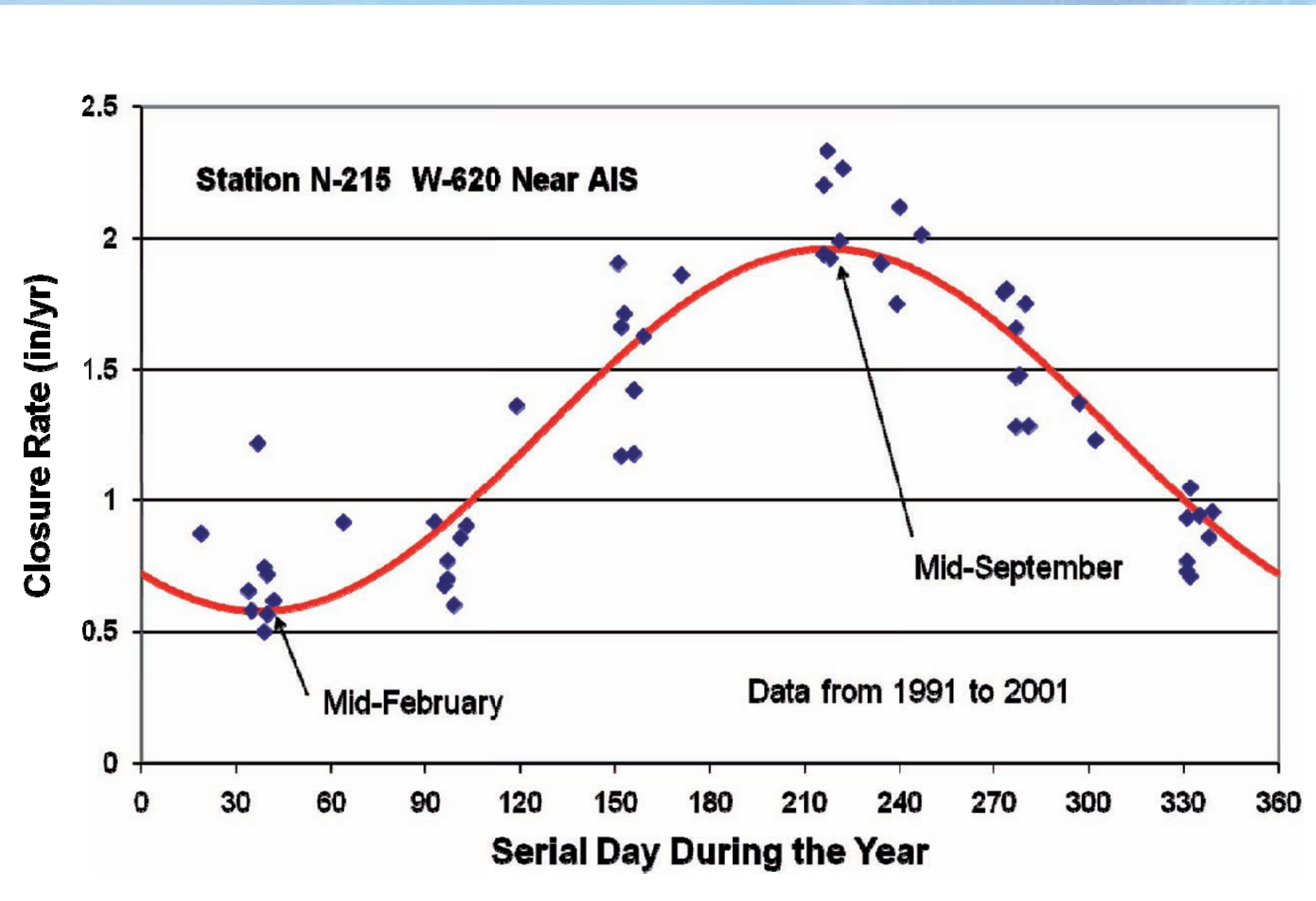
Damage & Healing in Salt

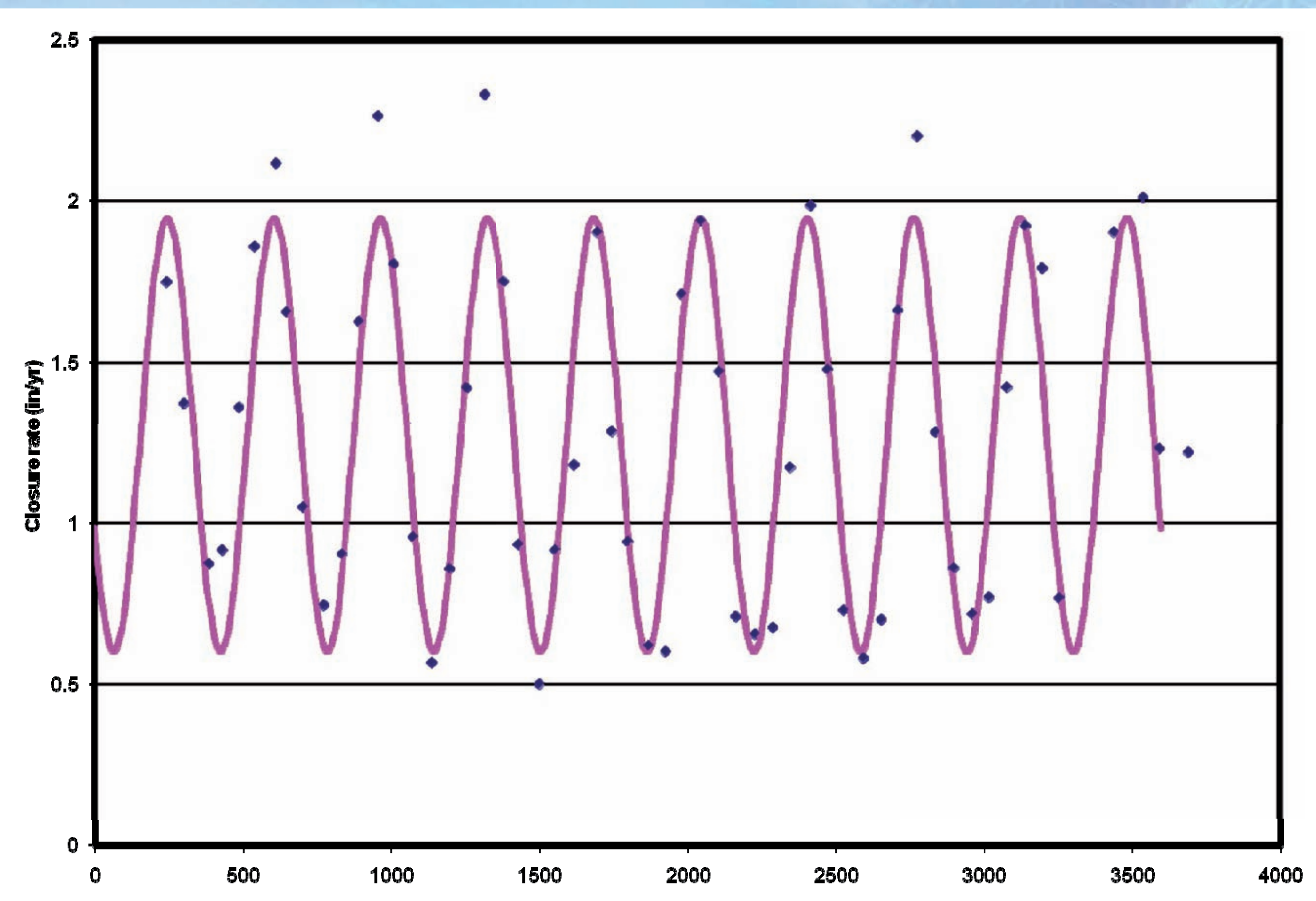
Clay Seams Near Bottom of Liner



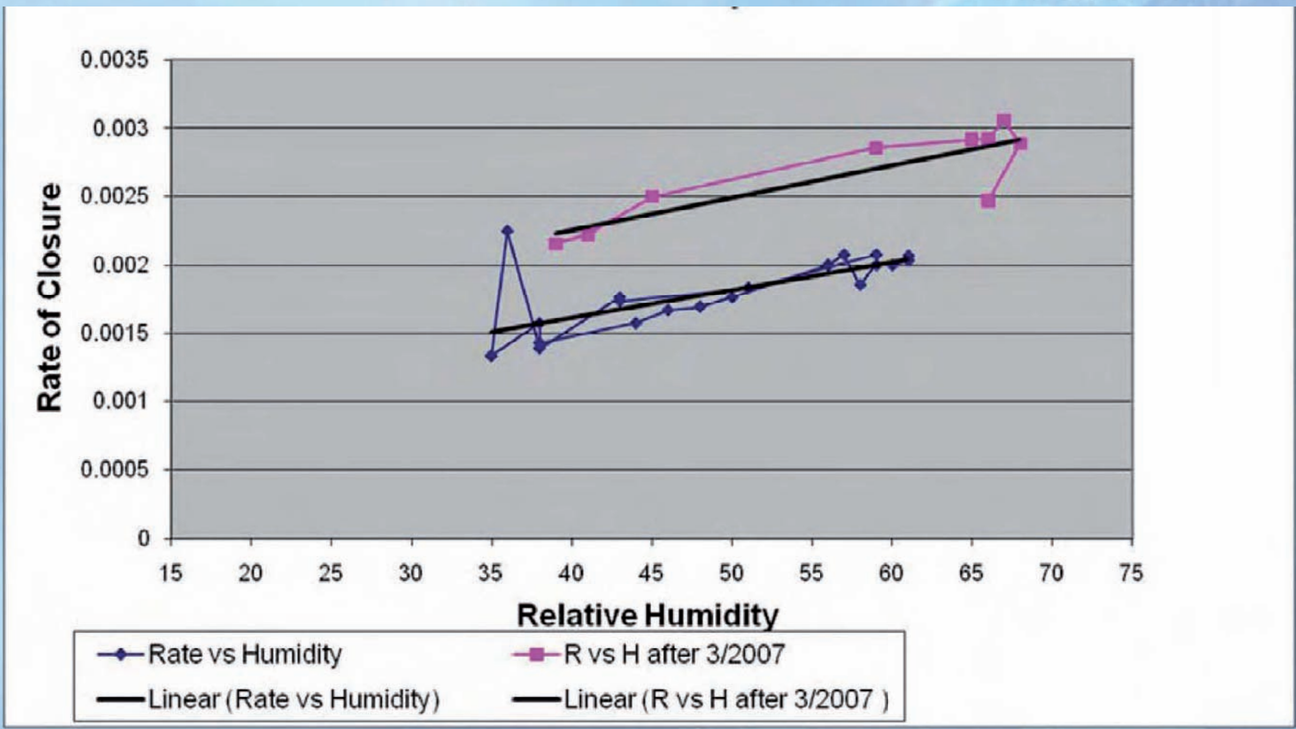
Interesting issue for salt mechanics

- Annual cycles in measured closure rates
- Next two slides from WIPP showing repeatability and annual cycle
  - *Blue data points are the same on both slides*
  - *Temperature and humidity effect*
- Third slide is from a salt mine where temperature is constant; only humidity changes


Station N-215 W-620 Near AIS
Closure Rate (in/yr)
Serial Day During the Year
Mid-September
Mid-February
Data from 1991 to 2001
2.5
2
1.5
1
0.5
0
0
30
60
90
120
150
180
210
240
270
300
330
360


Closure rate (in/yr)
2.5
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
3000
3500
4000

Another Salt Mine
Roof-Floor Closure over Two Years



Performance Assessment Examples

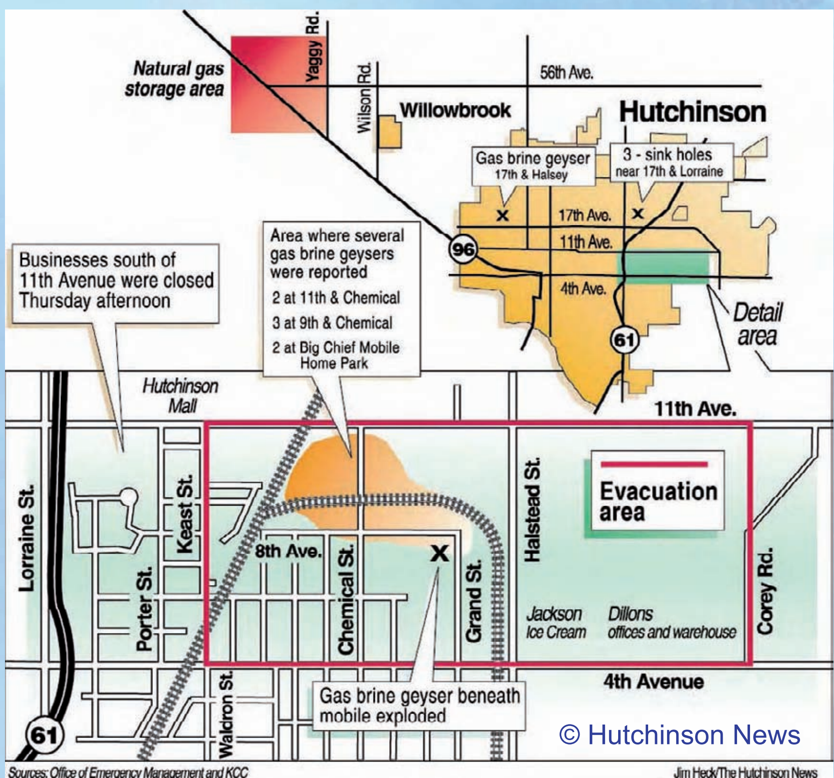
- Two case histories that might be of interest to performance assessment, safety analysis, etc.
  - *First is in Hutchinson, Kansas 2001*
  - *Second is near Kanopolis, Kansas 2000*

Explosion at 2nd and Washington

Brine/groundwater geysers from old "soda ash" wells

Explosion at trailer park - 2 deaths

Evacuation Area



Hutchinson Synopsis

- Natural gas leaked from an underground salt storage cavern
- Leak was through casing – bedded salt, salt storage caverns, etc. were not a factor
- Gas traveled 7 miles through the rock (fractured dolomite layer) to first explosion and even farther (9 miles?) to the second explosion.
- Gas escaped from dolomite through abandoned (uncased) solution mining wells drilled
- The 7-9 mile distance = “geological barrier”

Another Example

- Reference Van Sambeek’s paper at 9th World Salt Symposium, Beijing, September, 2009.

Shaft collapse rocks Kanopolis

After the initial eruption, the sink hole created by the collapsed mine shaft expanded, swallowing a train car. See more photos on page 12A. – photo by Dale Hogg

Blast takes bite out of economy

By Alan Rusch

Last Thursday's cave-in at the Acme Brick Company in Kanopolis and the jobs effected by the incident, had a big impact on economic development in Ellsworth County.

"Fifty employees in Kanopolis is a major thing for our community," said Jerry Aday, executive director of Ellsworth County Economic Development, Inc. "(Acme Brick Company) has been here for forty or fifty years now and it is an important

See ECONOMY page 8A

Water wells OK, says geologist

By Dale Hogg

KANOPOLIS – Initial testing of private water wells in the

Workers dazed by cave-in

By Dale Hogg

KANOPOLIS - Dazed and dirt covered, the employees of Acme Brick Company emerged from the blast-ripped plant here to tearful hugs from friends and family members last Thursday morning.

'The best news that we have is that nobody was injured'
– Lynn Ramsey, Acme Brick Plant Superintendent

No one was injured and all the workers were accounted for after an abandoned salt mine shaft adjacent to the plant caved in, sending a plume of dirt, bricks and debris towering above this small, Ellsworth County community, said Acme Plant Superintendent Lynn Ramsey.

Once airborne, the fallout rained on surrounding plant buildings, causing one to collapse. Vehicles parked nearby were also damaged.

The shaft that gave way

- What: Brick factory collapse caused by bricks falling from the sky
- Where: Acme Brick Factory
  Kanopolis, Kansas
- When: October 26, 2000
- Why: ?


Brick Factory Roof Collapsed
Under Weight of Bricks and Wet Sand


Parking Lot at Rear of Factory

“Minor” Damage to Truck in Parking Lot

Aerial Photo of Brick Factory

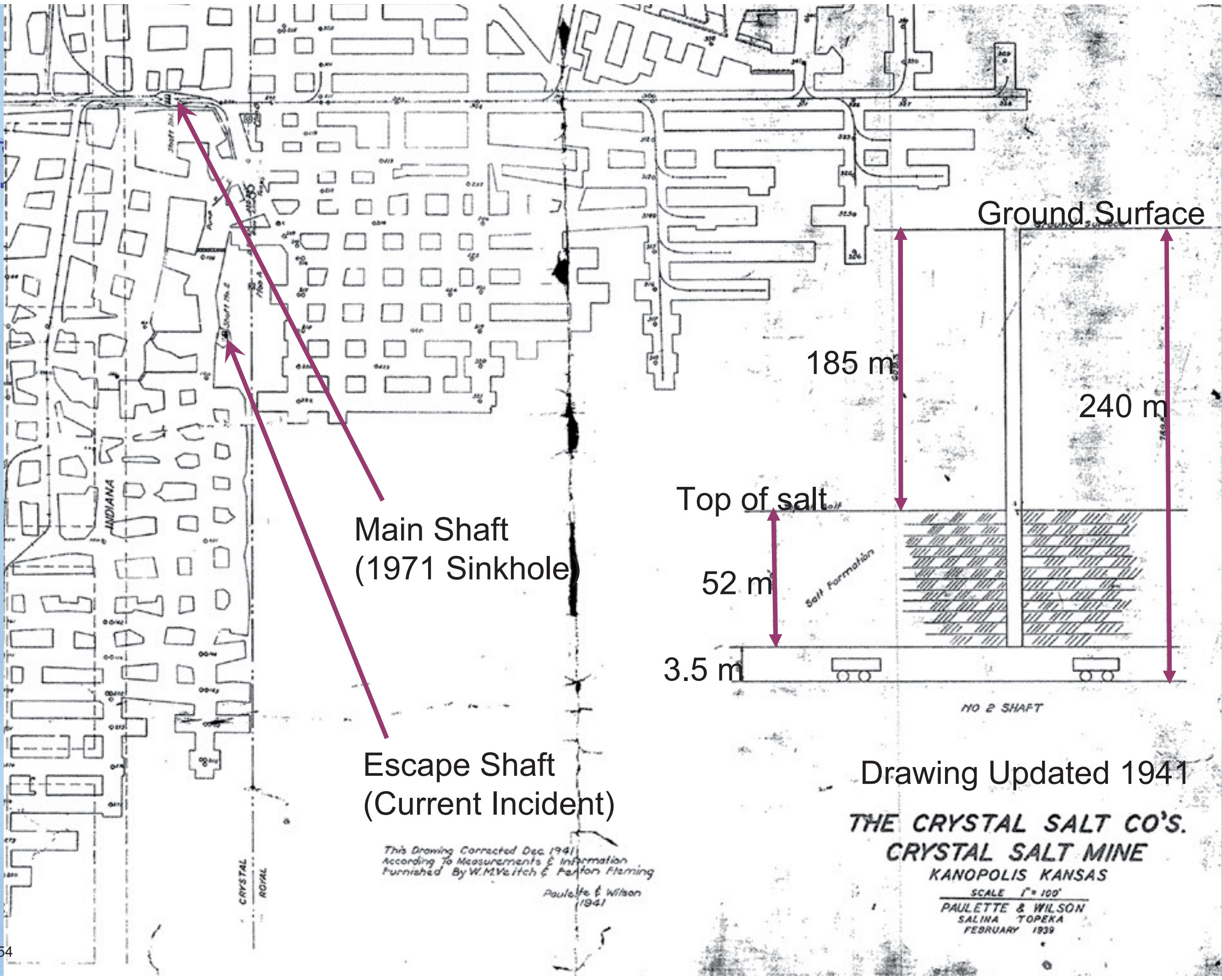
Videotaped from about 2.5 km away

Videotaped from about 2.5 km away

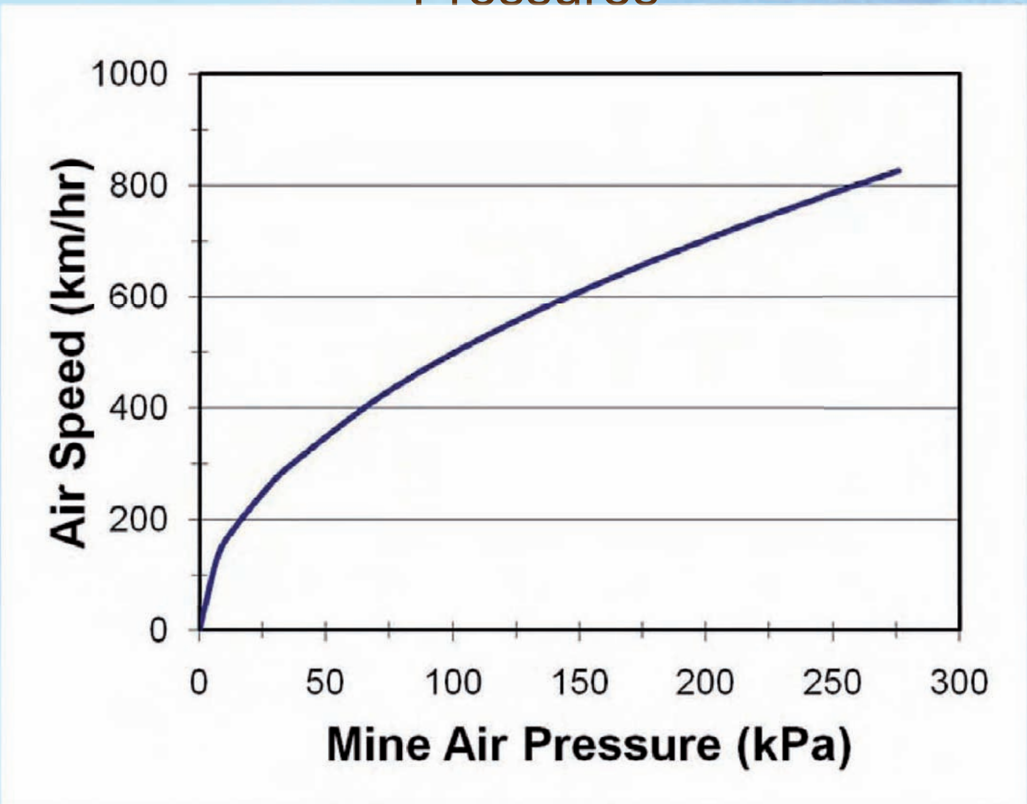
Looking Into 15-m Deep Crater After Air Stopped Blowing

Water Streams Off Top-of-Shale and Entering Shaft

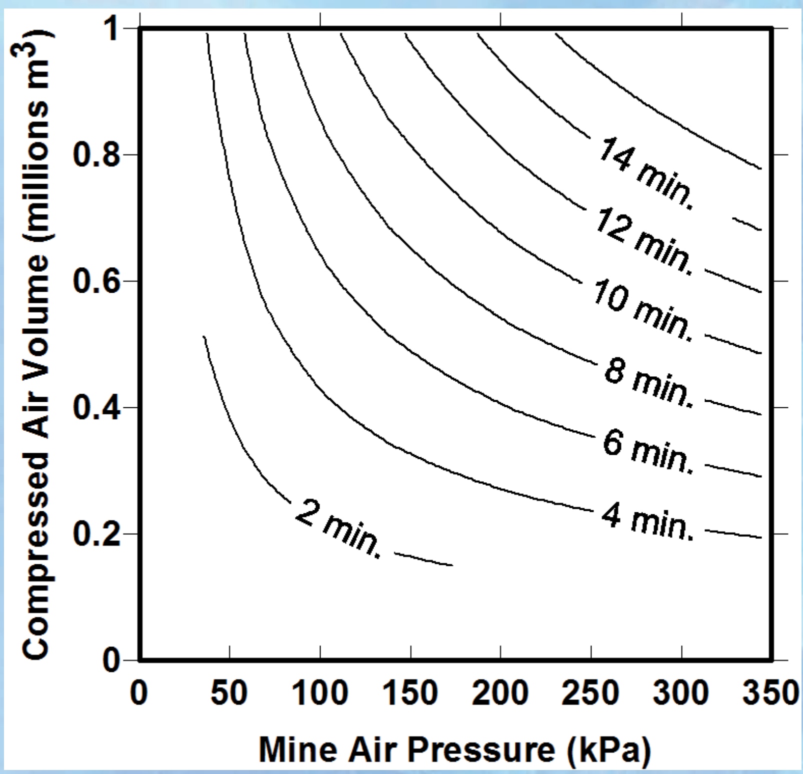
Exposed Salt Mine Shaft at Bottom of Crater (After Clearing Debris)



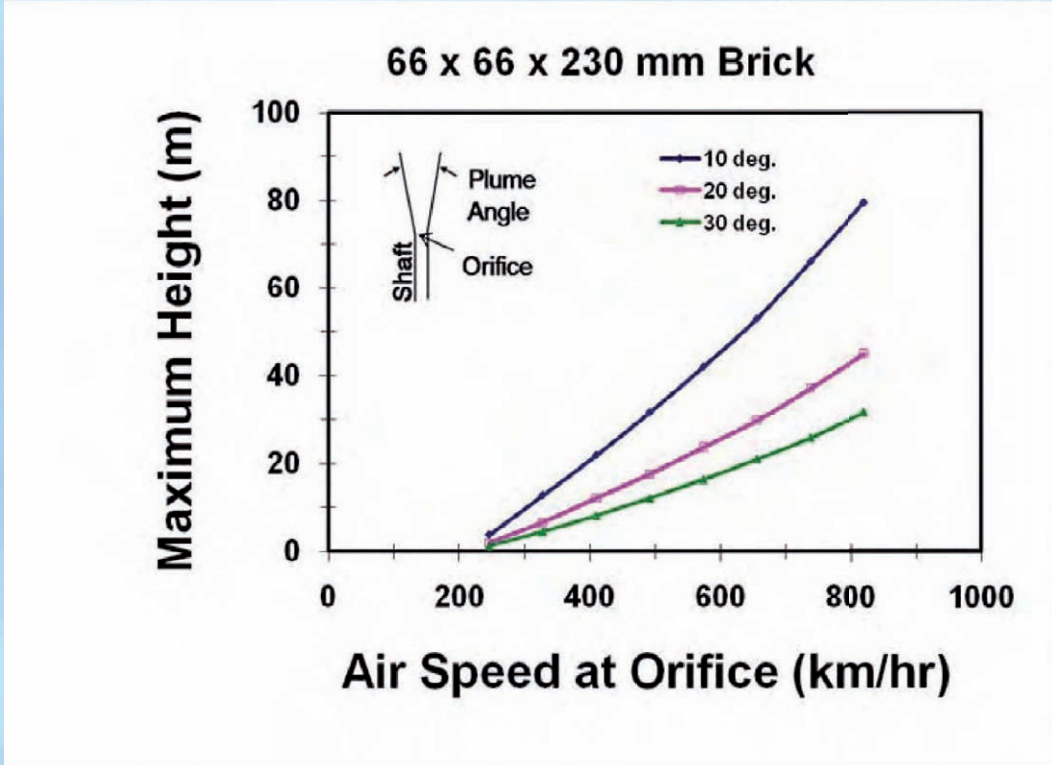
Air Speed Leaving Shaft for Range of Mine Pressures

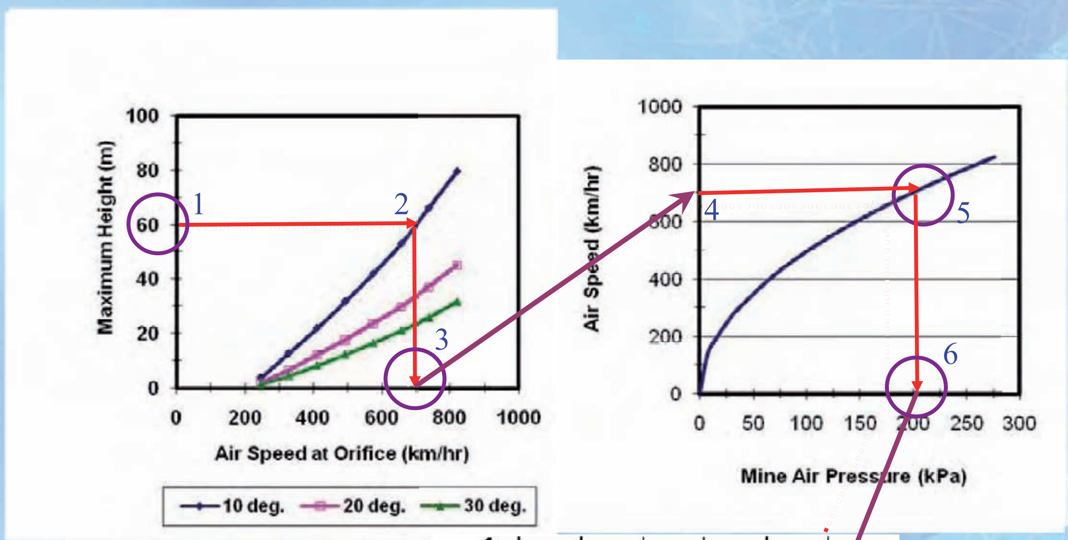


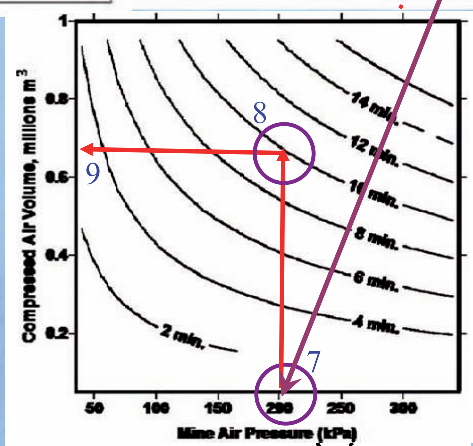
Minutes Until Air Speed Slows to 160 Km per Hour vs. Mine Volume and Air Pressure



Height a Brick Can Be Carried vs. Air Speed and Plume Angles







Assume:

- 10-deg plume
- 60-m height

So What *Might* Have Happened?

- Mine shafts filled with permeable materials in 1947-48
- Water permeates down, but air escape was blocked by saturated fill material
- Trapped air was compressed by mine closure and shaft water
- Shaft fill “failed” and compressed air was suddenly released through the shaft

Reality Check

Closure Rate	0.25 in/yr
Shaft Leak Rate	1 gpm
1948-1972 Leak Rate	2 gpm
1972-2000 Leak Rate	15 gpm

	ft^3	m^3
Volume of Salt Mined	**71,300,000**	**2,030,000**
Creep closure (1905-1948) @ 0.25 in/yr	**(4,100,000)**	**(120,000)**
Water in (1905-1948) @ 1 gpm	**(3,000,000)**	**(90,000)**
Free air volume in 1948	**64,200,000**	**1,830,000**
Creep closure (1948-1972) @ 0.25 in/yr	**(3,300,000)**	**(100,000)**
Water in (1948-1972) @ 2 gpm	**(3,300,000)**	**(100,000)**
Compressed air volume in 1972	**60,900,000**	**1,740,000**
Creep closure (1972-2000) @ 0.25 in/yr	**(4,900,000)**	**(140,000)**
Water in (1972-2000) @ 15 gpm	**(29,500,000)**	**(850,000)**
Compressed air volume in 2000	**26,500,000**	**750,000**
Compressed Air Pressure 1972	**0.8 psi**	**5 kPa**
Compressed Air Pressure 2000	**19 psi**	**132 kPa**

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

MONITORING AND PERFORMANCE CONFIRMATION

Frank Hansen
Sandia National Laboratories

Monitoring and Performance Confirmation

US-German Salt Workshop
Jackson, Mississippi, USA

Frank Hansen
Sandia National Laboratories

May 25 - 28, 2010

Introduction

Long-term Science and Monitoring programs support the Post-closure Safety Case

- Purpose of Long-Term Science and Monitoring
- Yucca Mountain Project (YMP) Analog – for Process
- Waste Isolation Pilot Plant (WIPP) Analog – for Implementation
- Components of Long-Term Science and Monitoring
  - Regulatory Requirements for Performance Confirmation
  - Influence of International Programs
  - Evolution of Technical Basis

Components of Long-Term Science

Regulations 10 CFR Part 63

- Performance Confirmation 63.131-134
- Research and Development 63.21
- Update to SAR 63.24 63.44 63.45

Evolution of Technical Basis

- Specific Tests for Process Models
- Updated Performance Assessment Needs
- Reduce Important Uncertainty
- Evolve Scientific Basis
- Inform Performance Confirmation
- Explore Mechanistic Processes

World

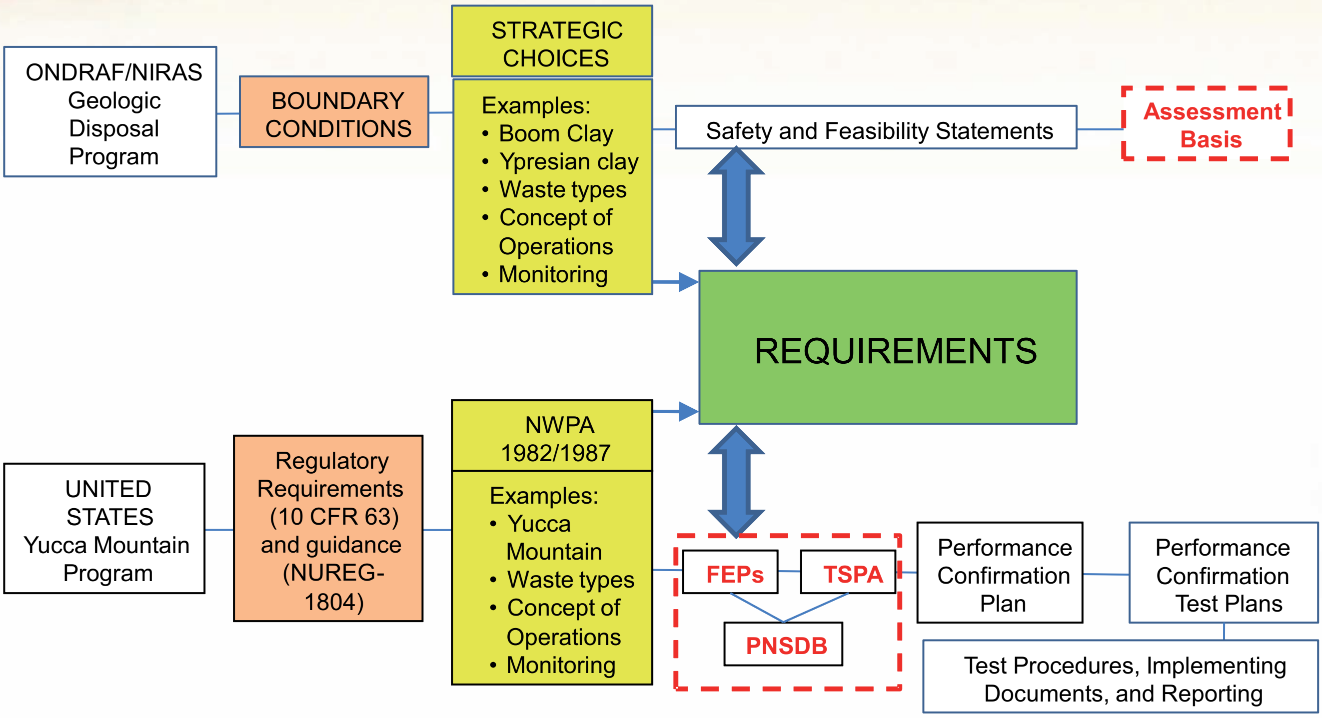
- Science and Technology
- Other Monitoring Programs
- General Literature
- International Programs

SAR - Safety Analysis Report

Performance Confirmation Process

- Regulatory requirements (Boundary Conditions) for Long-term Science and Monitoring, which includes Performance Confirmation
- Strategic Choices
- Requirements
  - Long-term Science and Monitoring includes elective activities
  - Performance Confirmation is driven by regulation
  - Required for License Application

Belgium/US Process Analog



FEPs – Features, Events, and Processes
TSPA – Total System Performance Assessment
PNSDB – Post-closure Nuclear Safety Design Basis
NWPA – Nuclear Waste Policy Act

Expectations

- **Public confidence**
- **Continuous assessment of evolving science and technology**
  - **State of knowledge**
  - **Emerging technologies**
  - **International perspective**
  - **Research and development**
- **Annual reporting**

Implementation

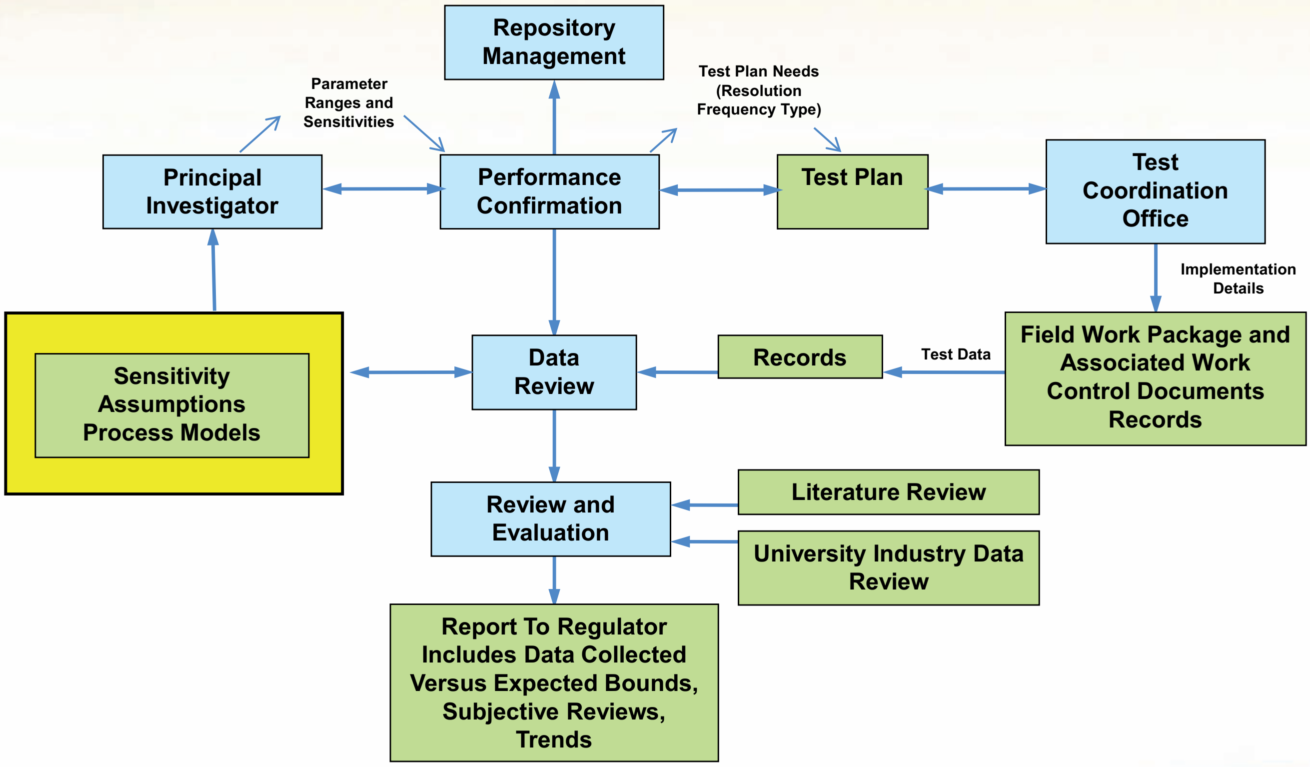
- **Management**
- **Planning**
- **Project Control**
  - Test plans
  - Reporting requirements
  - Developed jointly
  - Integrated
  - Quality Assurance

YMP Example

Site Recommendation 02/14/2002 — License Application 06/03/2008 — Construction Authorization — Receive and Possess — Closure

SITE CHARACTERIZATION	BASELINE PHASE	LICENSE APPLICATION	CONSTRUCTION	OPERATIONS / CONSTRUCTION/CLOSURE
SITE CHARACTERIZATION ACTIVITIES	ACTIVE PC	ACTIVE PC	ACTIVE PC	ACTIVE PC
1. Construction Effects Monitoring 2. Seismic Monitoring 3. Precipitation Monitoring	1. Construction Effects Monitoring 2. Seismic Monitoring 3. Precipitation Monitoring	1. Construction Effects Monitoring 2. Seismic Monitoring 3. Precipitation Monitoring	1. Construction Effects Monitoring 2. Seismic Monitoring 3. Precipitation Monitoring	1. Construction Effects Monitoring 2. Seismic Monitoring 3. Precipitation Monitoring
	ONGOING SCIENCE	ONGOING SCIENCE AND POTENTIAL PC TESTING		
4. Corrosion Testing 5. Waste Form Testing 6. SZ Monitoring 7. SZ Alluvium Testing	4. Corrosion Testing 5. Waste Form Testing 6. SZ Monitoring 7. SZ Alluvium Testing	4. Corrosion Testing 5. Waste Form Testing 6. SZ Monitoring 7. SZ Alluvium Testing	4. Corrosion Testing 5. Waste Form Testing 6. SZ Monitoring 7. SZ Alluvium Testing	4. Corrosion Testing 5. Waste Form Testing 6. SZ Monitoring 7. SZ Alluvium Testing
	ACTIVITIES ON HOLD THROUGH LICENSING		RE-INSTATED AND NEW PC ACTIVITIES	
8. Mapping 9. SS Rock and Water Testing 10. Seepage Monitoring 11. UZ Testing	8. Mapping 9. SS Rock and Water Testing 10. Seepage Monitoring 11. UZ Testing		8. Mapping 9. SS Rock and Water Testing 10. Seepage Monitoring 11. UZ Testing 12. Seals and Backfill Testing 13. Drift Inspection 14. Dust Monitoring 15. SZ Fault Zone Hydrology	8. Mapping 9. SS Rock and Water Testing 10. Seepage Monitoring 11. UZ Testing 12. Seals and Backfill Testing 13. Drift Inspection 14. Dust Monitoring 15. SZ Fault Zone Hydrology
SS = Subsurface SZ = Saturated Zone UZ = Unsaturated Zone				Thermally Accelerated Drift 16. Environment 17. Thermal-Mechanical 18. Near-Field 19. Corrosion 20. Waste Package Monitoring

Assessment Process



Summary

- Governed by boundary conditions (regulations)
- Long-term science and monitoring has less defined regulatory drivers
- Sequential, staged, flexible process
- Long-term science and monitoring demonstrates due diligence
- Continuously refined, consistent with staged repository program
- Testing and monitoring program
- Change and flexibility facilitated

WIPP Compliance Monitoring Example

- **WIPP Compliance Monitoring Program is based on an analysis of the performance assessment (PA) parameters and is required by the regulations**
- **Monitoring parameters must be assessed and reported to the U.S. Environmental Protection Agency (EPA) annually**
- **The EPA compliance monitoring requirements do not deal with operational releases; this compliance monitoring program addresses post-closure repository performance**
- **Each Compliance Monitoring Parameter (COMP) is assessed against PA expectations**
  - Impacts on PA conceptual model assumptions, data ranges or expectations of the modelers
  - Alert the project of conditions not accounted for or expected
  - Concept uses Trigger Values

Regulatory Requirements

- 40 CFR 194.42 (a) The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for pre-closure and post-closure monitoring required pursuant to paragraphs (c) and (d) of this section.

Performance Confirmation

- **EPA Monitoring requirements constitute performance confirmation**
  - Determine list of parameters
  - Determine method to assess "significance" of each parameter using the WIPP PA
  - Analyze the parameters
  - Determine criteria using the analysis results to determine monitoring parameters
- **The DOE's analysis that addressed the EPA pre-closure monitoring requirements was included in the original EPA compliance application (i.e., licensing application)**

Monitored Parameters

- **Drilling Rate**
- **Probability of Encountering a Castile Brine Reservoir**
- **Waste Activity**
- **Subsidence**
- **Changes in Culebra Groundwater Flow**
- **Change in Culebra Groundwater Composition**
- **Creep Closure**
- **Extent of Deformation**
- **Initiation of Brittle Deformation**
- **Displacement of Deformation Features**

Results of the Screening

Table 7-2. Potentially Significant Disposal System Parameters

NATURAL PARAMETERS

Impure halite effective porosity
Impure halite permeability
Impure halite pore compressibility
Impure halite far-field pore pressure
Anhydrite permeability
Anhydrite pore compressibility
Anhydrite two-phase flow model choice
Salado pore shape
Salado residual brine saturation
Salado residual gas saturation
Salado brine quantity
Salado brine flux
Salado brine spatial distribution
Salado brine composition
Culebra transmissivity
Culebra advective porosity
Culebra fracture spacing
Culebra diffusional porosity
Culebra longitudinal dispersivity
Climate change index
Culebra groundwater quantity
Culebra groundwater flux
Culebra groundwater spatial distribution
Culebra groundwater composition
Castile brine volume in reservoir
Castile brine reservoir volume selection index
Castile brine reservoir pressure
Castile brine reservoir permeability
Castile brine reservoir rock compressibility
Castile brine composition
Castile brine flux
Castile brine spatial distribution
Natural temperature distribution

WASTE AND REPOSITORY PARAMETERS

Closure rates and stresses
Extent of deformation
Initiation of brittle deformation
Displacement of major deformation features
DRZ permeability
DRZ effective porosity
DRZ brine flux
DRZ brine quantity
Waste area residual gas saturation
Waste area residual brine saturation
Brine wicking
Waste area permeability
Backfill porosity
Backfill permeability
Degree of backfill compaction
Backfill reconsolidation
Inundated steel corrosion rate with CO_2
Inundated steel corrosion rate without CO_2
Inundated microbial degradation rate
Humid microbial degradation rate
β-factor for microbial degradation process
Probability factor for types of microbial degradation
Gas quantity
Gas composition
Choice of oxidation state distribution
Solubility of nine radionuclides in Salado brine
Solubility of nine radionuclides in Castile brine
Humic colloid concentration in Salado brine
Humic colloid concentration in Castile brine
Clay shaft seal member permeability
Concrete shaft seal member permeability
Asphalt shaft seal member permeability
Shaft DRZ permeability
Crushed salt seal component permeability (permeability selection index)
Seal residual gas saturation
Seal residual brine saturation
Seal pore shape
Waste- and repository-induced temperature distribution
Salado K_ds for dissolved radionuclides
Culebra K_ds for six dissolved radionuclides
Salado K_ds for colloidal radionuclides

HUMAN INITIATED PARAMETERS

Drilling rate
Waste particle diameter
Effective shear resistance to erosion
Gravity correction factor for spalling
Strength correction factor for spalling
Time between intrusions
Borehole location
Probability of encountering a Castile brine reservoir
Borehole diameter
Borehole permeability
Borehole plugging pattern (probability index)
Change in Salado brine flow
Change in Culebra groundwater flow
Probability that mining will occur
Mining index for adjusting Culebra transmissivity
Waste activity
Waste tensile strength

Results of the Screening (continued)

Table 7-4. Parameters Related to Significant Disposal System Properties (Continued)

Parameter	Significance to Containment	Significance to Verification
Inundated steel corrosion rate without CO_2	MEDIUM	MEDIUM
Inundated microbial degradation rate	LOW	LOW
Humid microbial degradation rate	LOW	LOW
Gas quantity	MEDIUM	MEDIUM
Gas composition	LOW	LOW
Choice of oxidation state distribution	HIGH	HIGH
Solubility of nine radionuclides in Salado brine	HIGH	HIGH
Solubility of nine radionuclides in Castile brine	HIGH	HIGH
Humic colloid concentrations in Salado brine	HIGH	HIGH
Humic colloid concentrations in Castile brine	HIGH	HIGH
Waste particle diameter	HIGH	HIGH
Effective shear resistance to erosion	MEDIUM	MEDIUM
Waste activity	HIGH	HIGH
Waste tensile strength	MEDIUM	MEDIUM
Gravity factor for spalling	MEDIUM	MEDIUM
Strength factor for spalling	LOW	LOW
ENGINEERED BARRIER PROPERTIES		
Shaft DRZ permeability	MEDIUM	MEDIUM
Backfill porosity	LOW	LOW
Backfill permeability	LOW	LOW
Degree of backfill compaction	LOW	LOW
Backfill reconsolidation	LOW	LOW
Clay seal member permeability	MEDIUM	MEDIUM
Concrete seal member permeability	MEDIUM	MEDIUM
Asphalt seal member permeability	MEDIUM	MEDIUM
Seal residual gas saturation	LOW	LOW
Seal residual brine saturation	LOW	LOW
Seal pore shape	LOW	LOW
Long-term borehole permeability	HIGH	HIGH

Results of the Screening (continued)

Table 7-5. Listing of Parameters That Can Produce Meaningful Data During Monitoring Period

Parameter	Comment
SALADO PHYSICAL PARAMETERS	
Creep closure and stresses	Can be measured during operations
Extent of deformation	Can be measured during operations
Initiation of brittle deformation	Can be measured during operations
Displacement of deformation features	Can be observed during operations
SALADO HYDROLOGICAL PARAMETERS	
Salado brine composition	Can be measured during operations
NON-SALADO HYDROLOGICAL PROPERTIES	
Culebra groundwater composition	Can be measured for entire period
Castile brine reservoir location	Can be observed for entire period
Drilling rate	Can be observed for entire period
Culebra change in groundwater flow	Can be observed for entire period
WASTE RELATED PARAMETERS	
Waste activity	Can be calculated using measurements made during waste characterization

Trigger Values

- **Monitoring results are used to indicate conditions that are not within the PA data ranges, conceptual model assumptions or expectations of the modelers and to alert the project of conditions not accounted for or expected**
- **Values and ranges were developed such that exceedance of identified values, referred to as “trigger values” (TV), indicate a condition that is potentially outside PA expectations**

Conclusion

- **WIPP Compliance Monitoring Program is based on EPA-required analysis of PA parameters (40 CFR 194.42)**
- **Parameters must be assessed and reported to EPA annually**
- **Each monitored parameter is assessed against PA expectations:**
  - Impacts on PA conceptual model assumptions, data ranges or expectations of the modelers
  - Alert the project of conditions not accounted for or expected
  - Program uses Trigger Values to alert project of unexpected conditions

Collaboration

- **Sandia is active partner on MoDeRn (http://www.modern-fp7.eu/)**
- **WIPP has successful confirmation monitoring program**
- **YMP brought comprehensive rigor to performance confirmation**
- **Is there a need for a joint over-arching long-term testing and monitoring strategy?**

Performance Confirmation SAND Report Outline

1. **Introduction: Describe Performance Confirmation Program Goals and Objectives:**
   a) Program Goals
      1. Regulatory Needs
      2. Performance Assessment Needs
      3. Barrier Capability
   b) Objectives
      1. Model Validation and Confirmation
      2. Increase Confidence
      3. Public Acceptance
2. **Outline Performance Confirmation Program**
   a) Framework
      1. Evaluation Methodology
      2. Activity Selection
      3. Measurable Parameters
   b) Documentation
      1. Overarching Plan Strategy
      2. Specific Implementing Test Plans
   c) Periodic Evaluations
      1. Ongoing Science—Internal and External
      2. Integration—Long-Term Testing and Monitoring Programs
3. **Examples of PC Programs**
   a) Yucca Mountain
   b) WIPP
   c) International Programs – Belgium, MoDeRn
4. **Concluding Remarks**
5. **References**

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

CONSTITUTIVE MODELLING IN ROCK SALT MECHANICS - FROM PAST TO FUTURE - WITH SPECIAL RESPECT TO RADIOACTIVE WASTE DISPOSAL

K.-H. Lux
Technische Universität Clausthal

TU Clausthal

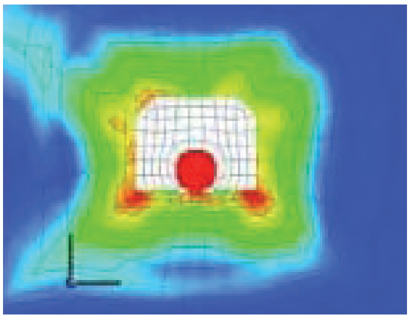
Jackson / Mississippi, May 25/26 2010

Constitutive Modelling in Rock Salt Mechanics

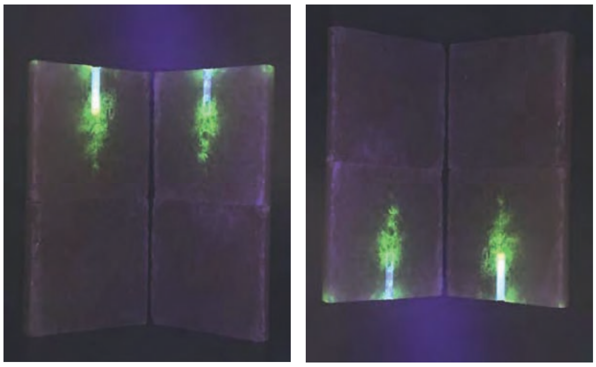
– From Past to Future –

With Special Respect to Radioactive Waste Disposal

K.-H. Lux



Thermomechanical Behaviour of HL-waste Disposal Drifts with Backfill



Fluid migration through rock salt mass

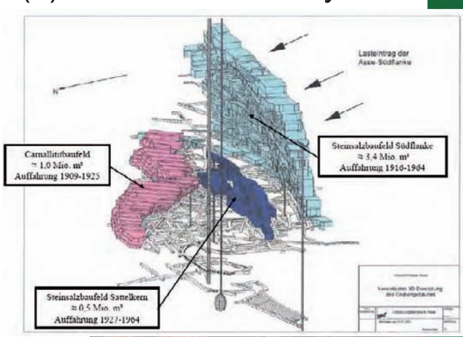
587

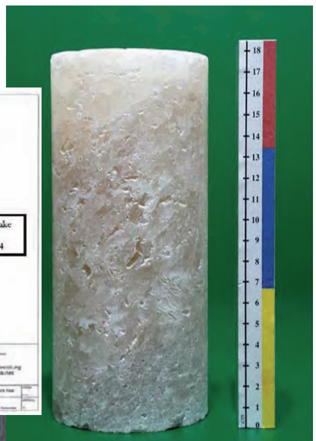
Overview

(1) Past / Introduction

(2) Past to Presence

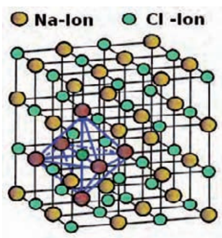
(3) Future / Summary





Rock Salt – a material

- very simple in chemical composition and atomic structure

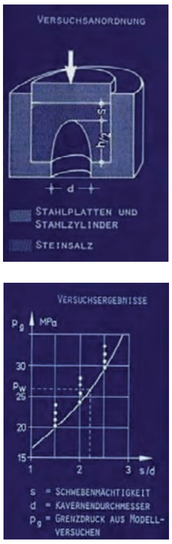


- but very complex in
  - geotectonic structure

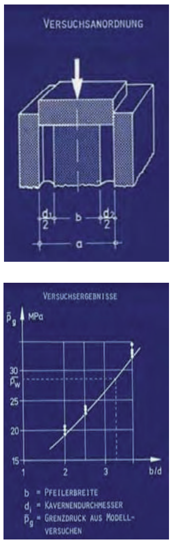
  as well as in
  - physico-chemical behaviour and related properties

(1) Past / Introduction
(2) Past to Presence
(3) Future / Summary

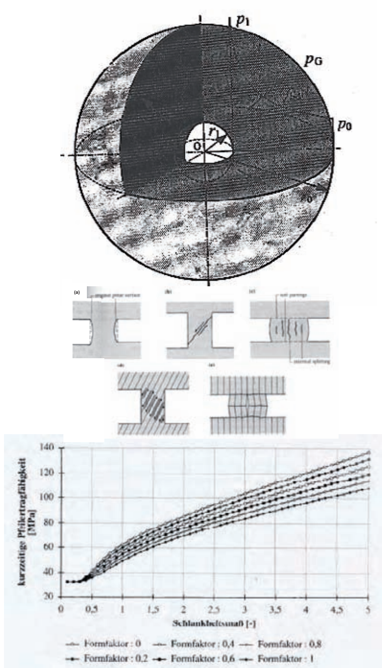
Solution Mining in Ancient China



Cavern Roof Stability



Cavern Pillar Stability



for centuries:
Empiricism /
Individual Experience

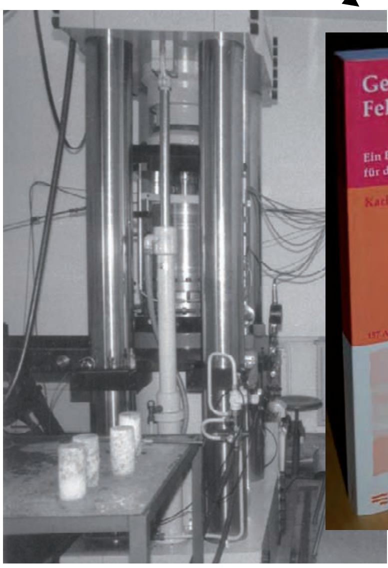
Analogy Mechanics

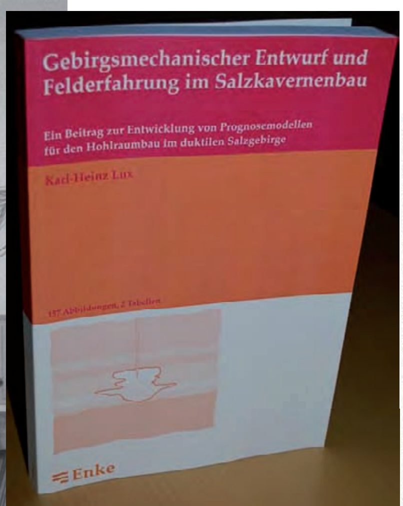
Analytical Continuum Mechanics
restricted to
- *simple geometric boundaries*
- *simple constitutive models (el-pl-vi)*

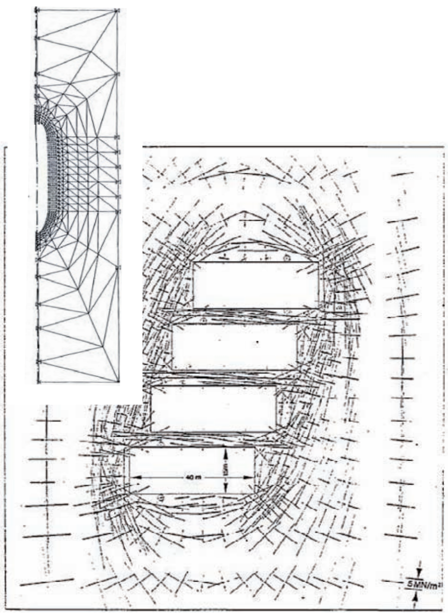
Advanced Lab Test Possibilities

Advanced Simulation Tools

(computer aided design)







⇒ Constitutive Laws in the Framework of Continuum Mechanics?

Constitutive Modelling – Time-dependent Behaviour – Past (3)

(a) Empirical Approach

$\dot{\varepsilon}_1^V(t) = m \cdot a \cdot \sigma_V^n \cdot t^{m-1}$ — **Boresi / Deere (1963)**

$\dot{\varepsilon}_1^V(t) = m \cdot a \cdot \sigma_V^n \cdot T^l \cdot t^{m-1}$ — **Lomenick / Bradshaw (1969)**

$\dot{\varepsilon}_1^V(t) = b \cdot 2^{b_1} \cdot \sigma_V^{2 \cdot b_1 + 1} \cdot T^{b_2} \cdot t^{b_3}$ — **Thoms / Char / Bergeron (1973)**

$\dot{\varepsilon}_1^V(\varepsilon_1^V) = a^* \cdot \sigma_V^{n^*} \cdot (\varepsilon_1^V)^{-\mu}$ — **Menzel / Schreiner (1977)**

(b) Phenomenological Approach (model rheologic)

$$\dot{\varepsilon}_1^V(t) = \left[\sum_{i=1}^{3}\left(\frac{1}{3 \cdot \eta_{Ki}} \cdot \exp\left(-\frac{G_{Ki}}{\eta_{Ki}} \cdot t\right)\right) + \frac{1}{3 \cdot \eta_M}\right] \cdot \sigma_V$$

Langer / Hofrichter (1969)

$$\dot{\varepsilon}_1^V(\varepsilon_1^V) = \left[\frac{1}{3 \cdot \eta_K(\sigma)} \cdot \left(1 - \frac{\varepsilon_1^{V,t}}{\sigma_V} \cdot 3 \cdot G_K(\sigma)\right) + \frac{1}{3 \cdot \eta_M(\sigma, T)}\right] \cdot \sigma_V$$

Lux / Rokahr (1982)

(c) Phenomenological Approach (structure rheologic)

$$\dot{\varepsilon}_1^V = a \cdot \exp\left(-\frac{Q}{R \cdot T}\right) \cdot \sinh(b \cdot \sigma_V)$$

dislocation glide — **Carter / Heard (1970)**

$$\dot{\varepsilon}_1^V = a \cdot \exp\left(-\frac{Q}{R \cdot T}\right) \cdot \sigma_V^n$$

dislocation climb — **Carter / Heard (1970), Wallner (1979)**

$$\dot{\varepsilon}_1^V(t) = \left[b \cdot m \cdot \exp(-m \cdot t) \cdot \exp\left(-\frac{Q_1}{R \cdot T}\right) + a \cdot \exp\left(-\frac{Q_2}{R \cdot T}\right)\right] \cdot \sigma_V^n$$

McVetty, Langer, Hunsche (1980)

$$\dot{\varepsilon}_V^V = a_1 \cdot \exp\left(-\frac{Q_1}{R \cdot T}\right) \cdot \left(\frac{\sigma_V}{G}\right)^{n_1} + a_2 \cdot \exp\left(-\frac{Q_2}{R \cdot T}\right) \cdot \left(\frac{\sigma_V}{G}\right)^{n_2} + 2 \cdot \left[b_1 \cdot \exp\left(-\frac{Q_1}{R \cdot T}\right) + b_2 \cdot \exp\left(-\frac{Q_2}{R \cdot T}\right)\right] \cdot \sinh\left(D\left\langle\frac{\sigma_V - \sigma_{V0}}{G}\right\rangle\right)$$

Munson / Dawson (1981)

increase in requirements
increase in knowledge
increase in complexity of models

Scientific Methodology

Path to Secured Knowledge

- collection of data
- development of models
- performance of computer aided simulations
- collection of more data
- realisation that data and modelling do not fit together completely
- …

This way we always try to complete our knowledge.

George v. Coyne, 2000

„Wanderer über dem Nebelmeer"

from Caspar David Friedrich (ca. 1818)

We can only hope each day to come closer to truth by our scientific work.

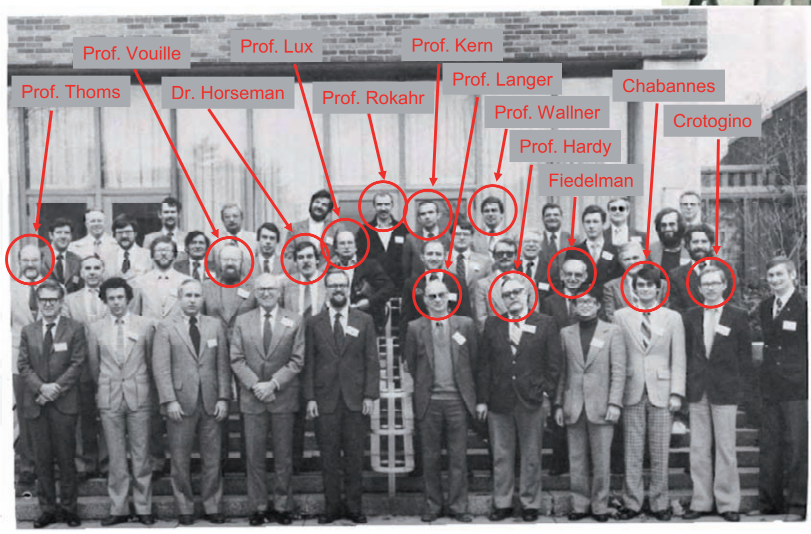
Who are those people trying to lighten the darkness?

(1) Past / Introduction

(2) Past to Presence

(3) Future / Summary

… American-German Cooperation in Old Days (1984) (example)



First Conference on the Mechanical Behaviour of Salt, 1981

Significant steps of development in mechanical structure analysis in rock salt mass:

- for centuries: empirical approach (trial and error)
- 1965/1985: model (analogy) mechanical approach (*Dreyer / Höfer*)
- 1975/1985: analytical approach (CM) (*Langer*, *Serata*)
- since 1980: numerical approach (CM) (FEM, FDM)

1980: continuum mechanics approach / CM

1990: inclusion of elements of Continuum Damage Mechanics into CM

→ CM/CDM (modelling / simulation of damage processes as well as damage reduction (healing?) processes)

2000: coupling of processes M/T/H/C

> 2010: *? evaluation of coupled processes*

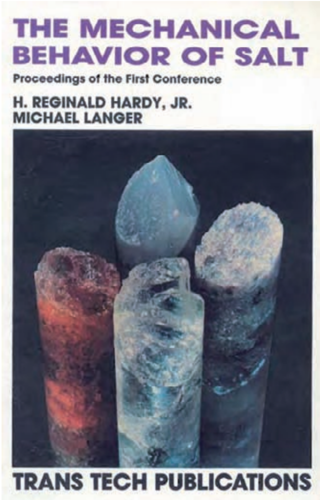
? demonstration of reliability

Salt Rock Mechanic Conferences = Documents of Involvement

1. ***Conference 1981, Penn State University***
2. ***Conference 1984, Hannover***
3. ***Conference 1993, Paliseau***
4. ***Conference 1996, Montreal***
5. ***Conference 1999, Bukarest***
6. ***Conference 2007, Hannover***

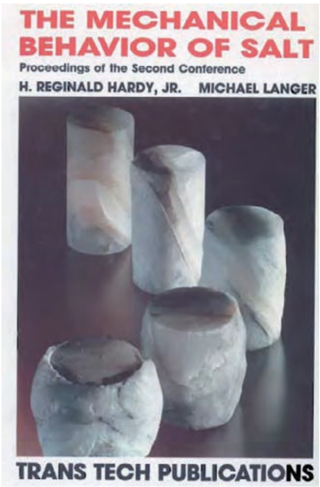
Content

Part 1: Laboratory Studies
Part 2: Field Studies
Part 3: Analysis and Design Studies
Part 4: General Aspects

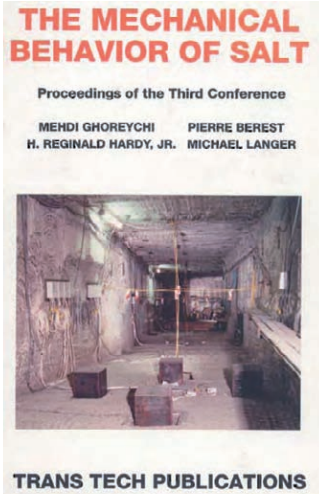


Content

Part 1: Mineralogy / Structural Studies
Part 2: Laboratory Investigations
Part 3: Field Measurements
Part 4: Constitutive Modelling
Part 5: Numerical Calculations
Part 6: General Aspects

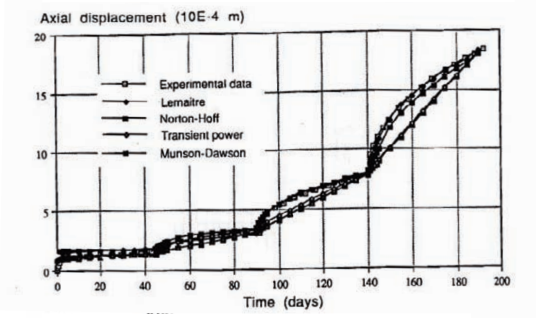


Content

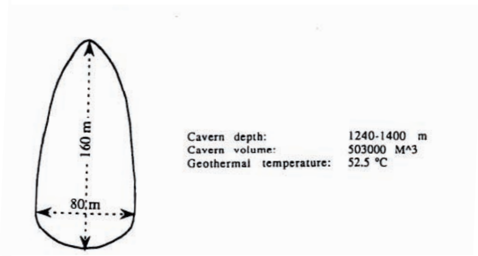


Durup, G. & Xu, J.: Comparative Study of Certain Constitutive Laws used to Describe the Rheological Deformation of Salts

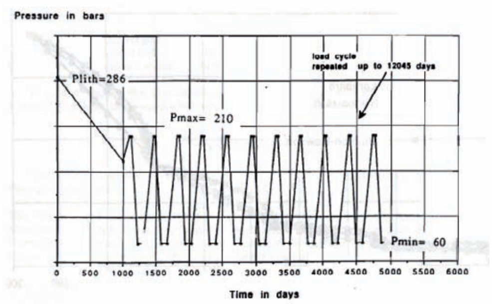
Evaluation of Constitutive Models



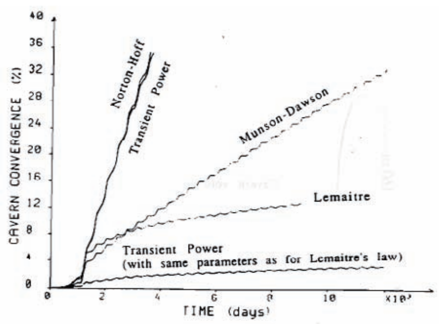
Geotechnical Construction – Salt Cavity



Operation History

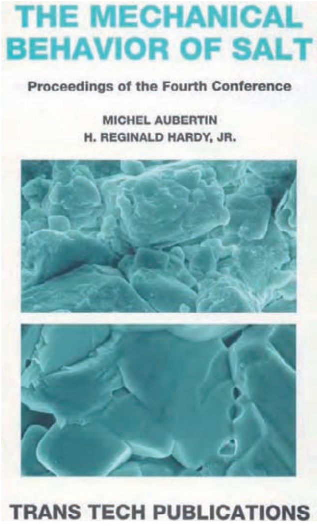


Comparison of simulated cavern convergences using different behaviour laws



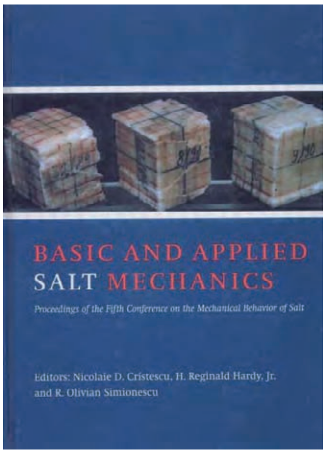
Content

Part 1: Laboratory and In-situ Testing
Part 2: Micromechanical Studies
Part 3: Damage, Fracture and Failure
Part 4: Constitutive Modelling
Part 5: Crushed Salt Behaviour
Part 6: Numerical Modelling
Part 7: Mining Applications
Part 8: Storage and Disposal Projects



Content

Part 1: Laboratory and In-situ Testing
Part 2: Coupled Effects and Permeability
Part 3: Creep / Damage and Dilatancy
Part 4: Constitutive Modelling
Part 5: Crushed Salt Behaviour
Part 6: Numerical Modelling
Part 7: Storage and Disposal Projects
Part 8: Mining Application
Part 9: Case Studies
Part 10: Salt Pillars and Cavities



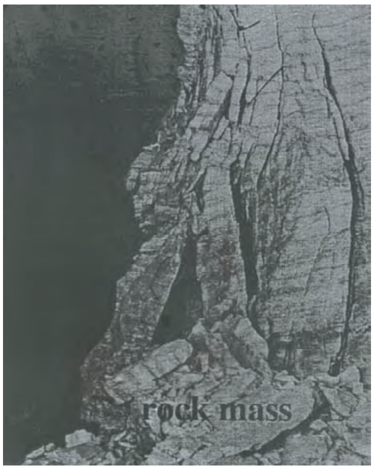
Further Development since 1999 until 2007?

Development Between 5. Conference (1999) and 6. Conference (2007) – Constitutive Modelling (1)

to Micro-Processes

between

1999 / 5. Conference



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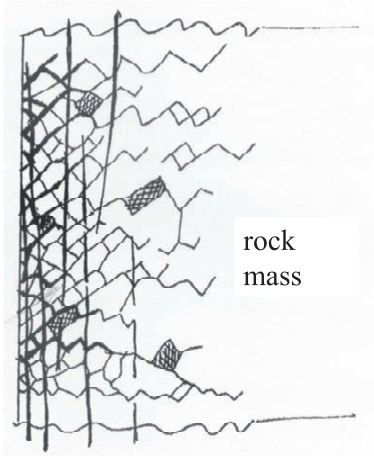


2007 / 6. Conference

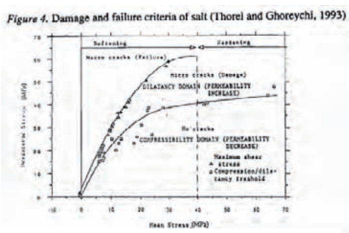
from Macro-Processes

⇒ 2 Important Improvements

Development Between 5. and 6. Conference – Constitutive Modelling (2)

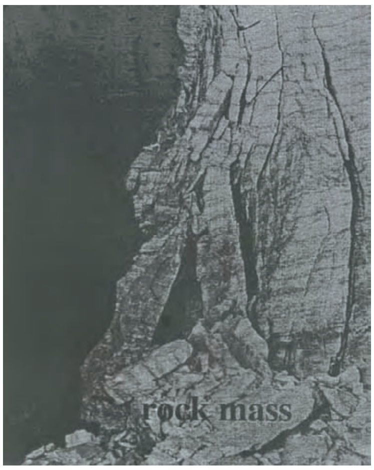
(I) Introduction of Elements of CDM in CM in Rock Salt Mechanics

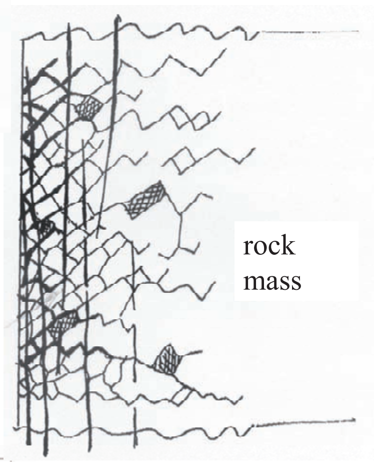
between



to Micro-Processes

1999 / 5. Conference





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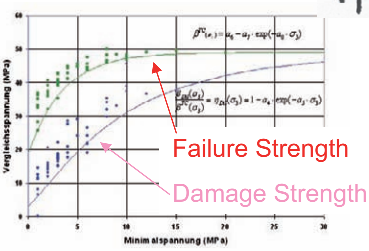
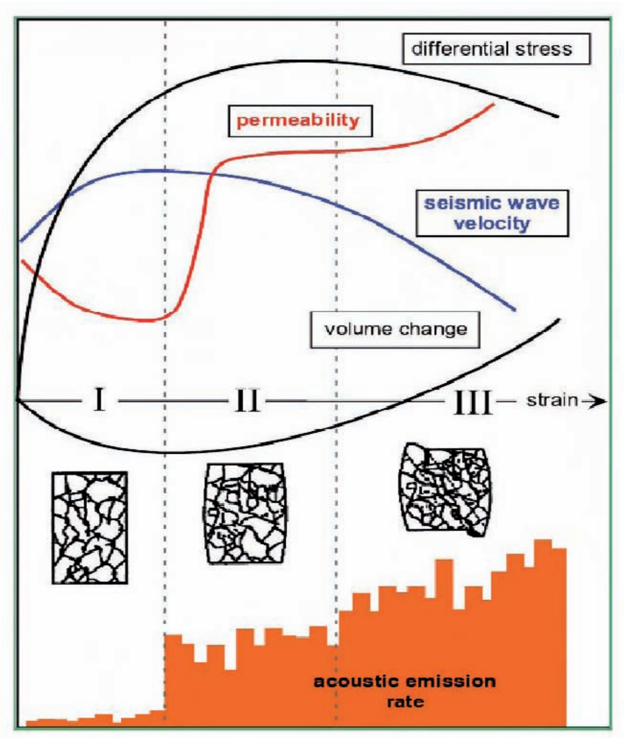


2007 / 6. Conference

from Macro-Processes

From CM to CDM – Rock Salt Behaviour during Deformation (schematic)



Development of physical properties is used for monitoring and determination of *Damage*

I - compaction

II - damage (micro)

III - rupture (macro)

Short-term behaviour of salt rocks, *Schulze (2001)*

Continuum Mechanics:

$$E, \nu; G_K, \eta_K, \eta_M; A, n; \ldots$$

Continuum Damage Mechanics:

$$D \rightarrow \varepsilon_{vol} \Rightarrow \phi_{eff} \rightarrow K$$

$$M \Rightarrow H$$

Development Between 5. and 6. Conference– Constitutive Modelling (3)

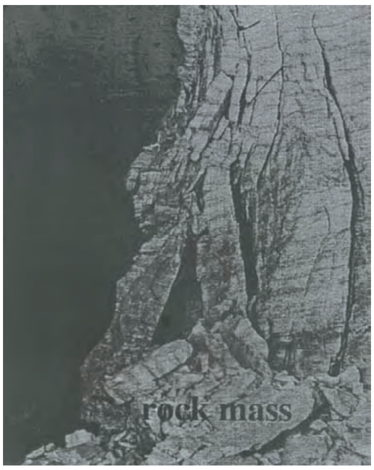
(II) Coupling of Processes T-M-H-C

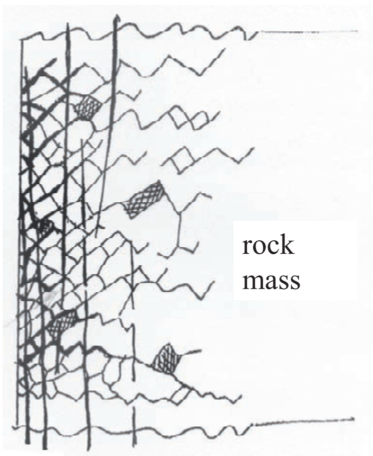
especially TM-H

to Micro-Processes

between

1999 / 5. Conference





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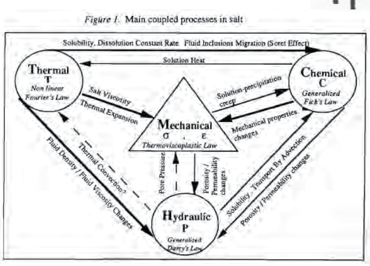

2007 / 6. Conference

from Macro-Processes

Investigation
Understanding
Modelling
Simulation
Evaluation
↓
Reliable Prognosis?

T
H
M
|
C

Lab Testing Facilities at TU Clausthal
for Investigation of Coupled Processes → *Examples for coupled processes →*

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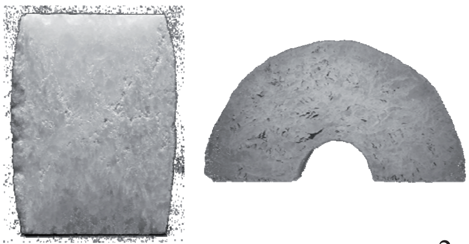
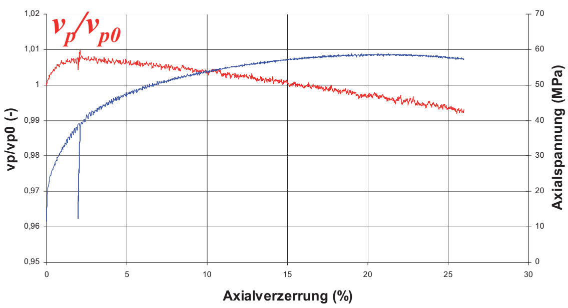
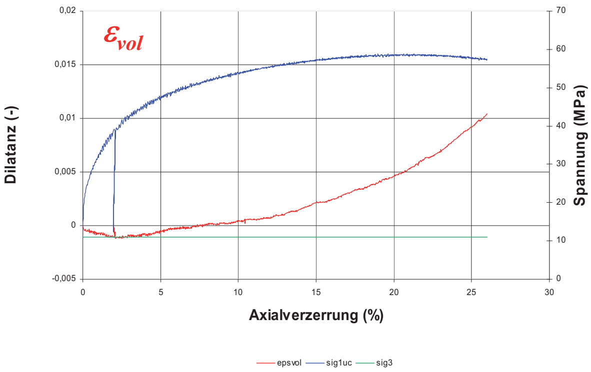
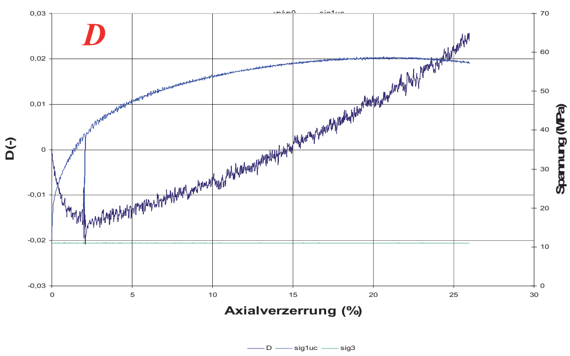
Professorship for Waste Disposal and Geomechanics





$$\boxed{D} = 1 - \frac{1}{1-\varepsilon_{vol}} \cdot \left(\frac{v_p}{v_{p0}}\right)^2$$





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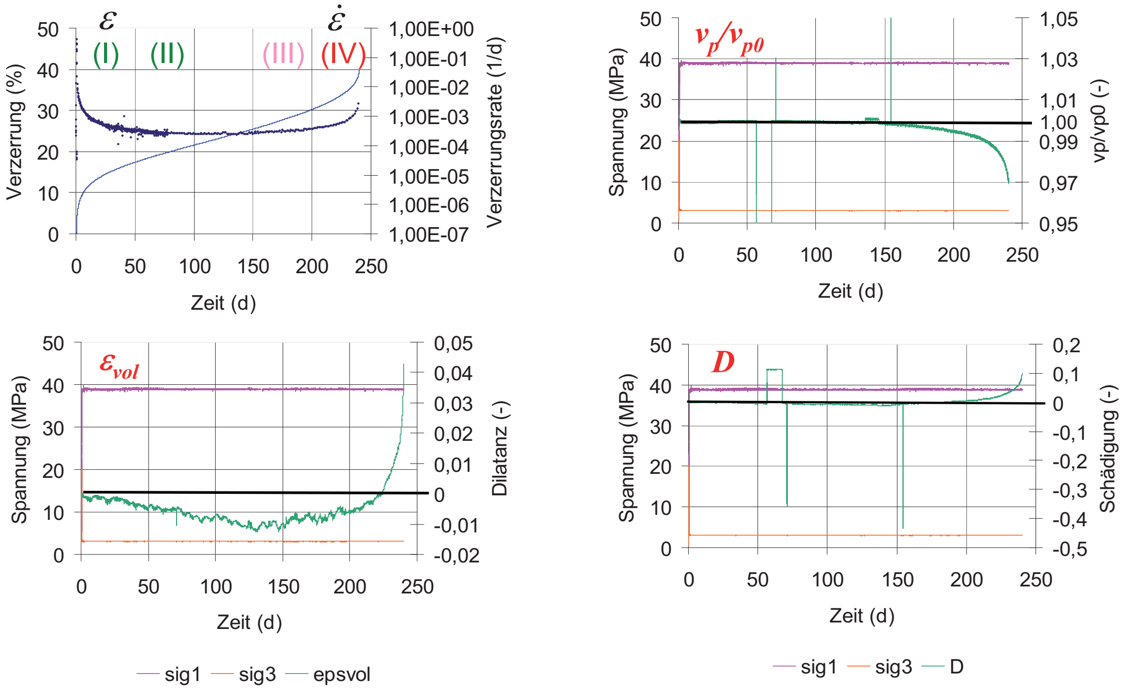
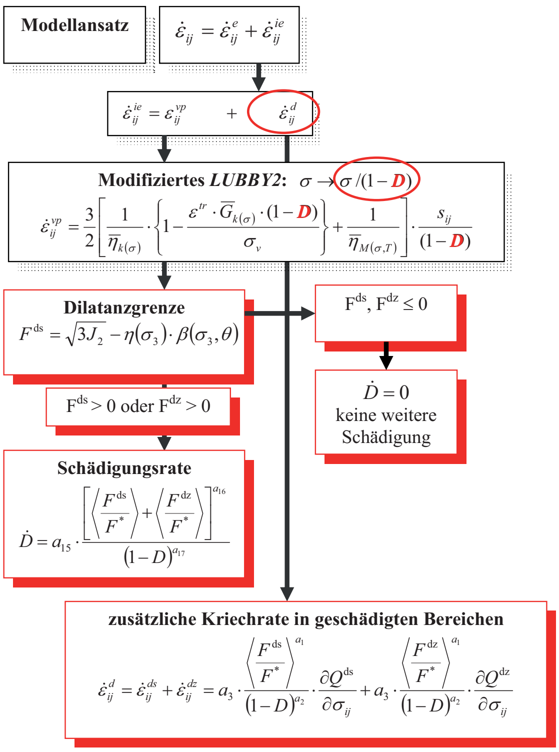
Creep Phases: (I) Transient Creep, (II) Stationary Creep, (III) Accelerated Creep, (IV) Creep Failure



Lab Investigations → Physical Modelling



Damage of Rock Fabric

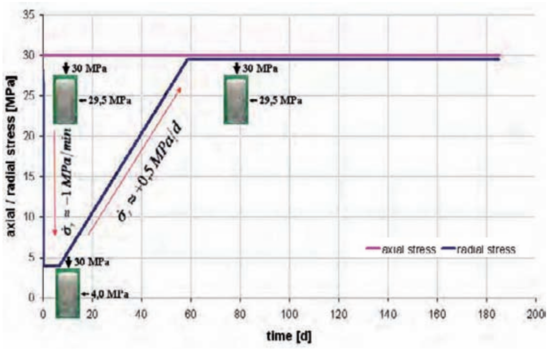
micro-/macrofissurisation
→ dilatancy / destrengthening
→ damage

Damage Intensity Factor:

$$D = 1 - \frac{1}{1 - \varepsilon_{vol}} \cdot \left(\frac{v_p}{v_{p0}} \right)^2$$

$$D \approx \left| \varepsilon_{vol} \right|$$

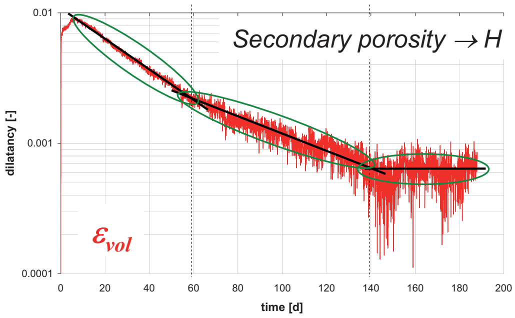
Implementation of Damage D as well as Damage-induced Creep in the Constitutive Model LUBBY2

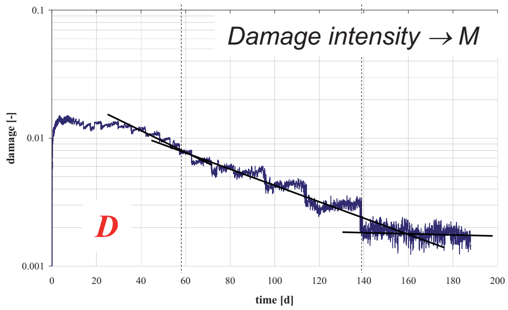


Back-formation of Damage

$$\dot{\varepsilon}_{ij}^{h} = -\varepsilon_{vol} \cdot \left(\frac{1}{fc1} \cdot \dot{F}^{h} + \frac{I_1}{fs1} + \frac{1}{fh} \right) \cdot \frac{\partial Q^{h}}{\partial \sigma_{ij}}$$

$$\dot{D} = -D \cdot \left(\frac{\dot{F}^{h}}{fc1 \cdot fc2} + \frac{I_1}{fs1 \cdot fs2} + \frac{1}{fh} \right)$$

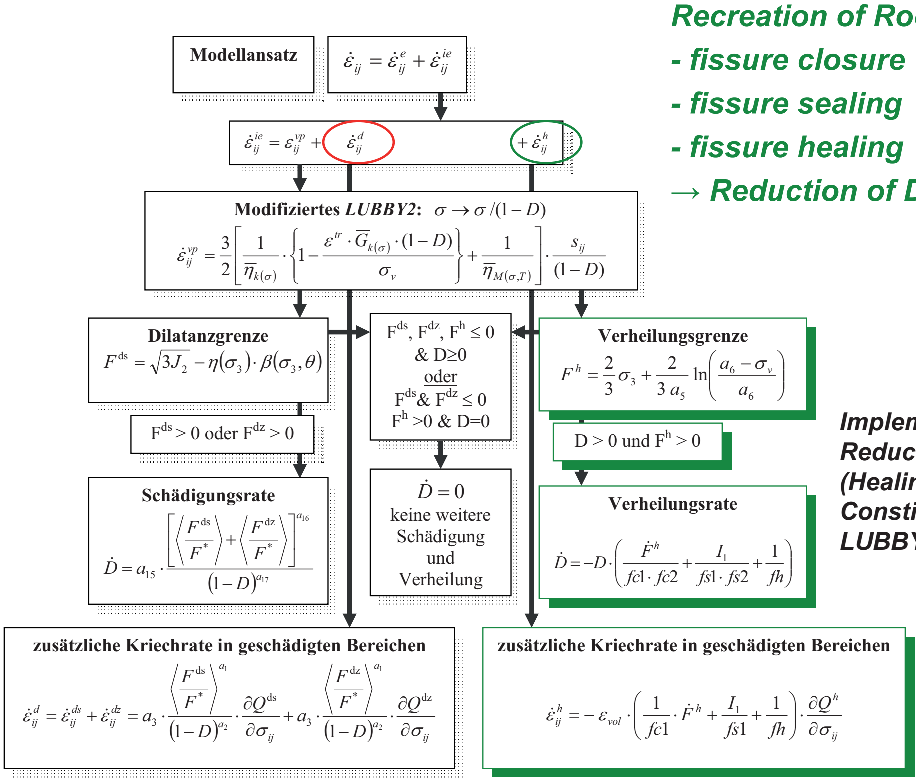




Recreation of Rock Fabric Quality

- fissure closure
- fissure sealing
- fissure healing

→ Reduction of Damage (Healing)



Implementation of Reduction of Damage (Healing) in the Constitutive Model LUBBY2

Advanced Constitutive Models with Respect to Damage / Healing 1995-2005

Phenomenological Approach (model rheologic)

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{vp} + \dot{\varepsilon}_{ij}^{d} + \dot{\varepsilon}_{ij}^{h}$$

with

$$\dot{D} = a_{15} \cdot \frac{\left[\left\langle \frac{F^{ds}}{F^{*}} \right\rangle + \left\langle \frac{F^{dz}}{F^{*}} \right\rangle\right]^{a_{16}}}{(1-D)^{a_{17}}}$$ damage process

$$\dot{D} = -D \cdot \left(\frac{\dot{F}^{h}}{fc1 \cdot fc2} + \frac{I_1}{fs1 \cdot fs2} + \frac{1}{fh} \right)$$ sealing / healing process

Hou / Lux (respectively ***Lux / Wolters***) – TUC
(elastic-viscous)

$$\dot{\varepsilon}_{ij}^{vp} = \left(\frac{1}{2 \cdot \eta_K(\sigma_V)} \cdot s_{ij} - \frac{G_K(\sigma_V)}{\eta_K(\sigma_V)} \cdot e_{ij} \right) + \left(\frac{1}{2 \cdot G_M} \cdot \dot{s}_{ij} + \frac{1}{2 \cdot \eta_M(\sigma_V, T)} \cdot s_{ij} \right) + H(f_s) \cdot \left(-\lambda^{*} \cdot \frac{\partial g_s}{\partial \sigma_{ij}} \right)$$

with

$$\left| \Delta\varepsilon_{vol}^{p} \right| = \frac{\sigma_{\psi}^{2}}{(\sigma_{\psi} - \sigma_3)^2} \cdot \Delta\varepsilon_{vol,0}^{p}$$

Minkley – IfG
(elastic-plastic-viscous)

Phenomenological Approach (structure rheologic)

$$\frac{d\varepsilon_{ges}}{dt} = P_F(\sigma_{okt}, \tau_{okt}, \sigma_3, \varepsilon_{ges}) \cdot \delta_{dam}(d_{dam}, \sigma_3) \cdot F_h(\Phi, \sigma_3, \tau_{okt}) \cdot \frac{d\varepsilon_{cr}}{dt}$$

with

$$\frac{d\varepsilon_{cr}}{dt} = \frac{b}{M} \cdot \frac{1}{r^2} \cdot v_0 \cdot \exp\left(-\frac{Q}{R \cdot T} \right) \cdot \sinh\left(\frac{b \cdot \Delta a \cdot \sigma^{*}}{M \cdot k_B \cdot T} \right)$$

Hunsche / Hampel – BGR
(CDM – Composite-Dilatancy-Model)

$$\dot{\varepsilon}_{eff}^{cr} = \frac{A}{\left(\varepsilon_{eff}^{V}\right)^{\mu}} \cdot \sigma_{eff}^{n}$$

with

$$\dot{\varepsilon}_{eff}^{V} = \dot{\varepsilon}_{eff}^{cr} - \dot{\varepsilon}_{eff}^{E} - \dot{\varepsilon}_{vol} \quad , \quad \dot{\varepsilon}_{eff}^{E} = \frac{\varepsilon_{eff}^{V}}{t_0} \quad , \quad \dot{\varepsilon}_{vol} = \left(A_1(\sigma_3) + A_2(\sigma_3) \cdot \exp(A_3(\sigma_3) \cdot U_{Dil}) \right) \cdot \dot{U}_{Dil}$$

Günther / Salzer – IfG
(strain-softening / strain-hardening)

$$\dot{\varepsilon}_{ij}^{I} = \frac{\partial G^{K}}{\partial \sigma_{ij}} \cdot F \cdot \dot{\varepsilon}_s + \frac{\partial G^{D}}{\partial \sigma_{ij}} \cdot F \cdot \exp\left[\frac{c_4 \cdot (\sigma_V - c_5)}{\sigma_0} \right] \cdot c_1 \cdot D_0 \cdot \exp(c_3 \cdot D) \cdot \left(\sinh\left[\frac{c_2 \cdot \sigma_{eq}^{D} \cdot H(\sigma_{eq}^{D})}{\mu \cdot (1-D)} \right] \right)^{n_3}$$

with

$$\dot{D} = \frac{x_4}{x_5} \cdot \left[\ln\left(\frac{1}{D} \right) \right]^{\frac{x_4+1}{x_4}} \cdot \left[\sigma_{eq}^{D} \cdot H(\sigma_{eq}^{D}) \right]^{x_3} - h(D, T, I_1)$$

Munson / Dawson → Fossum
(MDCF – Multimechanism Deformation Coupled Fracture)

source: *Comparison of advanced constitutive models for the mechanical behaviour of rock salt - results from a joint research project, I. Modeling of deformation processes and benchmark calculations. Proc. of the Sixth Conf. on the Mechanical Behaviour of Salt (Saltmech 6), Hannover, Mai 2007.*

6. Conference on the Mechanical Behaviour of Salt (2007)

Content

Part 1: THM-Processes in Salt Rocks – Observations at Laboratory and In-situ Scales

Part 2: Constitutive Models for the Mechanical Behaviour of Rock Salt

Part 3: Deformation Processes at Very Large Temporal and Spatial Scales – Geological Systems

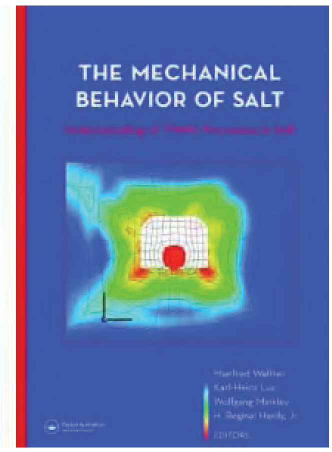
Part 4: THM-Processes in Crushed Salt Backfill of Final Repositories – Observations at Laboratory and In-situ Scales, Modelling

Part 5: THMC-Processes in Backfill Materials – Laboratory Observations and Modelling

Part 6: Studies of Mining and Mine Abandonment

Part 7: Cavern Design for Gas Storage and Solution Mining

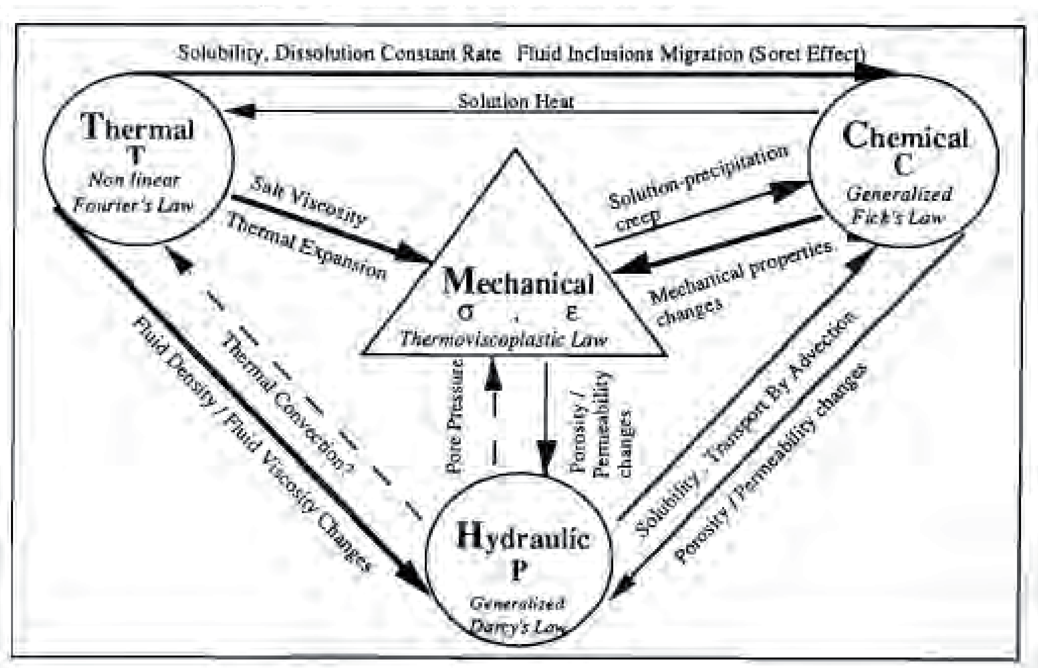
Part 8: Abandonment of Caverns



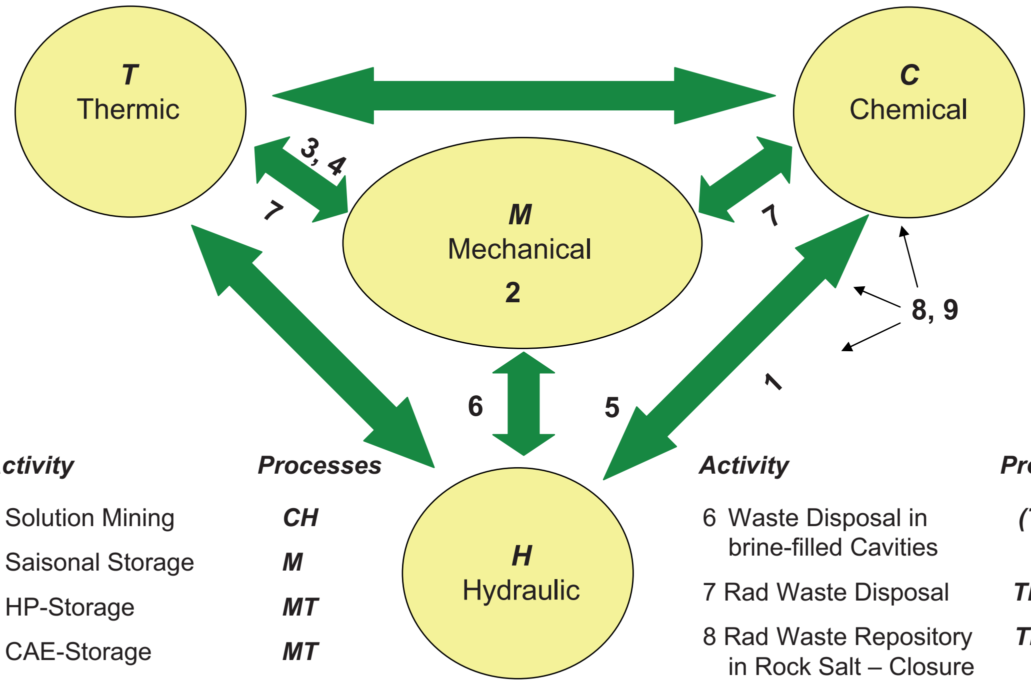
Some Selected Contributions / Activities with Respect to Constitutive Modelling

* Gas Storage in Salt Cavities
* Salt Cavern Abandonment
* Disposal of Chemotoxic Waste in Brine-filled Salt Cavities
* Behaviour of Geotechnical Barriers in Underground Repositories (Technical Construction ↔ Rock Salt Mass / EDZ)
* Modelling of Strain Softening and Dilatancy in the Mining System of the Southern Flank of the Asse II Salt Mine
* Investigations on Damage and Healing of Rock Salt
* Evaluation of In-situ Tests

⇒ Physical Modelling of Coupled Processes

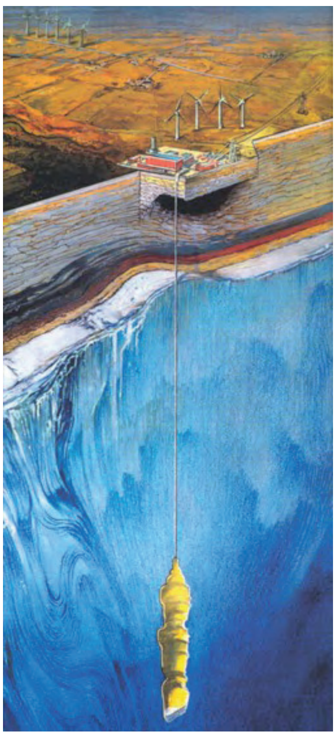


acc. to Ghoreychi et al. (1993)



Activity	Processes
1 Solution Mining	CH
2 Saisonal Storage	M
3 HP-Storage	MT
4 CAE-Storage	MT
5 Cavern Abandonment	MH

Activity	Processes
6 Waste Disposal in brine-filled Cavities	(T)HM
7 Rad Waste Disposal	TM / THC
8 Rad Waste Repository in Rock Salt – Closure	THM / THC
9 Rad Waste Repository in Rock Salt – Accident	THM-C

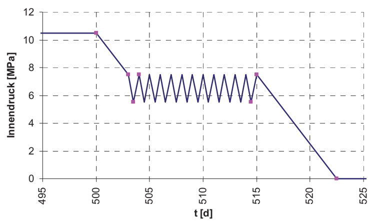


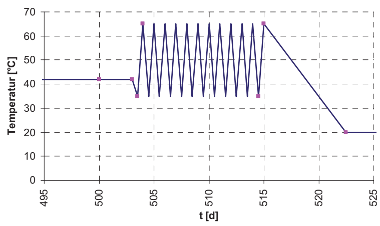
(KBB Underground Technologies)

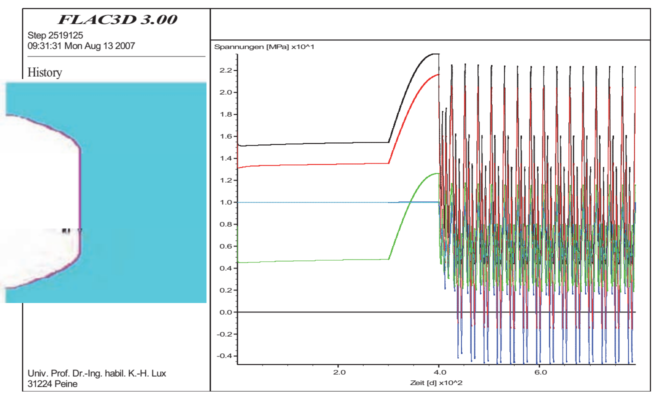
High-Performance Storage of Natural Gas

Storage of Liquified Natural Gas

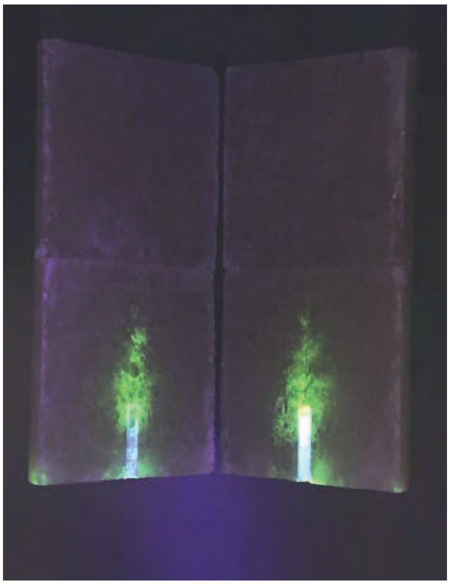
Compressed Air Energy Storage







Lab test experience

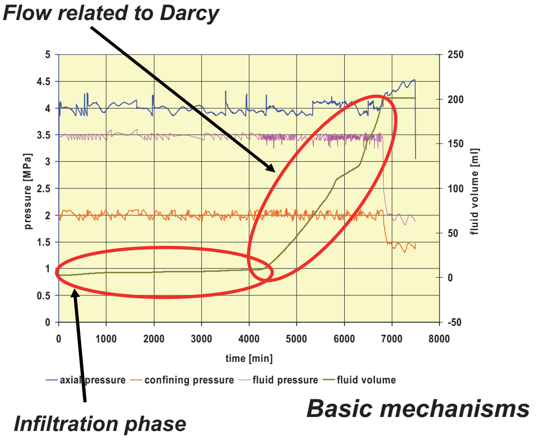


Salt rock sample with infiltration of liquid

$$-\bar{v}_{\text{inf}} = a \cdot \exp(b \cdot \Delta p_{Fl})$$

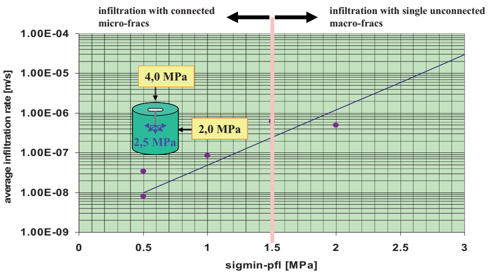
$$-\Delta p_{Fl} \uparrow = \beta \cdot \Delta K$$

$$-\Delta p_{Fl} \downarrow = \beta \cdot \Delta \phi^{s}$$



Basic mechanisms

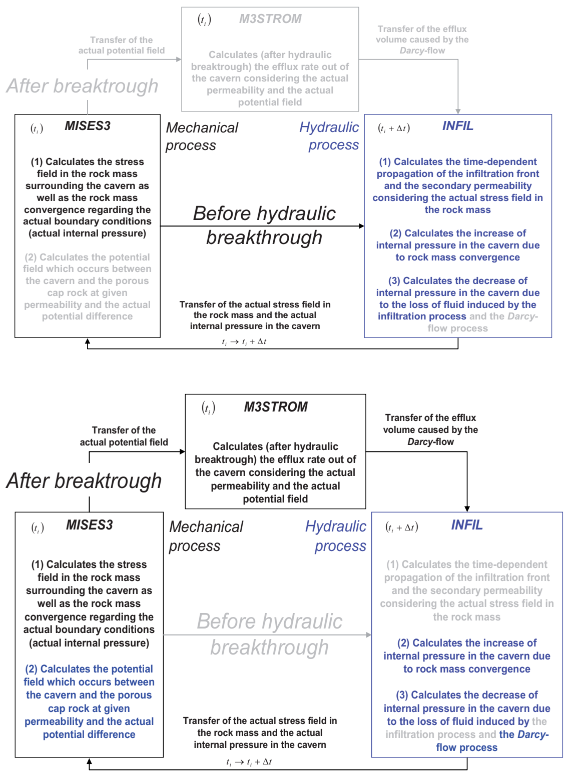
Physical Model



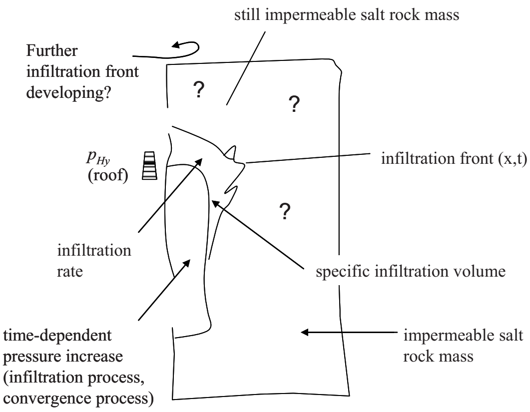
pressure-dependent representation of the average rate of infiltration v_{inf}

General Demands

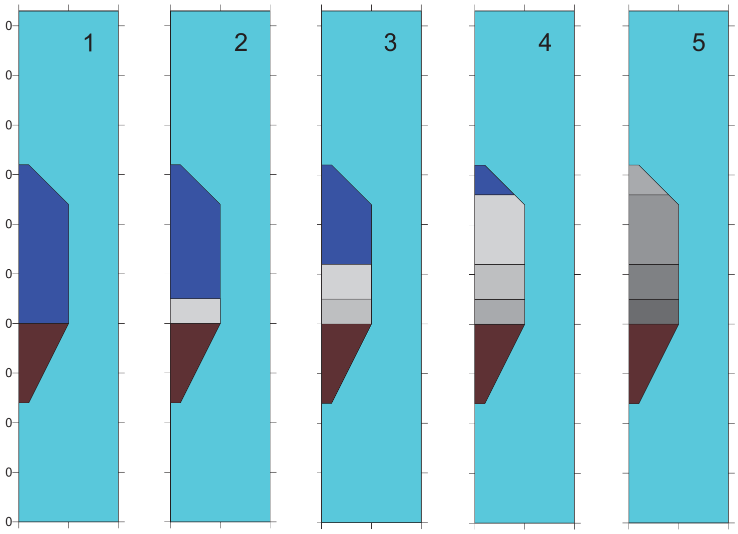
- Mechanical Stability
- Tightness
- Acceptable surface subsidence
- Environmental safe abandonment



Salt Cavern – Rock Mass Behaviour after Abandonment



THMC with Respect to Chemotoxic Waste Disposal in Abandoned Salt Cavities (1)



Explanation

1 Brine-filled Cavity, Cavern Sump

2/3/4 Waste Disposal (suspension) Solidification in-situ via
- Consolidation due to Gravity,
- Compaction due to Convergence of Salt Rock Mass,
- Solidification due to Chemical Processes ⇒
- *Brine-filled Pore Space?*
- *Pore Pressure Build-up?*
- *Waste Properties versus Time – Deformability / Permeability?*

5 Safe Cavern Closure ⇒
Behaviour in Long-Term?
Pressure-forced Infiltration of Brine / Gas into Rock Salt Mass?
Brine Propagation?
Brine / Gas Entry Pressure?

Main Steps in a Waste Disposal Cavity's Life Time

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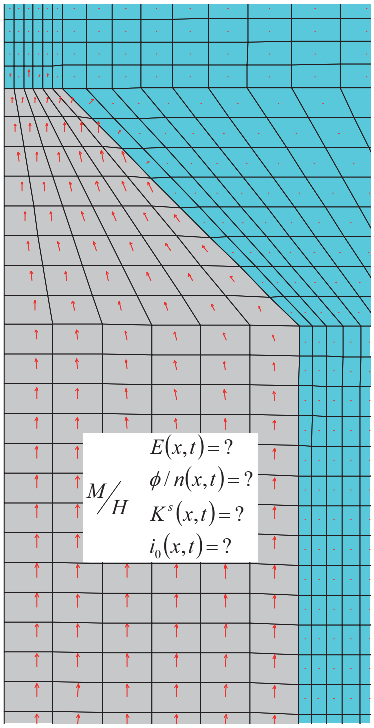
THMC with Respect to Chemotoxic Waste Disposal in Abandoned Salt Cavities (2)

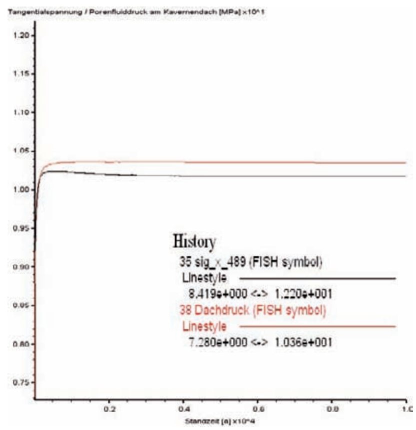


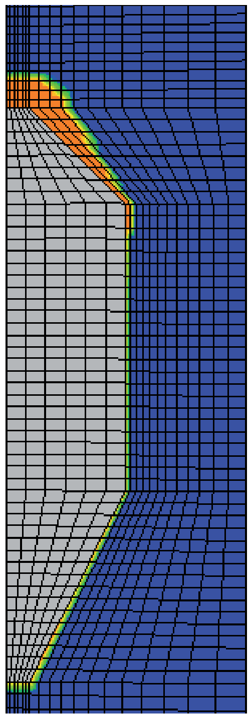
Coupling of Processes:

$$\left.\begin{array}{l} -\Delta p_{Fl}\uparrow = \beta\cdot\Delta K \\ -\Delta p_{Fl}\downarrow = \beta\cdot\Delta\phi^{s} \end{array}\right\} \text{Salt Rock Mass}$$

$$\left.\begin{array}{l} -E\downarrow\Rightarrow p_{Fl}\uparrow \\ -n\uparrow\Rightarrow p_{Fl}\uparrow \\ -\Delta n\Rightarrow\Delta\phi^{s}\Rightarrow\Delta K^{s} \end{array}\right\} \text{Waste}$$

pore pressure > fluid threshold pressure



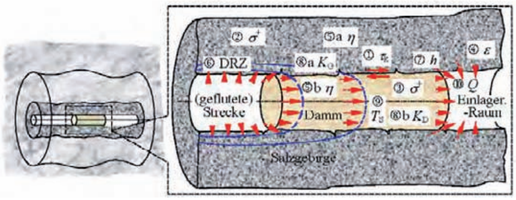


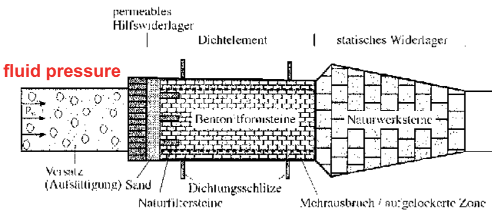
Pore-fluid Flow in Waste due to Rock Salt Mass Convergence

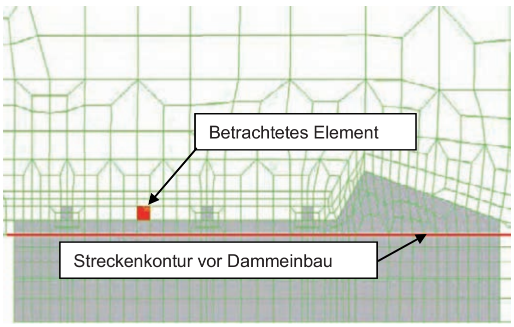
Infiltration of Contaminated Pore Fluid in Rock Salt Mass

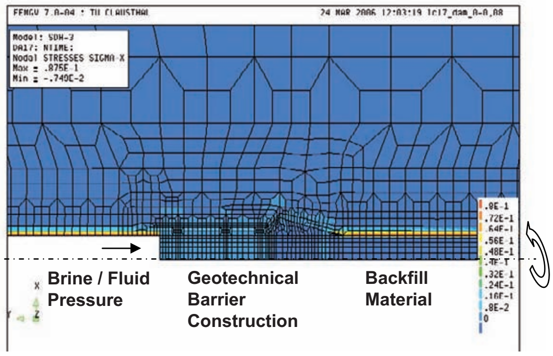
Univ. Prof. Dr.-Ing. habil. K.-H. Lux
Professorship for Waste Disposal and Geomechanics

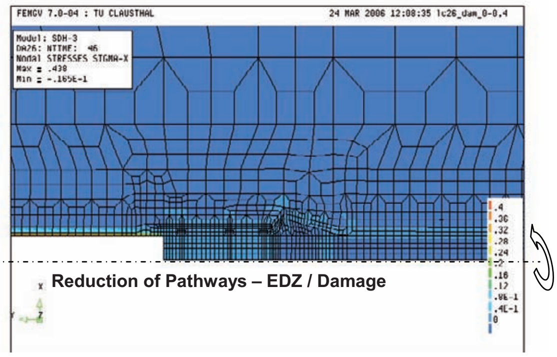
Geotechnical Barriers / Physical Modelling and Numerical Simulation





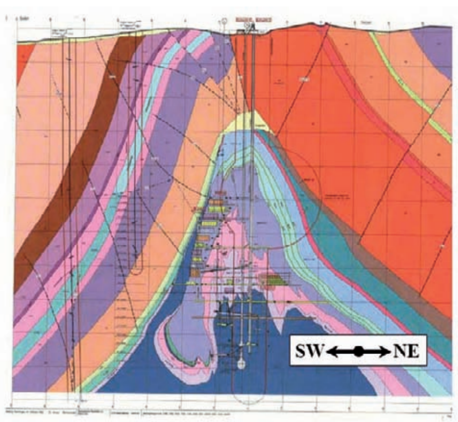


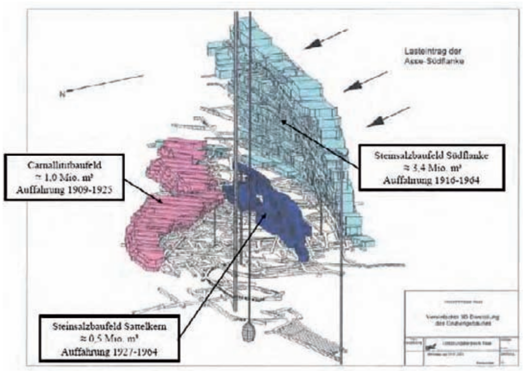


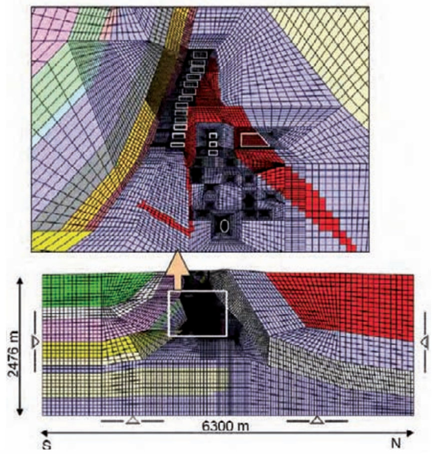


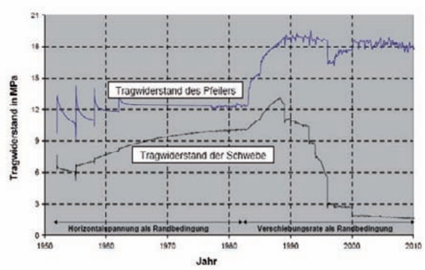
In-situ Test Sondershausen (Eberth, 2007)

Modelling of Strain Softening and Dilatancy in a Mining System





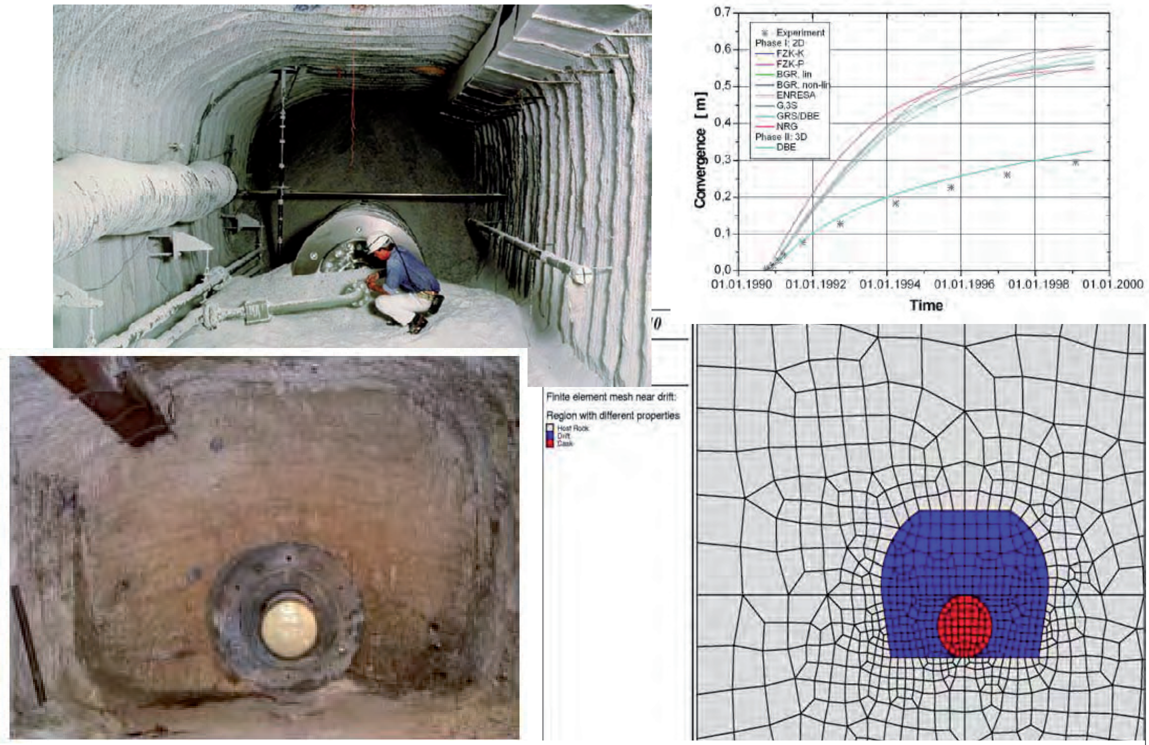




Stability of Southern Flank of the Asse II Salt Mine

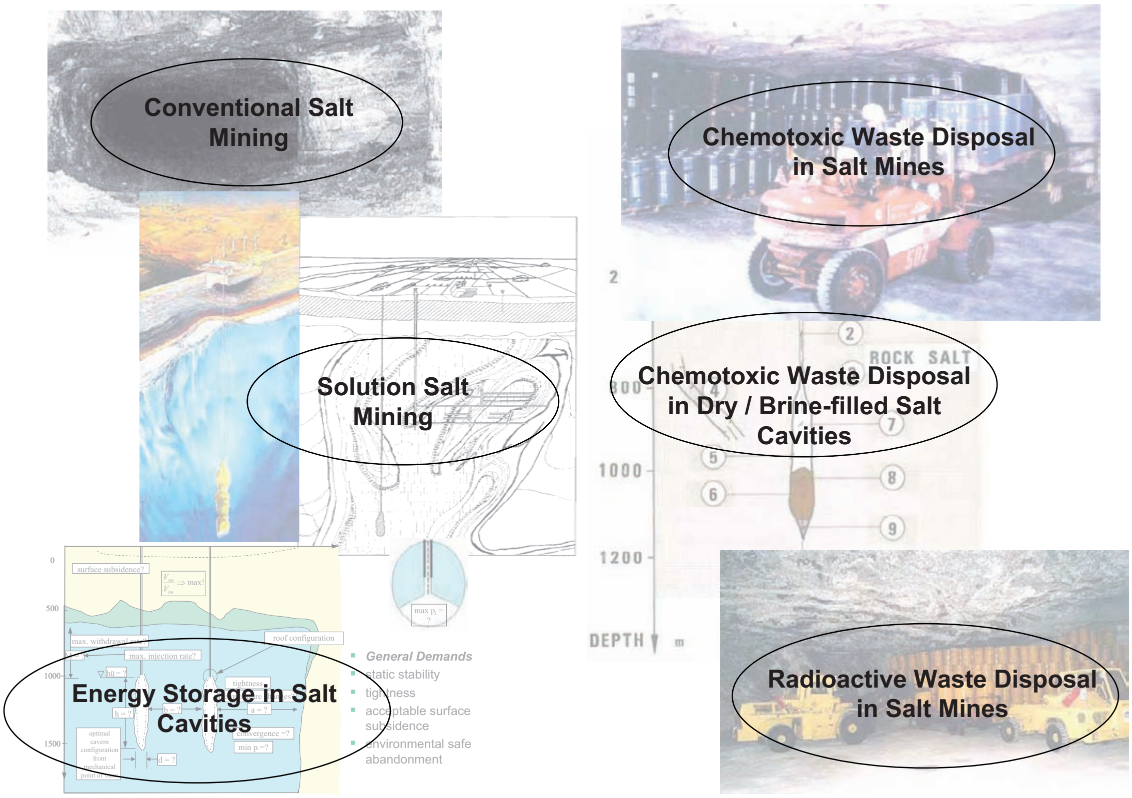
Prognosis of Load Bearing Behaviour (Kamlot et al., 2007)

THMC with Respect to Rad Waste Disposal in Salt Rock Mass

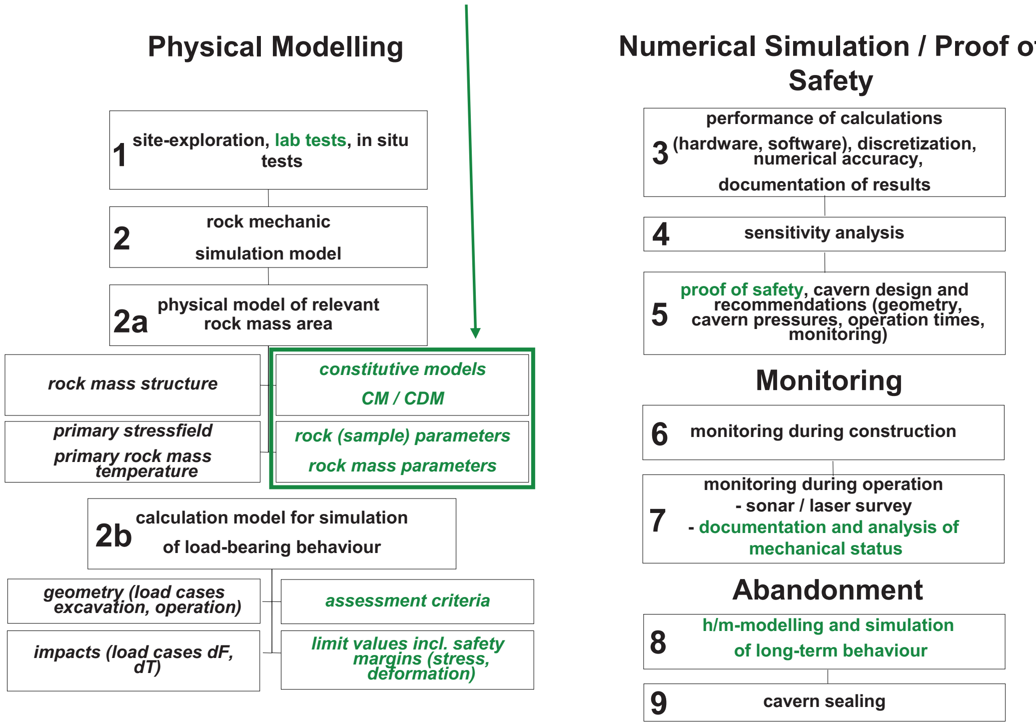


Prognosis of Load Bearing Behaviour of Backfilled Disposal Drift with special Respect to Heat Generation (Rothfuchs et al., 2004)

Recent Activities in Rock Salt Mass



Constitutive Modelling – Essential Part of Geotechnical Design



(a) Classic Design Concept – CM ***(b) Modifications for Advanced Design Concept – CDM***

Constitutive Modelling – Recent Activities

(I) EU-Research Project THERESA

THERESA = Coupled Thermal-Hydrological-Mechanical-Chemical (THMC) Processes for Repository Safety Assessment

Benchmark of Physical Modelling / Numerical Simulation

(II) German Joint Research Project – Constitutive Modelling

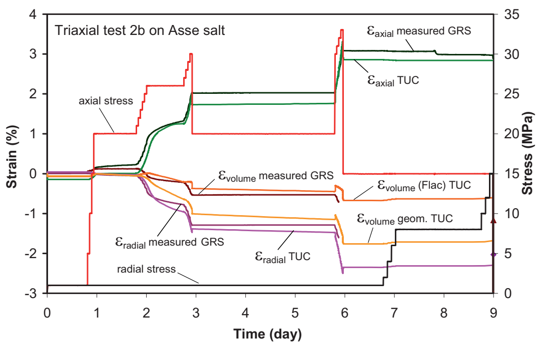
Phase 1: 2004 – 2006: Modelling of the Mechanical Behaviour of Rock Salt. Comparison of Advanced Constitutive Models and Methodologies.

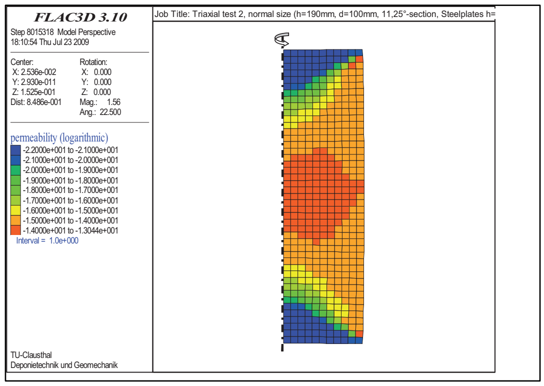
Phase 2: 2007 – 2010: Comparison of Advanced Constitutive Models and Methodologies based on 3D-Simulations regarding the Long-term Bahaviour of a Real Mine Structure in Rock Salt

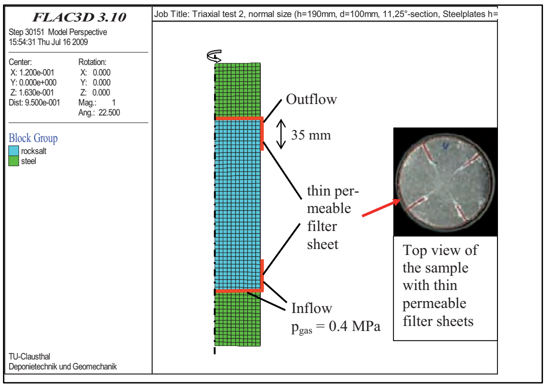
Phase 3: ? (Comparison of Advanced Constitutive Models and Methodologies based on Numerical Simulations regarding the Thermo-mechanical Behaviour as well as the Sealing / Healing Behaviour of Rock Salt)

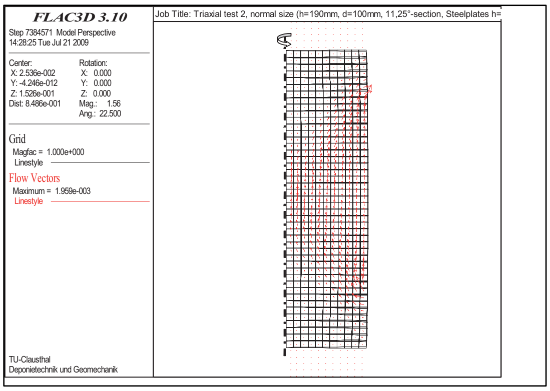
Benchmark of Constitutive Modelling / Numerical Simulation

(I) EU-Research Project THERESA

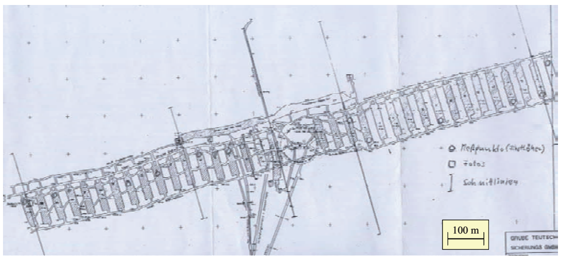


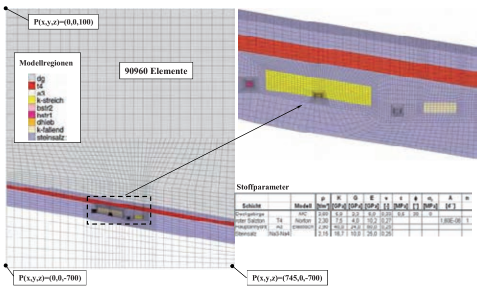


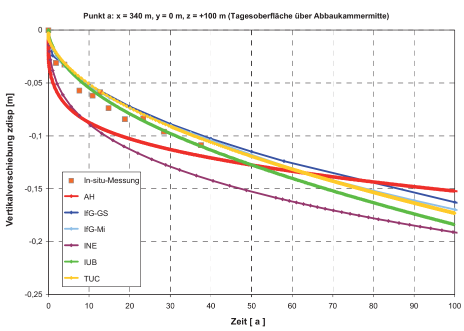


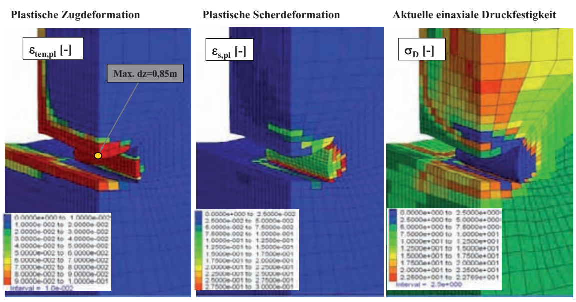


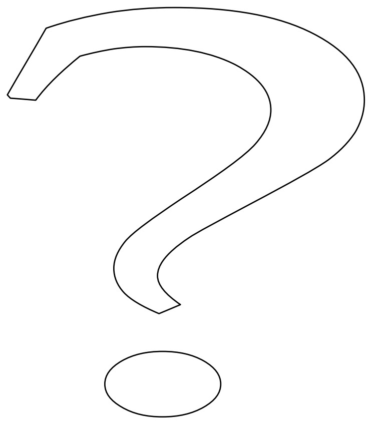
(II) German Joint Research Project – Constitutive Modelling











First simple answer:
I don't know – as less as you may do –

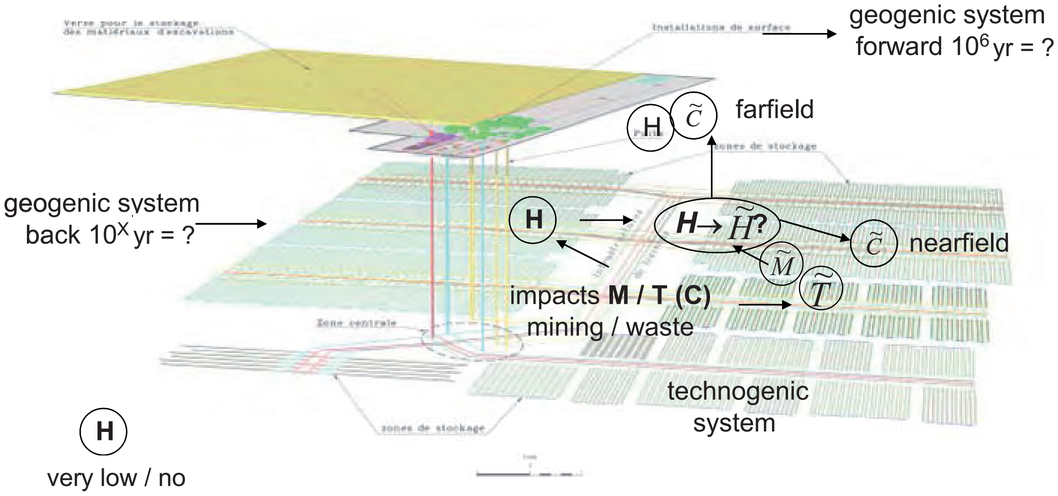
Second more complex answer:
We can try to follow our own business and extrapolate presence processes in future …

Physical Modelling / Numerical Simulation of Processes in the Nearfield

Level 1: Process level - THMC – Analysis of physico-chemical processes in the Nearfield

$$\mathbf{M} \rightarrow \tilde{\mathbf{M}} \,/\, \mathbf{T} \rightarrow \tilde{\mathbf{T}} \,/\, \mathbf{H} \rightarrow \tilde{\mathbf{H}} \,/\, \mathbf{C} \rightarrow \tilde{\mathbf{C}}$$

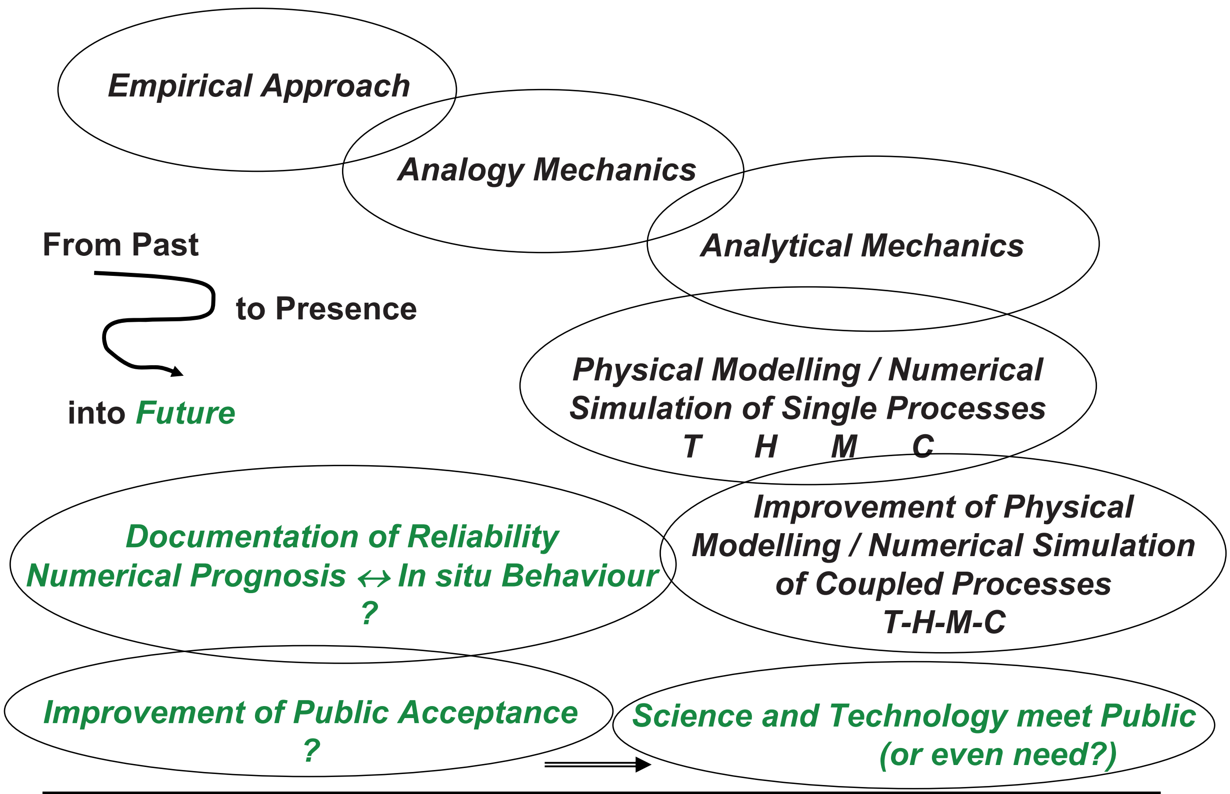
Improvement of Understanding as well as Physical Modelling / Numerical Simulation of Complex Geotechnical Processes



Improvement of Scientific State of the Art with Respect to Safety

probability of occurrence of FEP's (impacts on geosystem)
high → ordinary development ⇒ complete isolation
low → case scenario ⇒ admissible release

General Development – Future (2)



Future Development with Respect to Rad Waste Disposal (1)

What do we miss

… but would like to have most?

Public Acceptance

Future Development with Respect to Rad Waste Disposal (2)

What do we (think to) have?

What would we like to have?

Public Acceptance

Guarantee of Safety (technical-scientific)

(as a long dynamic process)

Reliable Physical Modelling ⇒ Constitutive Models are Essential Part of Safety Case

Demonstration of Reliability and Safety?

The (A) Way to get Public Acceptance

Future Development with Respect to Rad Waste Disposal (3)

What can – should – perhaps must – we do?

Precondition

Information and Communication (in a complex field)

Intention

Technical-scientific Acceptance

(as a dynamic process)

based on

Guarantee of Safety

Improvement of Reliable Physical Modelling ⇒ Constitutive Models are Essential Part of Safety Case

Demonstration of Reliability and Safety?

⇓

Reliability of Science and Technology

via

Dialogue

↓

Participation → Persons Concerned Become Actors Considering Regional Mannerisms

Public Monitoring

national / international

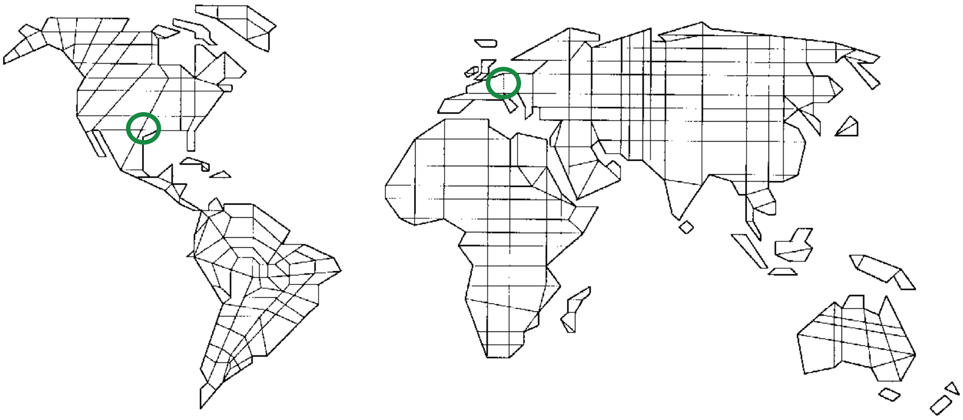
⇓

Updated Management Structures for Rad Waste Disposal

↑

Public Acceptance based on Confidence, Transparency, Fair Proceeding (political)

Thank you for your Attention



Welcome to Clausthal University

Univ. Prof. Dr.-Ing. habil. K.-H. Lux
Professorship for Waste Disposal and Geomechanics

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

EVOLUTION OF DAMAGE AND HEALING IN THE EDZ

Otto Schulze
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover

Evolution of damage and healing in the EDZ

Otto Schulze, Federal Institute of Geosciences and Natural Resources (BGR)

0. Introduction - some information about BGR

1. Site investigation Gorleben
2. Evolution of damage in the EDZ
3. Evolution of "healing"
4. Summary

Federal Institute for Geosciences and Natural Resources (BGR)

The BGR is the central geoscientific authority providing advice to the German Federal Government in all geo-relevant questions.

BGR is a subordinated agency of the Federal Ministry of Economics and Technology (BMWi)

http://www.bgr.bund.de http://www.bmwi.de

Main working areas of BGR

Geo - Resources

- Natural gas, petroleum, coal, uranium
- … mineral resources
- Groundwater

Geo - Safety

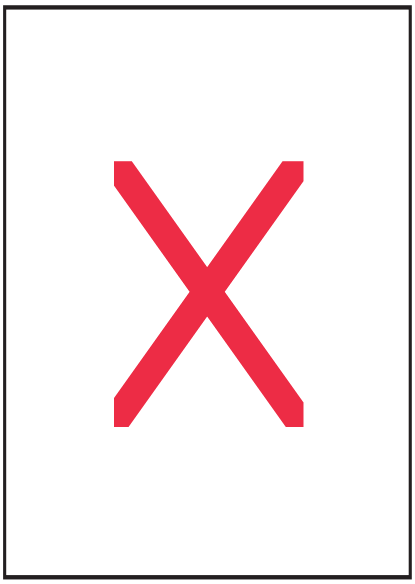
- Final disposal of waste
- Geohazards
- Seismology/ nuclear test-ban

Cross Section

- geological basics
- …

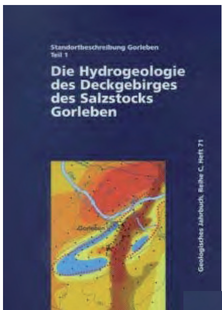
Important recent publications

Proceedings of the
6th Conference on the
Mechanical Behavior of Salt



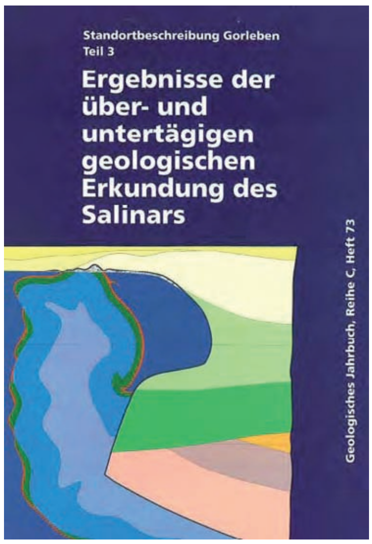
Investigation of the Gorleben Salt Dome, Germany

Hydrogeology of the overburden rock



Geology of the Overburden and Adjoining Rock

Underground Exploration of the Salt Formation



In preparation - part 4:
Geotechnical Exploration

Evolution of damage and healing in the EDZ

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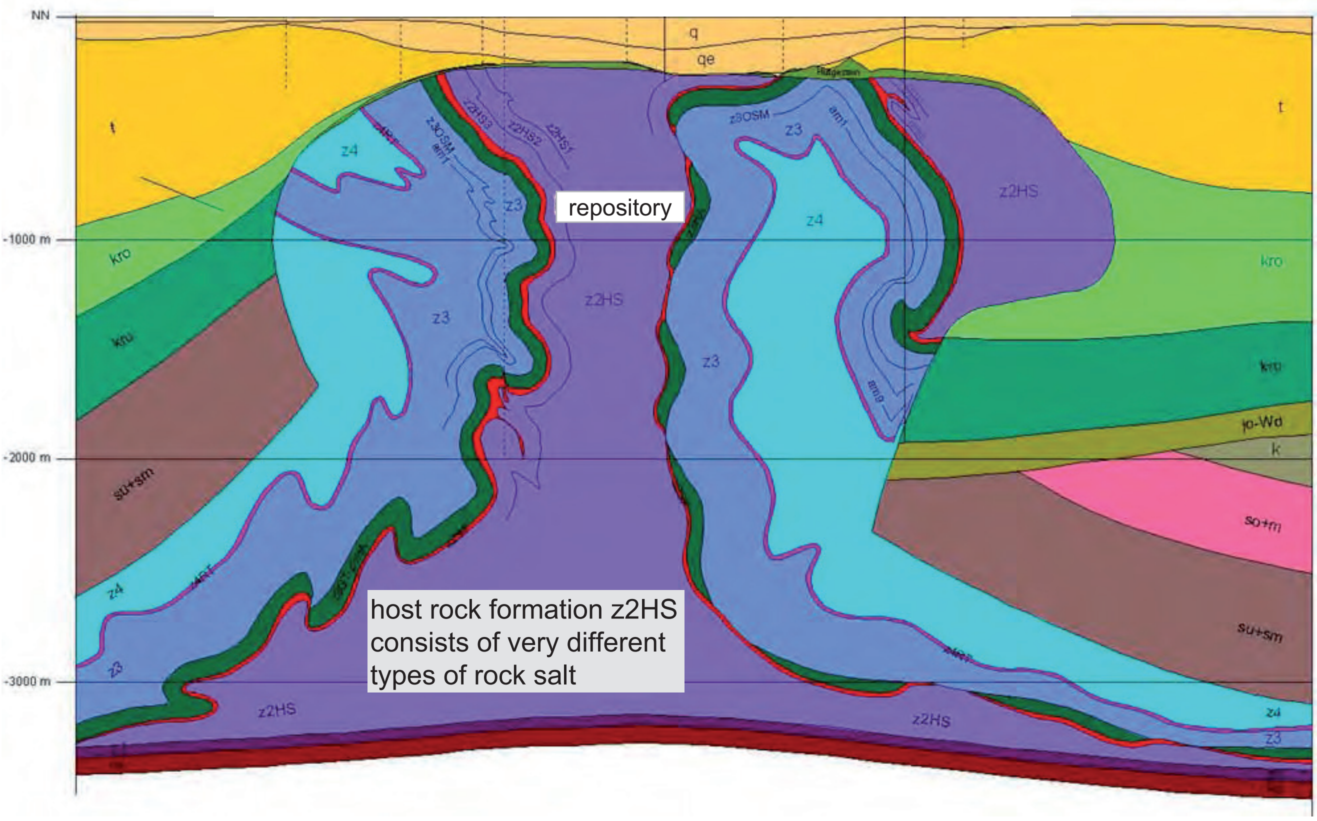
NW SE

Gorleben salt dome - internal structure



Site investigation ?? what will be the main tasks ??

>> there will be many, of course (Federal Office for Radiation Protection, BfS)

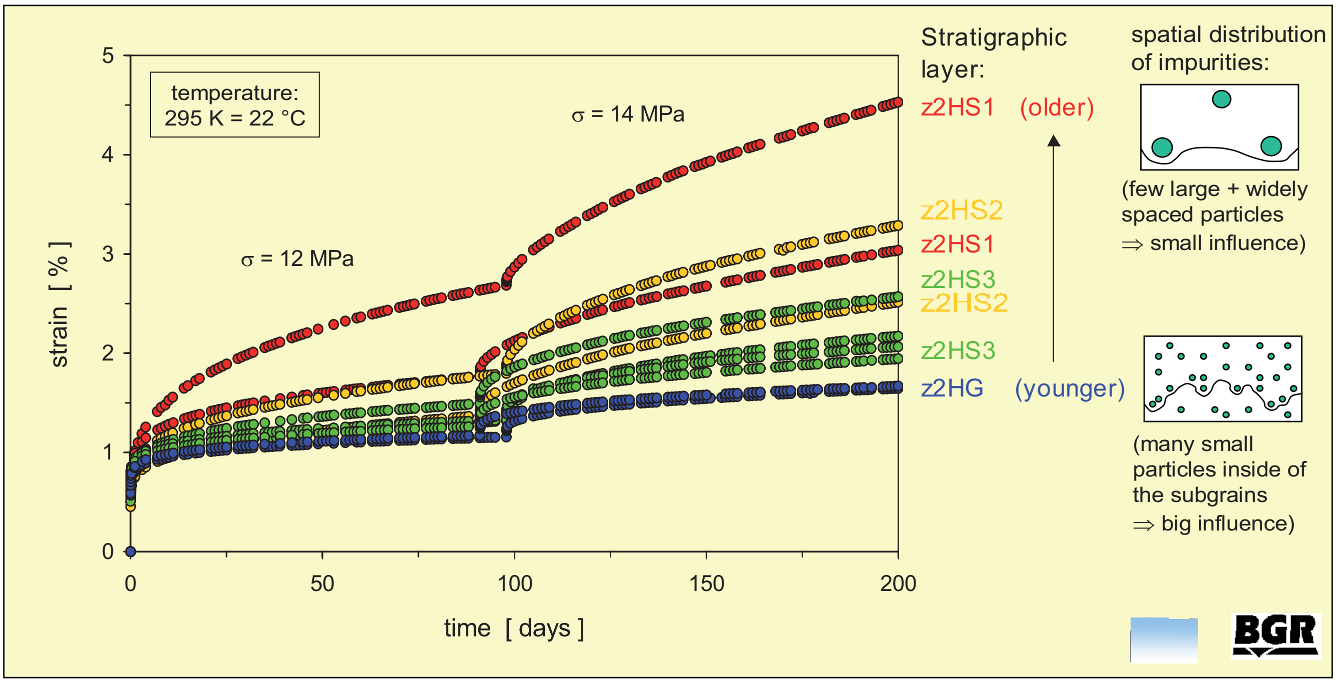
>> **long-term creep of the rock salt** is really important,
because rock salt is dominating the structure of the salt formation

- **long-term closure** of the underground openings by **convergence**
- **stress re-distribution and re-compaction in the EDZ**
- **self-sealing of the damaged rock salt** … and the compaction of backfill

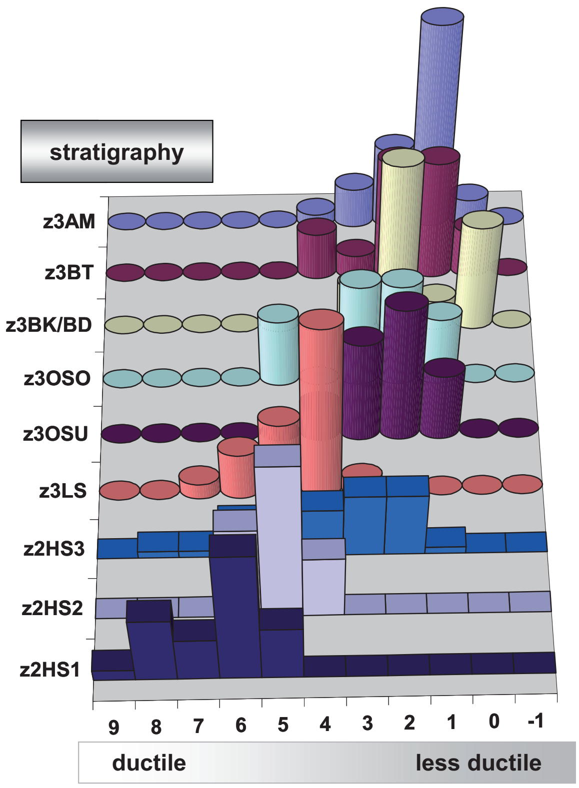
convergence by creep: source term for pressurization of fluids (… and gases)

1. **modeling of creep: BMBF - joint research project**
   >> SaltMech 6 (2007) ; ARMA (Salt Lake City, June 27–30, 2010)
2. **… dependence of creep on … macro- and micro-structure …**
   >> … a few remarks on creep of different types of rock salt

... rock salt from the Gorleben salt dome - "Stassfurt cycle" (z2)



Differences in the deformation behavior of various types of natural rock salt are mainly caused by different types of impurities and their spatial distribution.



Frequency distribution of creep ductility.

mapping of creep behavior

> determination of creep classes (c-cl)

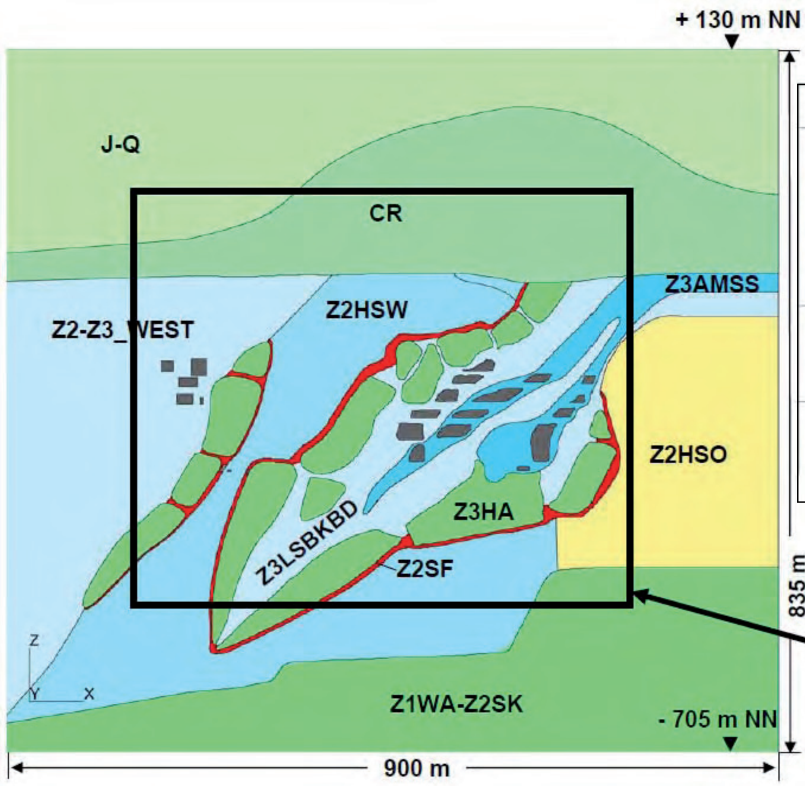
>> $(d\varepsilon/dt)^* = A^* \cdot (d\varepsilon/dt)_{ref}$

BGR - reference creep law
(Norton power law): $d\varepsilon/dt \sim \sigma^n \cdot f(T)$

creep class
(c-cl) = round[5 + $LOG_2(A^*)$]

>> frequency distribution of creep classes (c-cl)
… and representative mean value

however:
care for deviations from the general trend



(c-cl) in homogenized areas

- A*=10 — high ductility
- A*=1/2
- A*=1/8
- A*=1/16
- A*=1/32 — low ductility
- E<2 000 MPa
- E<10 000 MPa — elastic behavior
- E<100 000 MPa
- open rooms
- backfilled rooms

application of the strategy:
- simplified geologic model
- correlations and mapping
- specified numerical modeling

Evolution of damage and healing in the EDZ

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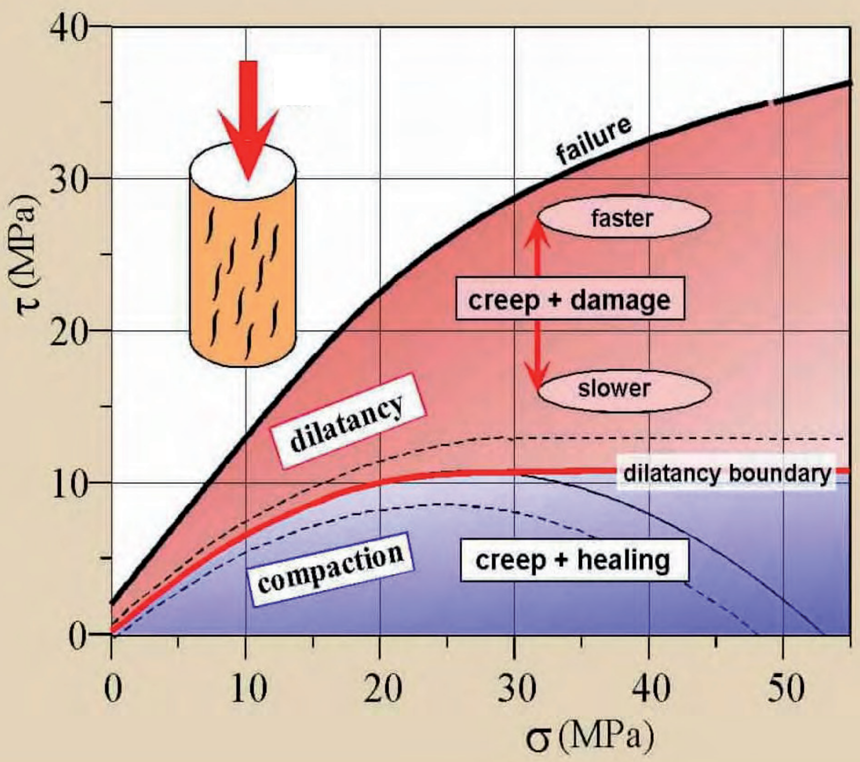


Deformation in salt

1. Creep (predominantly carried by dislocations in the crystals)
2. Deformation related to crack development

dilatancy
microcracks ↑
damage ↑
permeability ↑
creep failure
humidity induced creep

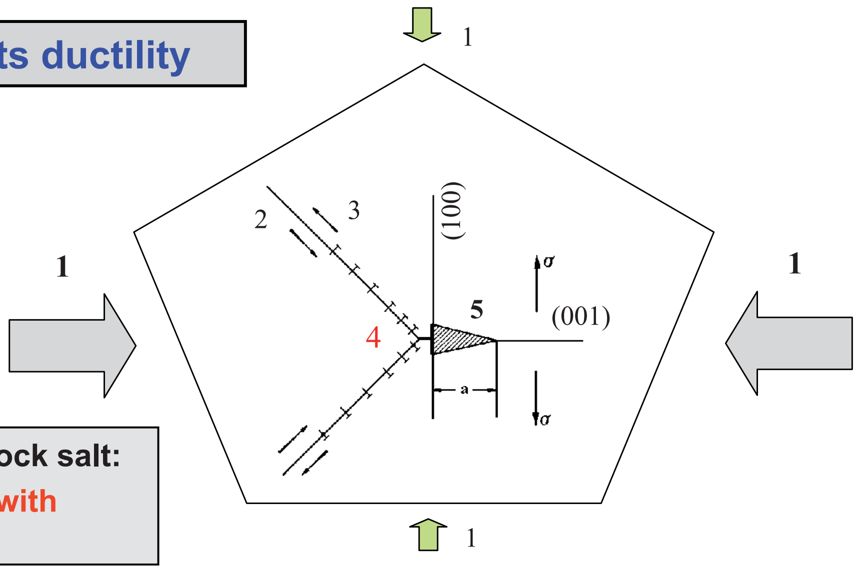
compression
microcracks ↓
damage ↓
permeability ↓
no creep failure

EC - Conference , Luxembourg 2003

Modeling: dilatancy affects ductility

micro - processes

1: stresses activate dislocations
2: gliding plane
3: gliding direction
4: pile-up of dislocations
5: micro-crack formation



The CDM dilatancy concept for rock salt:
Evolution of damage is coupled with deformation by dislocations.

non - dilatant deformation		dilatancy, damage and failure			
transient and steady state creep	compaction and healing	humidity induced creep processes	softening: damage induced deformation	failure	post-failure behaviour

$(\Delta\varepsilon/\Delta t)_{tot} = (\Delta\varepsilon/\Delta t)_{creep} \cdot f(\Phi) \cdot F_h \cdot \delta(d_{damage \dots max}, \sigma_{min}) \cdot P_F$

Modeling of dilatancy related effects on ductility

Composite-Dilatancy-Model (CDM) Hampel et al. (2007, 2002)

$$\dot{\varepsilon}_{tot} = P_F \cdot \delta \cdot F_h \cdot \dot{\varepsilon}_{cr}$$

coupled processes

$\dot{\varepsilon}_{cr}$	Creep rate of dry and compacted rock salt
F_h	Function for the humidity induced creep
δ	Function for the influence of damage on the strain rate
P_F	Function for the acceleration of the creep rate at failure

$\delta = f(d_{dam}, \sigma_{min})$ damage function depends on damage evolution

$\dot{d} = \sigma_o \; \dot{\varepsilon}_v$ ... depends on volumetric strain rate

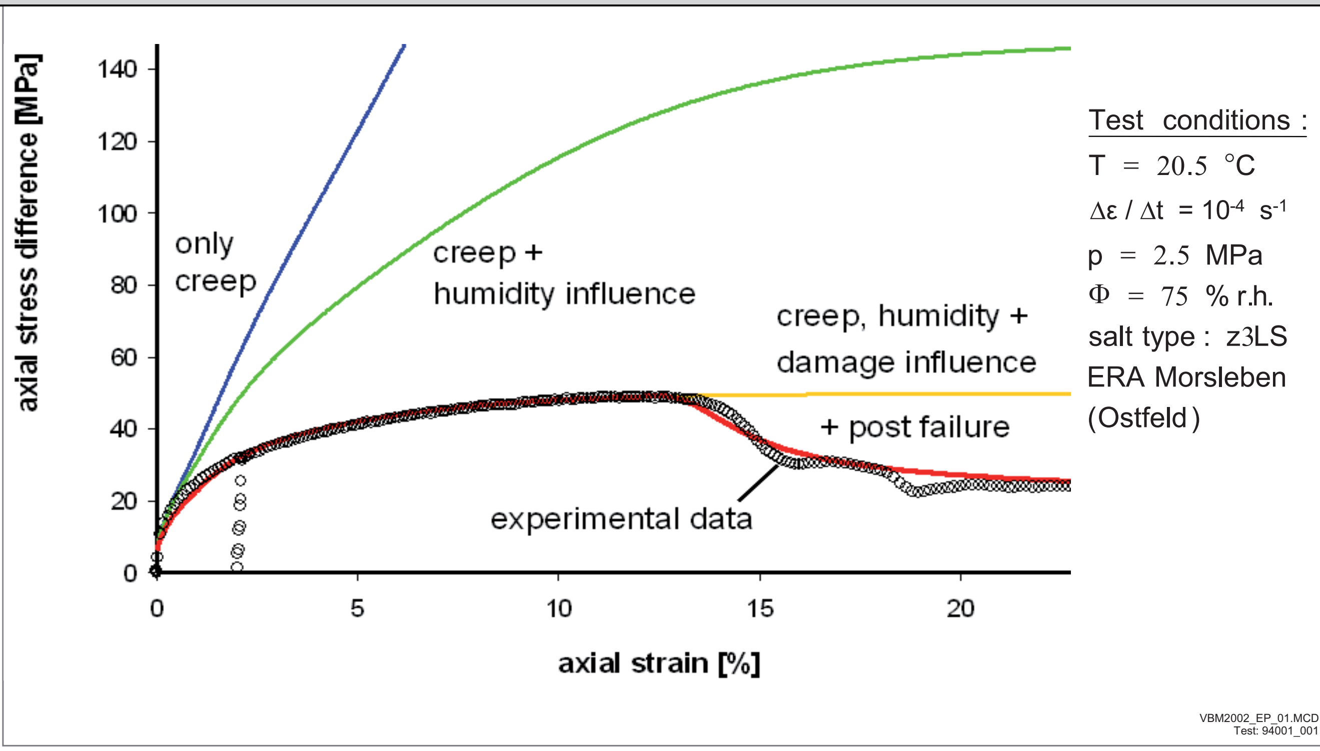
$\dot{\varepsilon}_v = r_v \cdot \dot{e}_{eff}$ ... depends on r_v and deviatoric strain rate

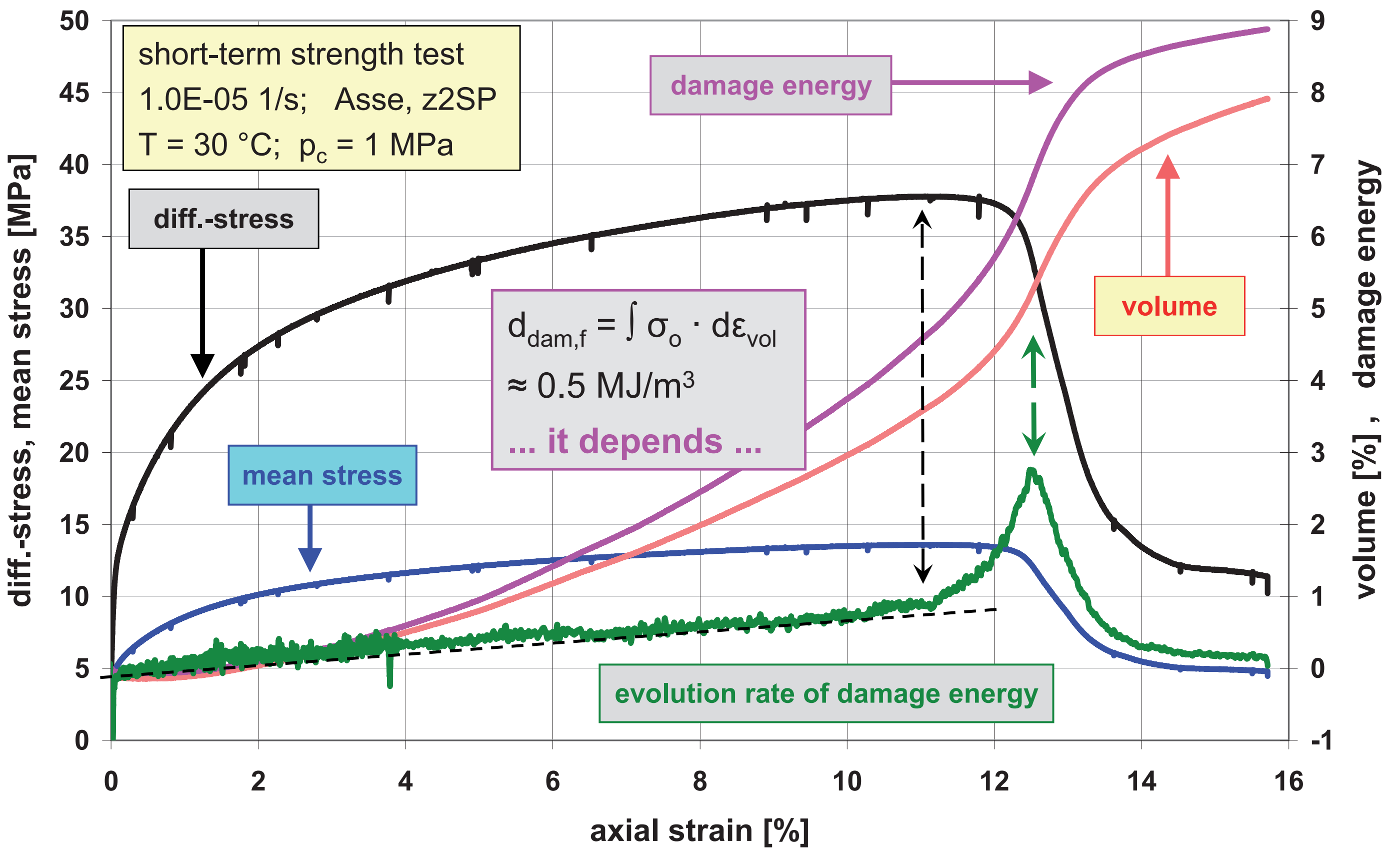
$$r_v(\tau_o, \sigma_o) = c_{rv} \cdot \frac{\tau_o - \tau_{DCH}}{\sqrt{2}\,\sigma_o - \tau_{DCH}}$$

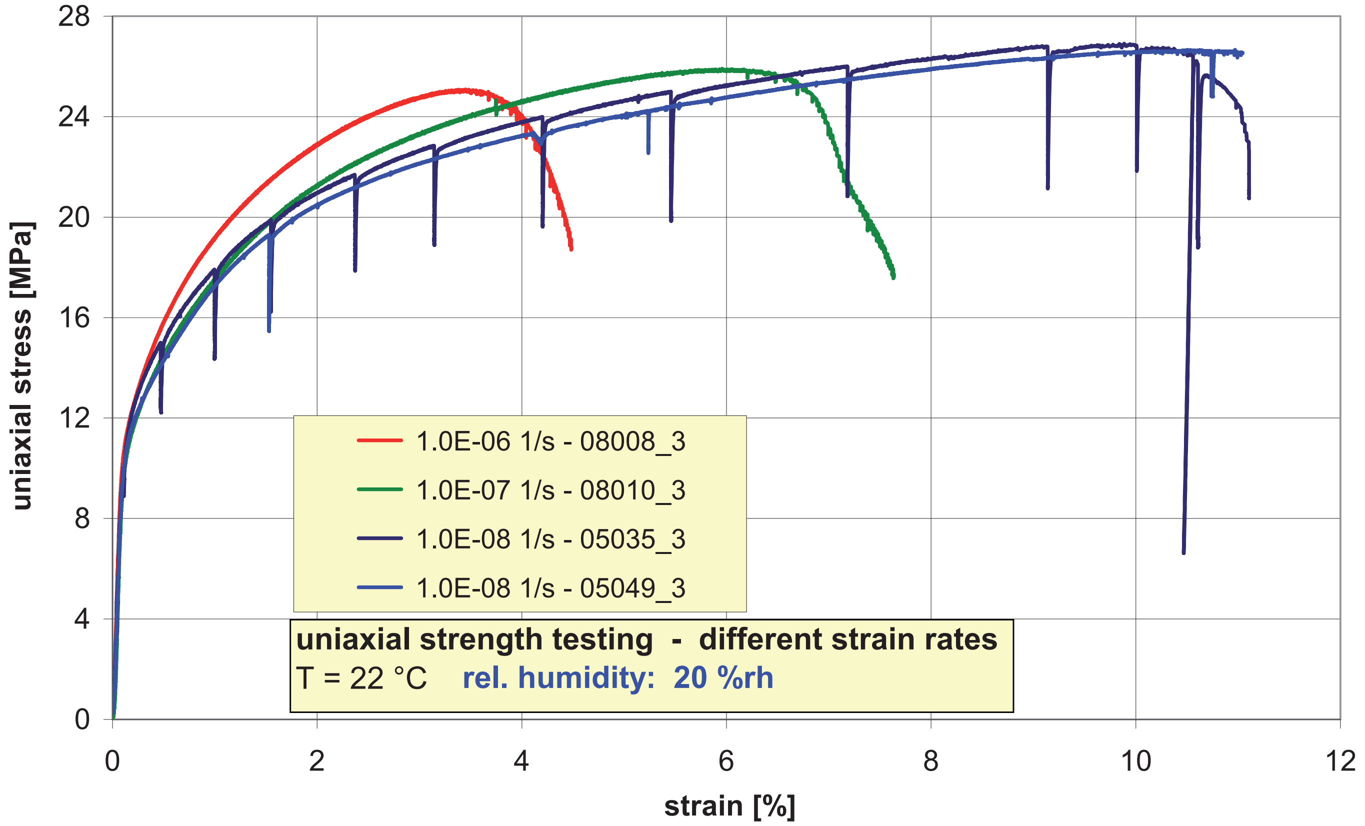
... depends on the state of stress τ_o, σ_o and the dilatancy boundary τ_{DCH}

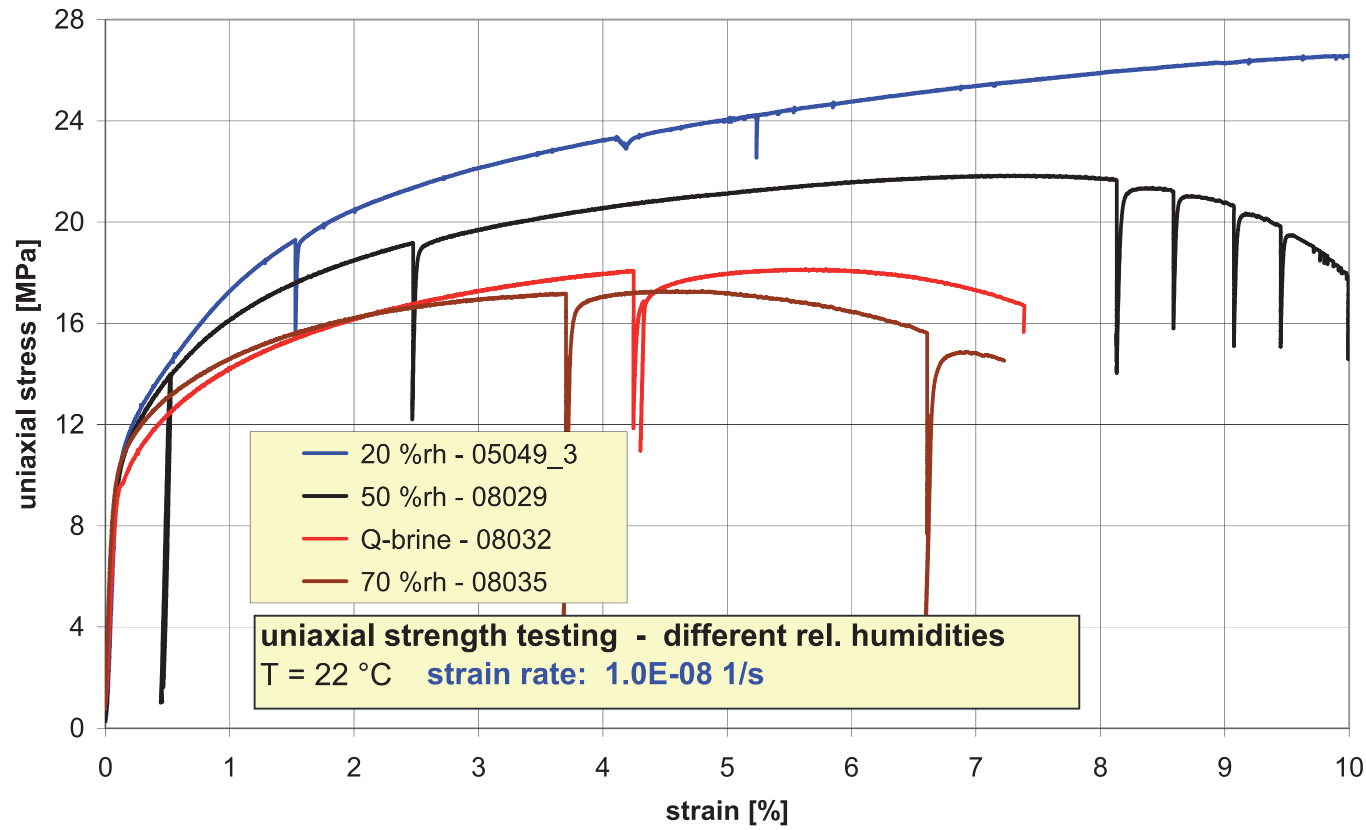
CDM - features: Simulation of a laboratory test with constant strain rate

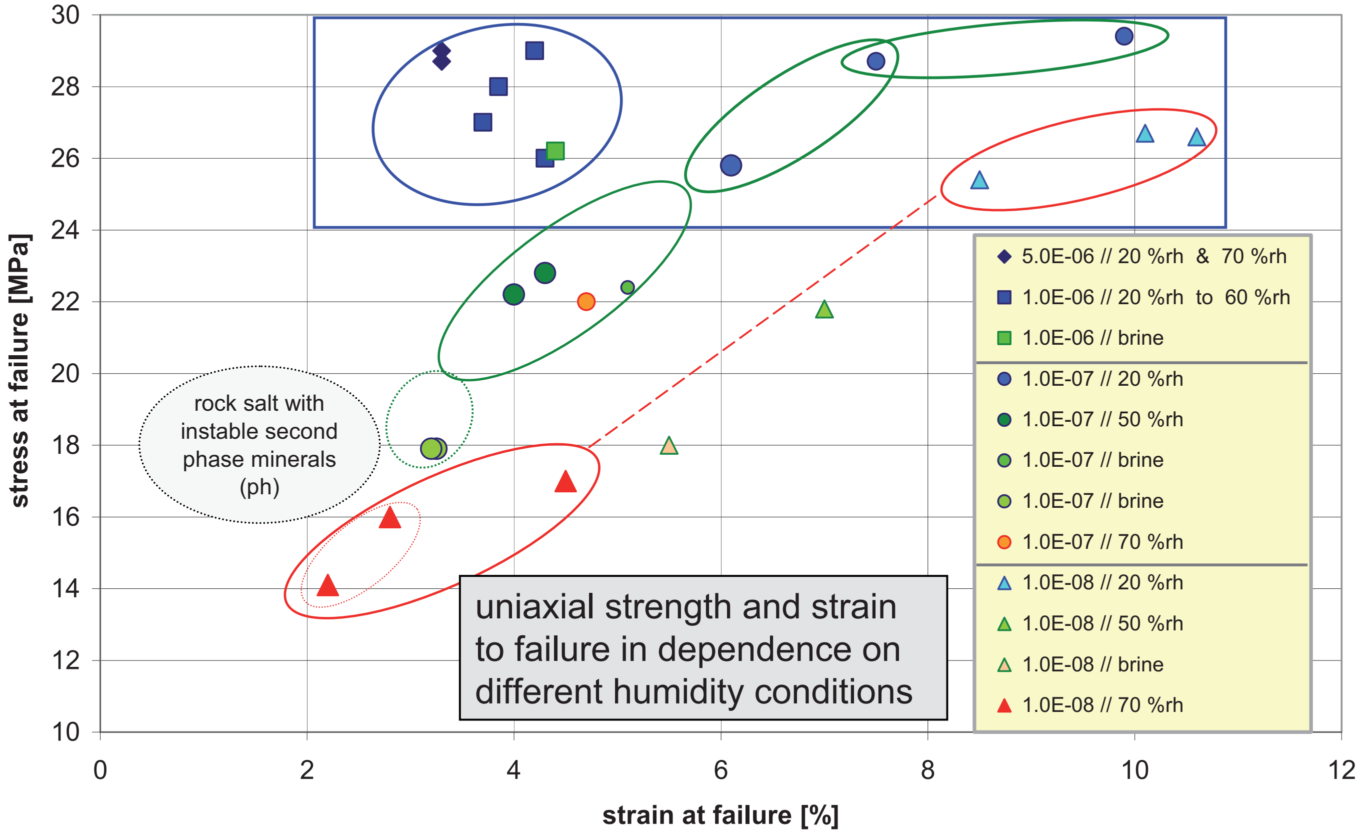
taking into account the dilatancy related effects

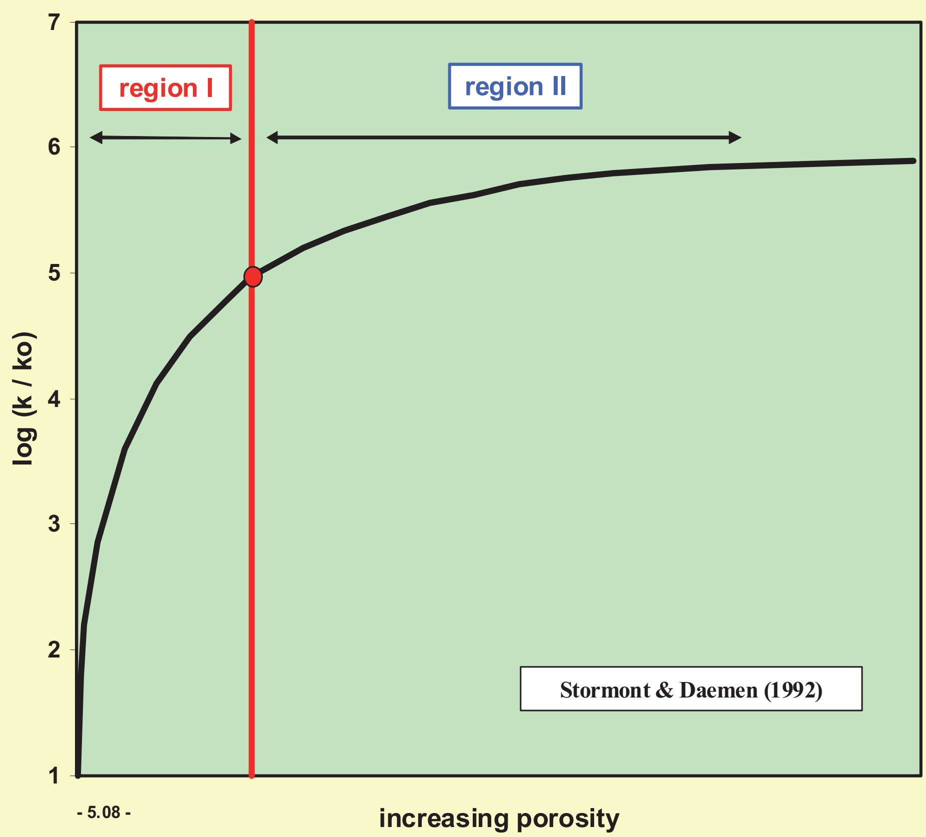





uniaxial stress [MPa]
28
24
20
16
12
8
4
0
0
2
4
6
8
10
12
strain [%]
1.0E-06 1/s - 08008_3
1.0E-07 1/s - 08010_3
1.0E-08 1/s - 05035_3
1.0E-08 1/s - 05049_3
uniaxial strength testing - different strain rates
T = 22 °C rel. humidity: 20 %rh


uniaxial stress [MPa]
28
24
20
16
12
8
4
0
0
1
2
3
4
5
6
7
8
9
10
strain [%]
20 %rh - 05049_3
50 %rh - 08029
Q-brine - 08032
70 %rh - 08035
uniaxial strength testing - different rel. humidities
T = 22 °C strain rate: 1.0E-08 1/s





region I

undisturbed rock salt :

$k < 10^{-20}$ m^2

dilatant deformation:

"spontaneous" interconnection of pores & cracks → spontaneous increase in permeability

region II

disturbed rock salt :

$k \geq 10^{-17}$ m^2

dilatant deformation:

interconnections are existing, cracks widen → "moderate" increase in permeability

German-CBFO Salt repository Workshop, April 25-27, 2001 Carlsbad, NM

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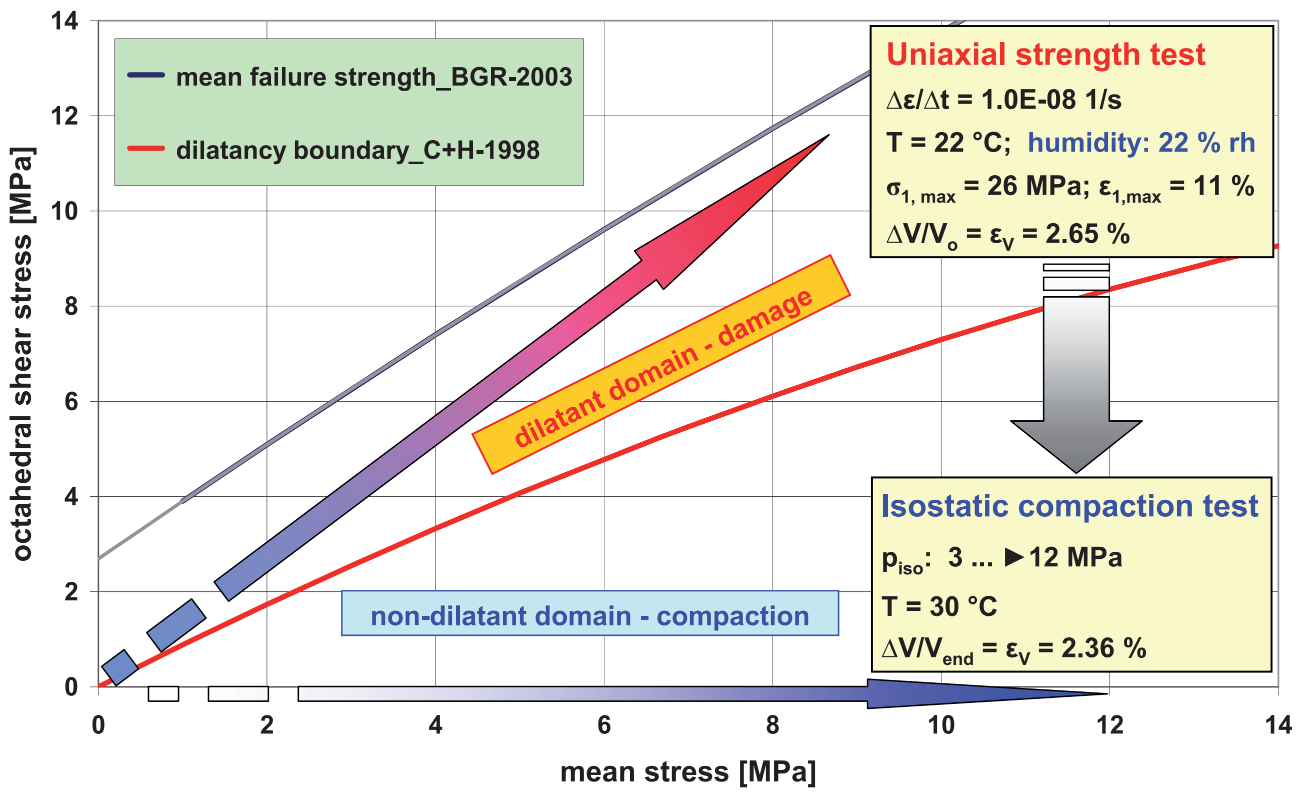
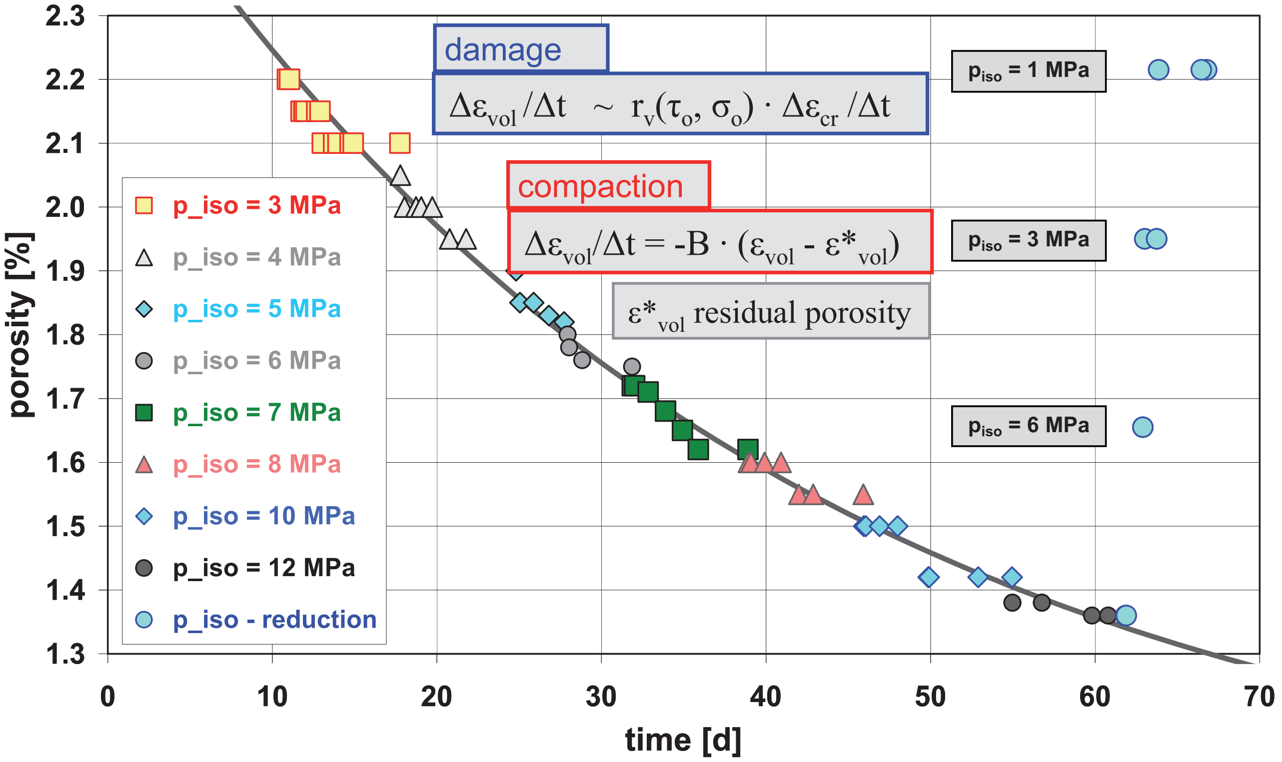
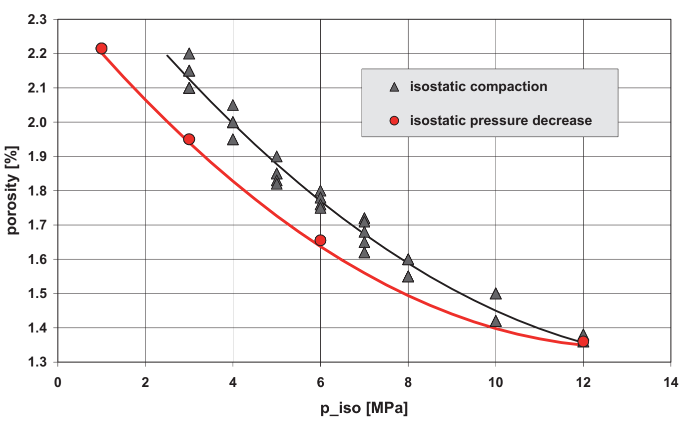
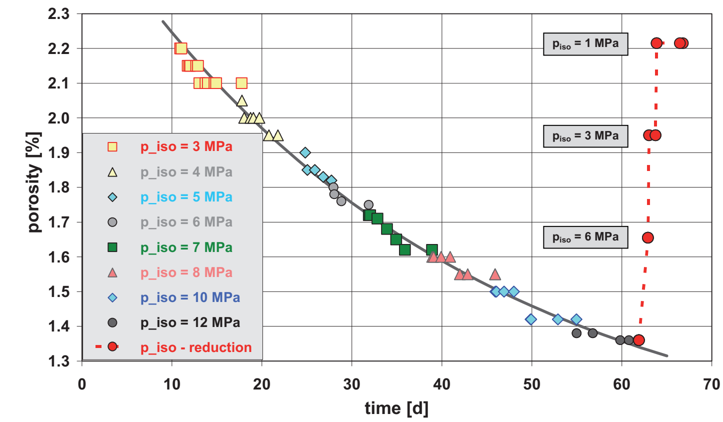
Domains of dilatancy and compaction - investigation of "healing"



Compaction behaviour … of pre-damaged rock salt ►time dependence

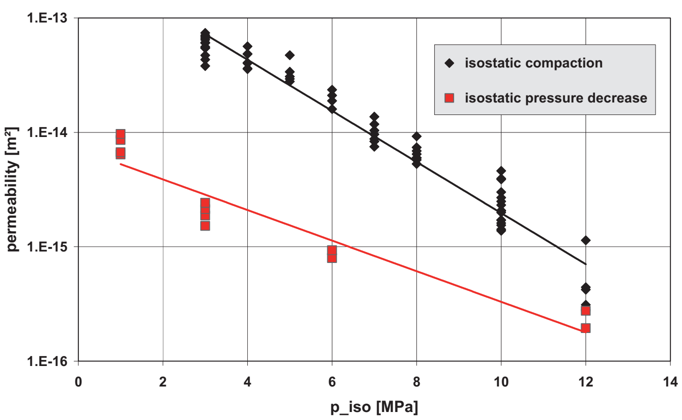


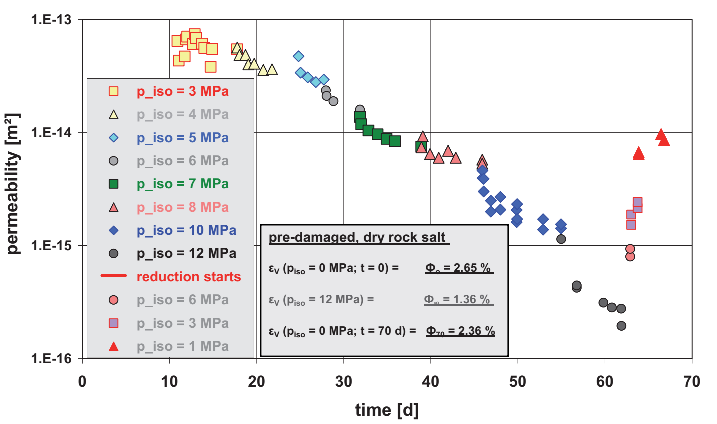


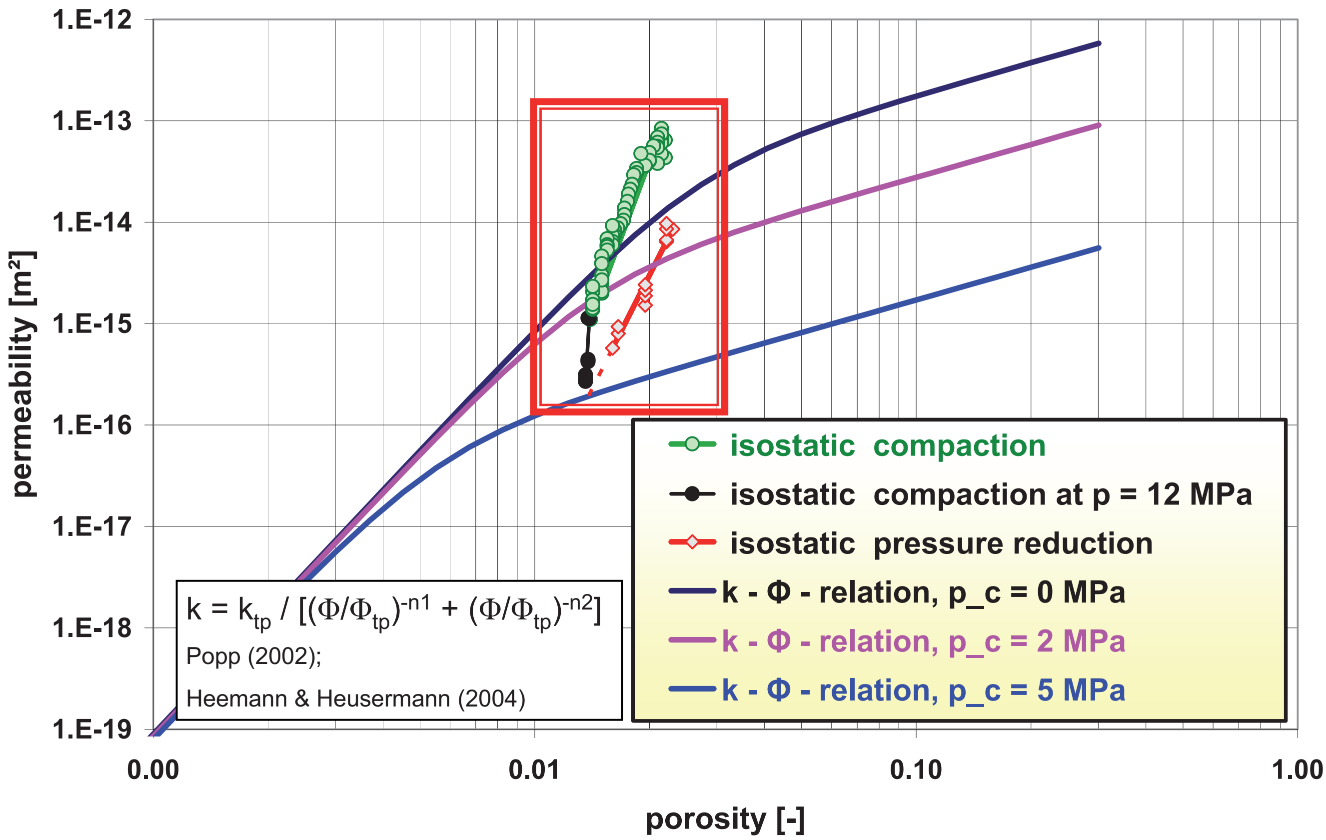


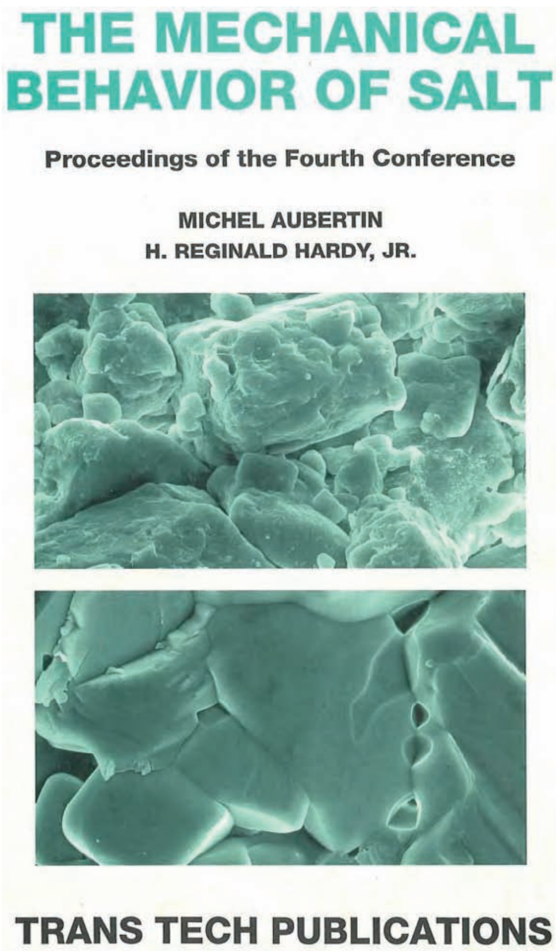
$(k/k_o)^{1/3} \sim 1 - \log(p/p_o)$ Walsh (1981)

$k = k_{tp} / [(\Phi/\Phi_{tp})^{-n1} + (\Phi/\Phi_{tp})^{-n2}]$ Popp (2002)









Microstructural study of reconsolidated salt

G.M.Pennock, X. Zhang, C.J. Peach & C.J. Spiers

Proceedings of the Sixth Conference

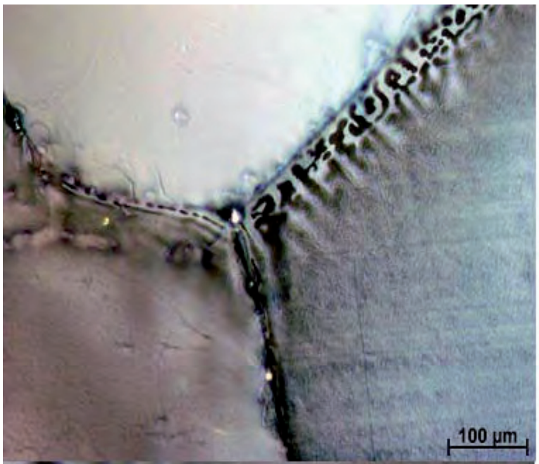
SEM of dynamically compacted salt
(tampered; width of image: ~ 0.1 mm)

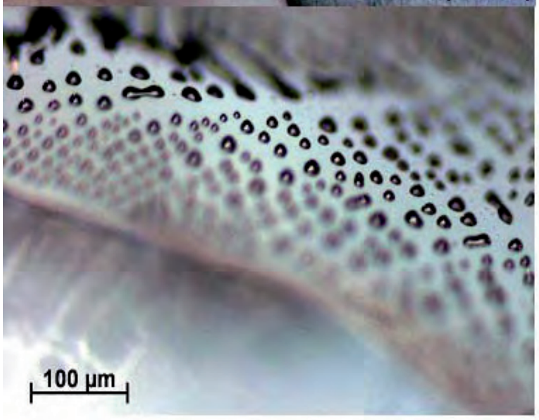
top: initial state, $\rho = 0.90 \cdot \rho_o$

bottom: after hydrostatic consolidation,
$\rho = 0.97 \cdot \rho_o$

permeability decreases four orders of magnitude to less than 10^{-18} m² …
… so far as pressure solution / re-deposition processes eliminate pore space

F.D. Hansen, SNL





thick-slide: isolated GB-pores …
… in traces of migrated brine
Y. Küster (Diss., Göttingen)

permeability reduction of compacted crushed rock salt

pre-compaction in an Oedometer device at elevated temperature, T = 100 °C

mean grain size:	2 mm (d_{max} < 30 mm)	(density ≤ 1.6 g/cm³)
compaction rate:	$6.9 \cdot 10^{-6}$ 1/s to $6.9 \cdot 10^{-7}$ 1/s	
hydrostatic stress:	35 MPa after ca. 6 days	(incl. 4 d - relaxation sections)
density:	2.06 g/cm³	(porosity: ≤ 5 %)
interim storage:	22 °C and 45 %rh	(rather dry condition)

preparation of a cylindrical specimen and permeability testing:
T = 30 °C; p_{hydro} = 38 MPa; 30 days ► p_{gas} = 0.5 MPa **$k = 2 \cdot 10^{-14}$ m²**

humidity treatment in a closed box with saturated NaCl-brine at bottom:
T = 22 °C; Φ ~ 75 %rh; 7 days

hydrostatic re-compaction (I):
T = 30 °C; p_{hydro} = 10 MPa; 30 days ► p_{gas} = 0.2 MPa **$k = 1 \cdot 10^{-16}$ m²**

hydrostatic re-compaction (II):
T = 30 °C; p_{hydro} = 20 MPa down to p_{hydro} = 4 MPa ► p_{gas} = 0.2 MPa
► **no decay of gas pressure detected …** during two month of observation

Challenge: re-compaction … dominating processes and modeling !

Evolution of damage and healing in the EDZ

Otto Schulze, Federal Institute of Geosciences and Natural Resources (BGR)

0. Introduction - some information about BGR

1. Site investigation Gorleben

2. Evolution of damage in the EDZ

3. Evolution of "healing" … humidity !

4. Summary

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

GEOLOGICAL EXPLORATION AND 3D-MODELLING OF A SALIFEROUS HOST ROCK FORMATION - GORLEBEN SALT DOME -

J. Hammer, G. Mingerzahn, J. Behlau, S. Fleig, T. Kühnlenz, M. Schramm
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

Investigations of barrier properties of salt rocks for HRW disposal started in Germany already at the end of the 1950th, at the beginning of the 1960th. At the same time began the collection and preparation of geological, economic, ecological and social political data for the site selection process. These works were highly influenced by studies on salt rocks in the USA and the evaluation of their suitability as host rocks for radioactive waste (e. g. THEIS 1956, BLOMEKE et al. 1963, STRUXNESS 1963, BRADSHAW et al. 1963). The main reasons for selection of salt diapirs as host rocks for HRW in Germany are the very low water concentrations of the halitic rocks, especially in central parts of diapirs (the Hauptsalz of the Zechstein 2 in the Gorleben salt dome is characterized by water content variations between 0,014 and 0,017 wt.-%; JOCKWER 1981) as well as plastic behaviour and creeping of rock salt (healing of joints) and high thermal conductivity of rock salt (lower areas for the repository are required in relation to granitic rocks or claystones). Other important reasons are long-term stability of underground excavations without support, long experience in salt exploration and mining as well as relatively high homogeneity of rock salt in central parts of salt domes.

The Gorleben salt dome was chosen in 1977 on the basis of geological, infrastructural and social political selection criterias (f. i. 400 – 500 m thickness of rock salt; top of the salt dome 300 – 800 m under floor; missing of thick, industrially relevant potash layers; see HAMMER et al. 2009) to clarify the suitability as repository for highly radioactive waste in Germany. Extensive surface geological exploration works were provided to clarify the shape of the salt structure and the stratigraphy of Zechstein beds and of overburden since 1979. The other goals of the site investigations from the ground surface were to have a first idea about the internal structure of salt dome and to study subrosion processes and the halokinetic history of the dome as well as to identify sites for shafts.

The following exploration methods used during surface investigations: seismic profiling, deep throughout cored exploration boreholes with measurements of orientation of cores, geophysical measurements in the boreholes (Gamma Ray, Sonic Log, Density Log and Deviation Log), spatial GPR measurements in boreholes and geochemical investigations of salt rocks, brines and hydrocarbons. 145 boreholes drilled to investigate the stratigraphy and hydrology of the Cenozoic cover of the salt dome. 326 observation wells of various depths constructed and 4 pumping tests of about 3 weeks each provided. A very detailed new stratigraphic subdivision of Zechstein sediments in Gorleben salt dome developed basing on detailed documentation and lithological investigations of cores from deep exploration boreholes. 16 seismic profiles carried out and interpreted in 1984/1985 with an overall length of 156 km. The seismic data enable to build up a detailed picture of the extent and shape of the salt dome and the geological structure of the overburden. A seismic array, consisting of 6 stations in boreholes installed to detect local seismic activity. Additionally, extensive creep and strength tests conducted on specimens from borehole cores to study the mechanical behaviour of rocks as well as sorption and desorption coefficients measured on 38 samples from the Tertiary and Quarternary cover of the salt dome.

A preliminary geological model of the internal structure of the salt dome build up the BGR on the basis of four, up to nearly 2000 m deep exploration boreholes, two pilot shaft boreholes and 44 salt surface boreholes. This preliminary geological model and preliminary evaluation of the long-term suitability of Gorleben salt dome represented the basis for decision on underground exploration in 1983. The underground exploration of the salt dome started in 1986 with sinking of shafts Gorleben 1 and Gorleben 2 at a distance of about 400 m. The goals to be proved were to investigate the spatial position of host rocks for the emplacement areas (Hauptsalz of Staßfurt-Formation) and the distribution and interconnection of Hauptanhydrit blocks within the salt dome as well as the existence and distribution of saline solutions, gas reservoirs and hydrocarbon condensates within the salt dome. It must be shown, that there are no flow paths for saline solutions between the planned emplacement area and the aquifers in overburden basing on exploration data.

The underground exploration must be carried out in a way that the integrity of the rock salt barrier will be preserved. Therefore the disturbance of the potential disposal area by excavations and drilling activities should be as low as possible. BGR and the Federal Office for Radiation Protection (BfS) developed the geological and geotechnical underground exploration program for the site characterization. The principle of the stepwise exploration realized in the Gorleben salt dome is to permanently optimize the excavation strategy by geological results. The main exploration methods were exploration boreholes, detailed geological mapping of drifts, cross-cuts and other excavations, GPR measurements in boreholes and drifts as well as geochemical and mineralogical investigations.

BGR provided complex interpretation of exploration results (BORNEMANN et al. 2008) and build up a detailed geological 3D-model. A good, very sensitive method for reconstruction of the internal structure of salt domes is the analysis of bromide distribution in salt rocks basing on experiences in exploration of the Gorleben salt dome and other salt structures (for the cavern industry). Basing on the bromide content of core samples or cuttings we are able to fix vicinity to potash seams. There is a characteristic increase of bromide concentrations in halites (from 44 – 115 ppm in the Knäuelsalz to 177 – 299 ppm) in the Hangendsalz and Kieseritische Übergangsschichten near the Staßfurt potash seam (SCHRAMM et al. 2005). Another, very effective exploration method are ground penetration measurements (GPR), either in bore holes or in drifts nearly parallel to geological borders, which have to detect. Using of GPR can get valuable information about the spatial position of characteristic reflectors as z2/z3 border or Gorleben-Bank within the z3 Orangesalz, which are useful for modelling.

A detailed geological 3D-model of the Gorleben salt dome was constructed on the basis of surface and subsurface geophysical data as well as of borehole documentation and mapping of drifts. The 3D-model is valuable as instrument for complex interpretation of exploration data, as tool for planning of further geological exploration and as basis for long-term safety analysis. Geological modelling carried out with the program openGEO®. The model yielded out by BGR reached a high quality and high degree of detailization in last years. For illustration, the part of model, describing the transition zone of infrastructure zone of Gorleben exploration mine to planned emplacement area EB 1 will be shown. The southern flank of the main anticline with intensively deformed Hauptanhydrit is explored at this position, which is characterized by boudinage and rotation of Hauptanhydrit blocks.

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The underground exploration of the Gorleben salt dome, stopped in October 2000 by governmental moratorium, points to the potential suitability of salt dome for disposal of highly radioactive waste. The results of the geological investigations in the EB 1 show a large area of potentially suitable host rocks (Hauptsalz) in a simple anticline structure. The exploration has to be continued in order to clarify finally its suitability.

BLOMEKE, J.E., BOEGLY, W.J.JR. et al. (1963): Disposal in natural salt formations. In: Union Carbide Corporation, Oak Ridge National Laboratory, Report no. ORNL-3492: 19-37.

BORNEMANN, O., BEHLAU, J., FISCHBECK, R., HAMMER, J., JARITZ, W., KELLER, S., MINGERZAHN, G. & SCHRAMM, M. (2008): Standortbeschreibung Gorleben, Teil III: Ergebnisse der über- und untertägigen Erkundung des Salinars. Geol. Jahrbuch, Reihe C, 73, 211 pp., 50 fig., 7 tab., 5 app.

BRADSHAW, R.L., BOEGLY, W.J.JR. et al. (1963): Ultimate storage of high-level waste solids and liquids in salt formations. In: Treatment and storage of radioactive waste. Proceed. of a symposium, Vienna, Austria 1962, IAEA, Vienna (1963): 153-175.

HAMMER, J., SÖNNKE, J. & MINGERZAHN, G. (2009): Grundlagen und Beispiele für Standortauswahlverfahren für HAW-Endlager in unterschiedlichen Wirtsgesteinstypen. unpubl. Bericht, BGR, Hannover, 161 pp., 56 fig.

JOCKWER, N. (1981): Untersuchungen zu Art und Menge des im Steinsalz des Zechsteins enthaltenen Wassers sowie dessen Freisetzung und Migration im Temperaturfeld endgelagerter radioaktiver Abfälle. GSF, Inst. F. Tieflagerung, Wiss. Abt., GSF-Bericht T119: 134 pp.; Braunschweig.

SCHRAMM, M., BORNEMANN, O., SIEMANN, M., WILKE, F. & GELUK, M. (2005): Correlation between bromine concentrations in halites and their stratigraphical position in Zechstein 2 salt deposits of North-West Europe. Abstracts of the contributions of the General Assembly of the European Geophysical Society, Vienna, Austria, 24-29 April 2005. Geophysical Research Abstracts, vol. 7, 04552 (CD): 1 S..

STRUXNESS, E.G. (1963): Storage of radioactive waste in mine cavities. In: BERSTICKER, A.C. (Ed.): Symposium on salt - Abstracts. Northern Ohio Geol. Society, Inc., Cleveland, Ohio, p. 412

THEIS, C.W. (1956): Problems of ground disposal of nuclear wastes. In: United Nations (Ed.): Proceedings of the Internat. Confer. on the peaceful uses of atomic energy, vol. 9: Reactor technology and chemical processing, New York, 679-683

Geological exploration and 3D-modelling of a saliferous host rock formation - Gorleben salt dome -

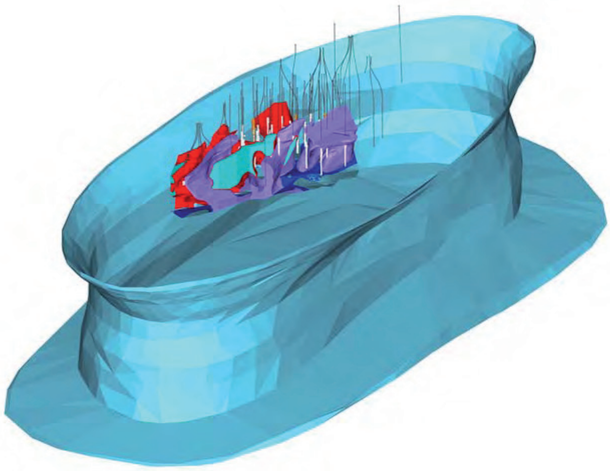
Jörg Hammer, Gerhard Mingerzahn, Joachim Behlau, Stephanie Fleig, Tatjana Kühnlenz, Michael Schramm

Federal Institute for Geosciences and Natural Resources (BGR), Hannover

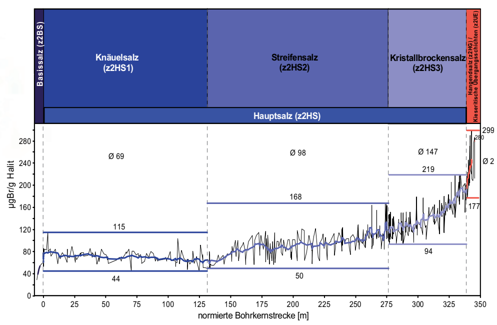
joerg.hammer@bgr.de

Fields of working

- preparation of basic data, geological attendance in site selection (f. i. host rock distribution, selection criteria, assessment of suitability)
- Planning and realisation of site exploration
- Evaluation and interpretation of exploration data (3d modeling)
- Salt rock research (geochemistry, bromide distribution, deformation, subrosion, distribution and composition of hydrocarbons)

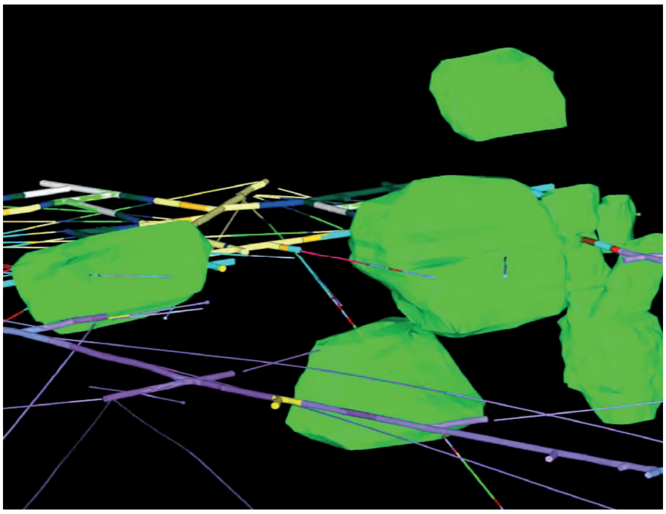


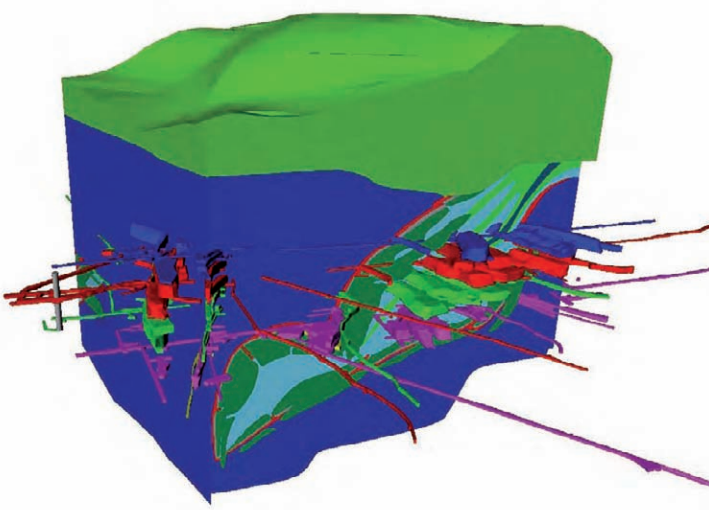
Bromide distribution



Geological 3d models – tools for data storage and planning of geological exploration

- AutoCAD-linked openGEO 3d models based on real coordinates
- 3d models – instruments for interpretation of exploration data
- 3d models – basis for planning of spatial orientation of bore holes
- 3d models – basis for long-term safety analysis





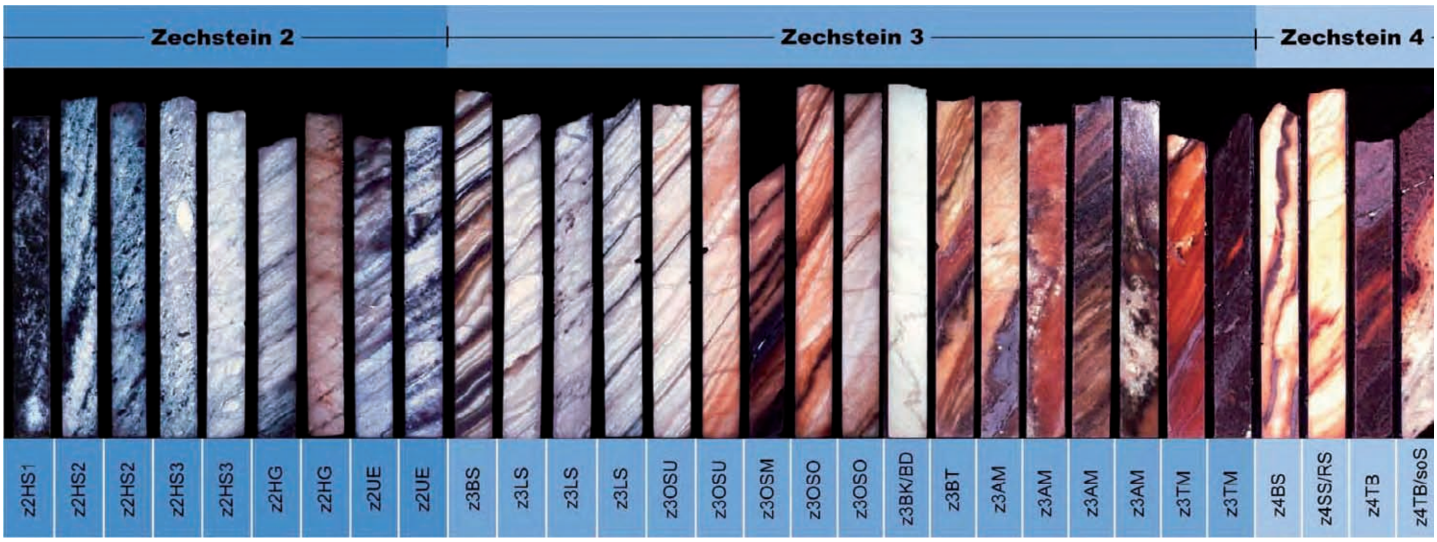
Geological Exploration of Gorleben salt dome

- salt diapirs – highly suitable medium for HLW disposal
- surface/aboveground exploration of Gorleben salt dome
- Subsurface/underground exploration of Gorleben salt dome
- geological 3D-model of Gorleben salt dome

Reasons for selection of salt diapirs as host rocks for HRW (1)

- very low water content, especially in central parts of diapirs
- plastic behaviour and creeping of salt is responsible for healing of joints (no inflow of waters from outside the diapir, "impermeable enclosure")
- Long-term stability of underground excavations (without support)
- high thermal conductivity of rock salt (no heat accumula-tion or damming, relatively small volumes are required for disposal)
- high homogeneity of cental parts of many diapirs because of halokinesis (good possibilities for prediction of composition and properties)

Lithological standard profile of the Zechstein halite beds (Gorleben)



Lithology of the halite beds (Gorleben)

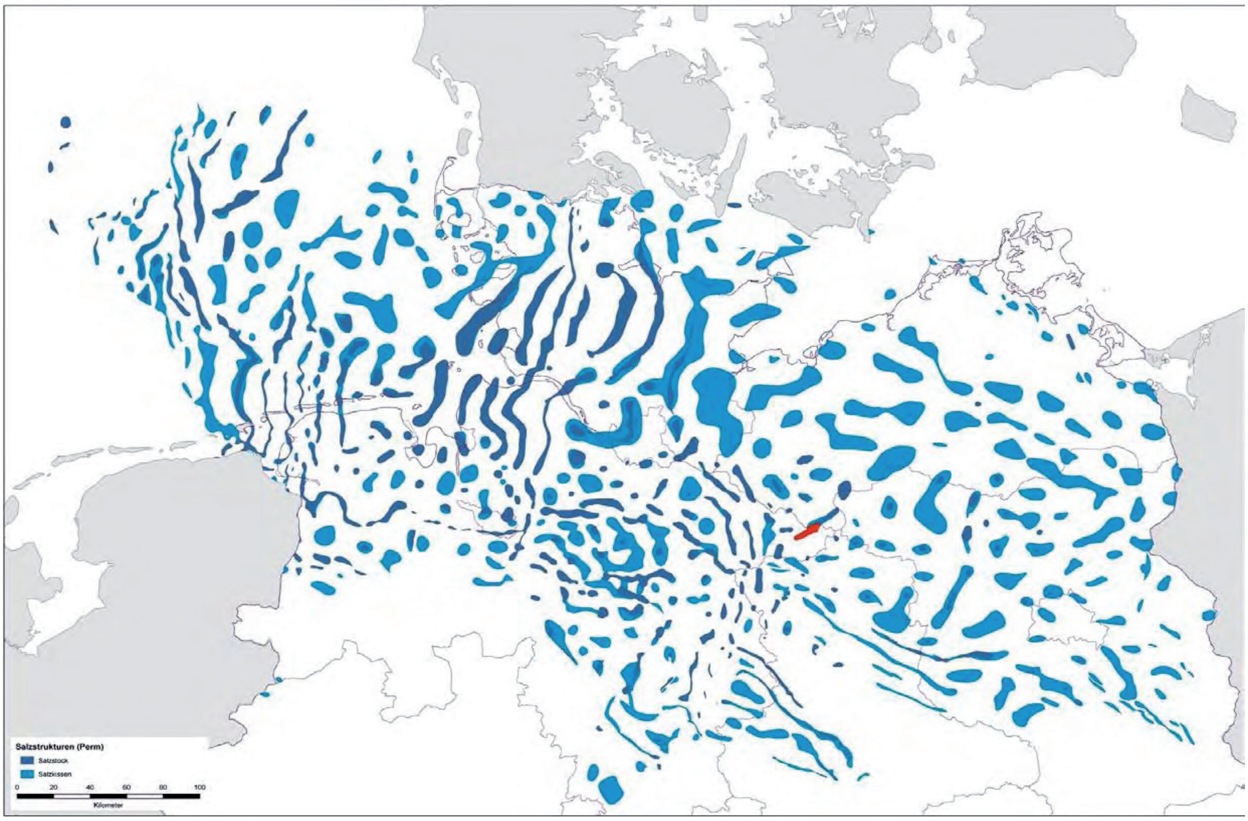
Staßfurt-Folge (z2)

Leine-Folge (z3)

Reasons for selection of salt diapirs as host rocks for HRW (2)

- long experience in salt exploration and mining (since 1850)
- a lot of in-situ and experimental/laboratory data about long-term behaviour of salt
- high stability and isolation properties of salt rocks– all solutions observed in Gorleben diapir are intrasalinar and of late Permian age (ca. 250 Mio. a old), no groundwater inflow from outside the diapir
- deposition of HRW in clayey or crystalline rocks is often problematic: water inflow via faults, highly expansive exploration and geotechnical barriers, low stability of excavations in clayey rocks, evidence of long-term stability and safety is difficult
- existence of many salt diapirs in Germany (potentially many alternatives for selection procedure)

Salt structures in Northern Germany



criterias for selection procedure

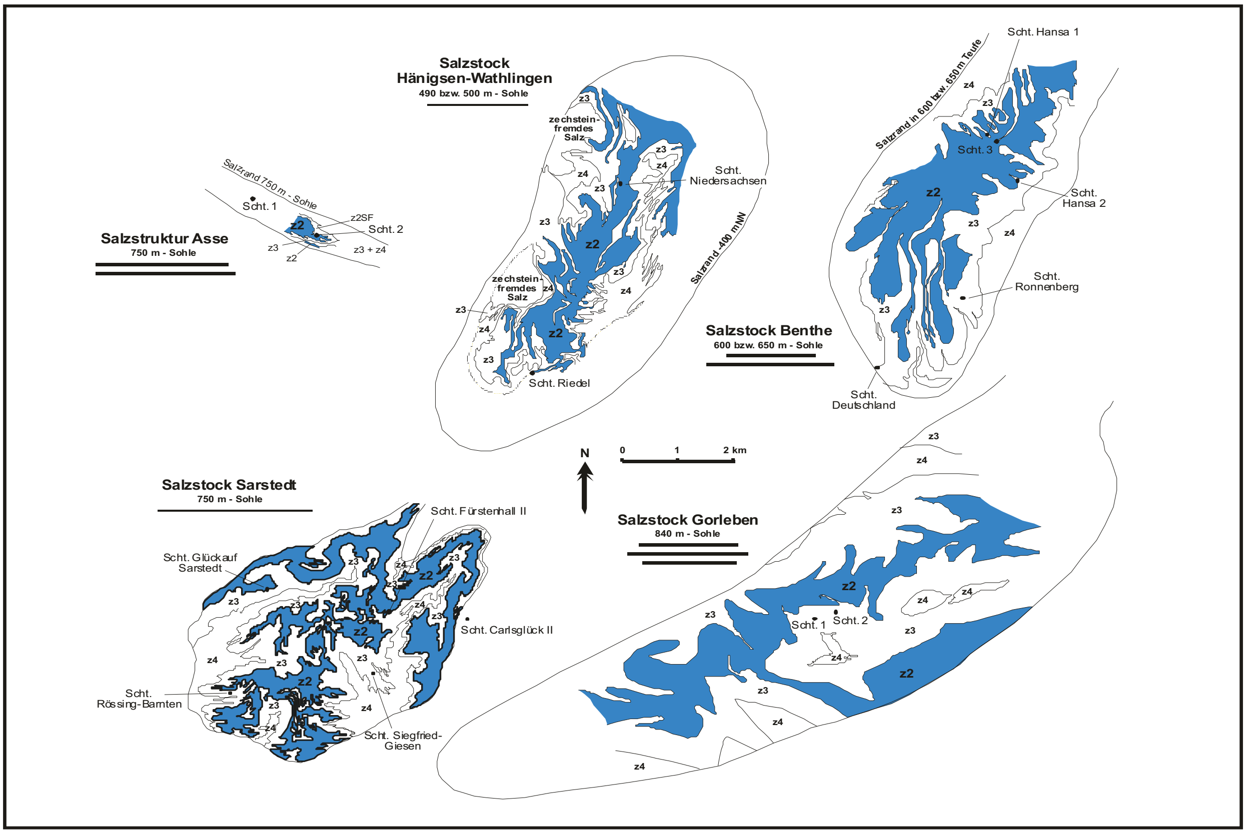
Richter-Bernburg & Hofrichter (1964)

- 400 – 500 m thickness of salt formation
- „nearly“ homogeneous rock salt (without thick layers of carnallite or anhydrite)
- sufficient extent/size (horizontal extent)
- top of the salt structure 300 to 800 m under floor
- lowly permeable overburden (better fixation of borehole tubing)
- possibilities for disposal of salt solutions from leaching (in case of HRW disposal in caverns)
- good infrastructure (streets, train)
- neighbourhood of planned atomic power stations

Examples of unsuitable salt diapirs

- low extent / size in 1000 m depth – 11 km^2 (Gorleben ca. 45 km^2)
- contour / internal structure – not nearly round forms of diapirs (very complicated internal structure, volumes of host rocks are to small)
- stage of geological development of salt diapirs (high thickness of salt rocks in rim synclines, high rates of uprising of salt diapirs)
- other forms of using the salt diapirs (competition – f. i. mining, caverns)

Structure of Gorleben Salt Dome in Comparison with other Salt Domes



Time scale of exploration

- selection of Gorleben salt dome in 1977
- Exploration since 1979 to prove the suitability for the storage of radioactive waste
- Exploration from above ground from 1979 to 1985
- Underground exploration from 1985 to 2000

Geological Exploration of Gorleben salt dome

Exploration methods

- Seismic exploration (if possible 3D)
- Exploration boreholes (totally cored)
- Detailed description of the cores
- Geophysical measurements in the boreholes (indispensable are: Gamma-Ray, Density-Log, Sonic-Log, Deviation-Log)
- Measurement of orientation of the layers (all 50 to 100 m; if possible Dip-Log)
- Spatial GPR-measurements (if possible)
- Geochemical investigations (qualitative mineral composition, bromine, rubidium, strontium, $\delta^{34}S$, $\delta^{18}O$; thermodynamic modelling of brine-rock interaction, hydrocarbon analyses and genetic interpretation)

If subrosion of the salt structure has to be examined:

- Several boreholes distributed in the top of the structure (cored in the caprock and several meters in the saliniferous itself)

Geological Exploration of Gorleben salt dome

Following answers should be given about

- shape of the salt structure (top, bottom, flanks)
- internal structure
- stratigraphy of Zechstein beds and overburden
- subrosion (long term safety)
- petrographical facies of rocks
- geological map of the top of dome
- halokinetic history of the dome
- gas and brine content
- geochemical characterisation of salt rocks and overburden
- identification of sites for shafts

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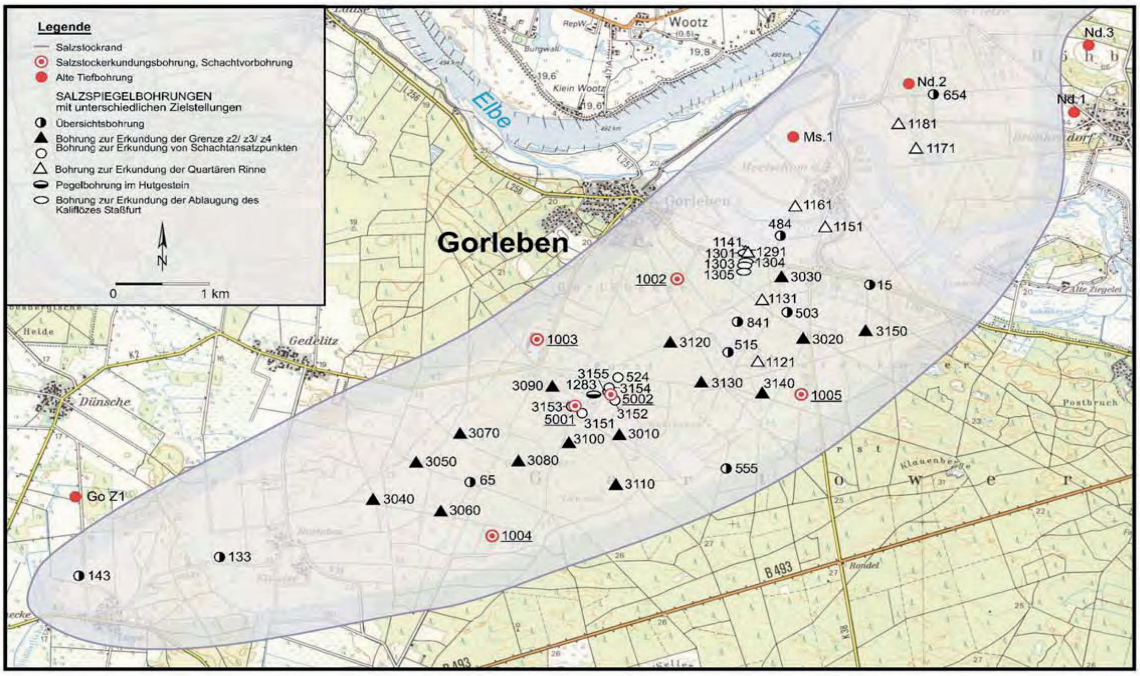
map of exploration boreholes



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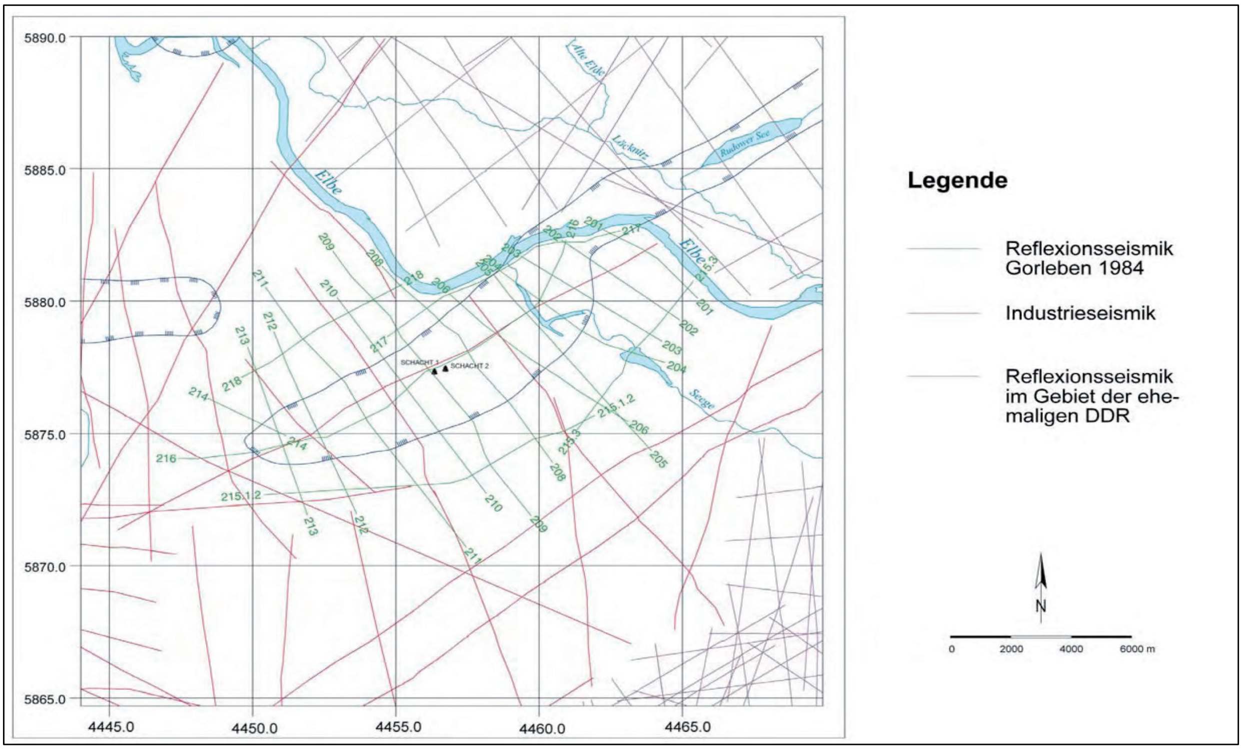
Seismic Investigation



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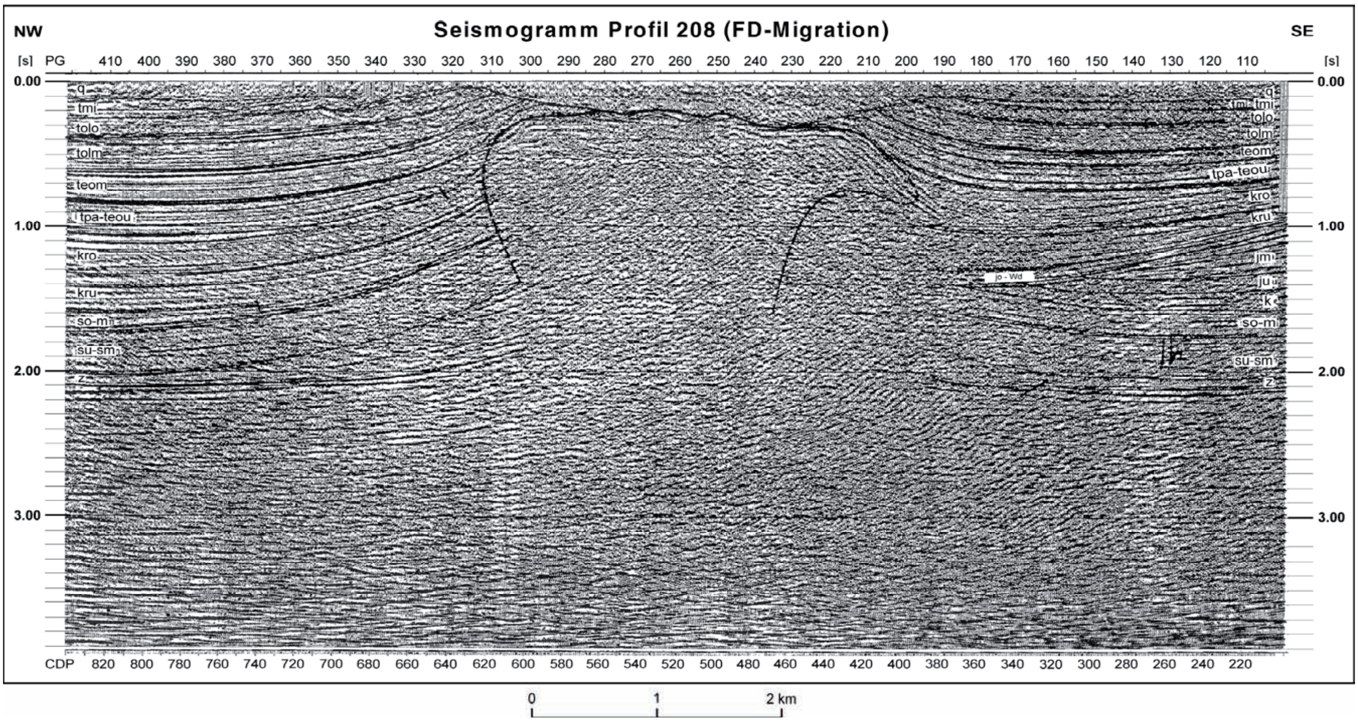
Seismic cross-section



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Stratigraphic table

Zechstein 7 (Mölln-Folge)	z7
Zechstein 6 (Friesland-Folge)	z6
Zechstein 5 (Ohre-Folge)	z5
Zechstein 4 (Aller-Folge)	**z4**
Zechstein 3 (Leine-Folge)	**z3**
Zechstein 2 (Staßfurt-Folge)	**z2**
Zechstein 1 (Werra-Folge)	z1

Stratigraphic table (details)

Zechstein 7 (Mölln-Folge)	z7
Zechstein 6 (Friesland-Folge)	z6
Zechstein 5 (Ohre-Folge)	z5
Zechstein 4 (Aller-Folge)	z4
Zechstein 3 (Leine-Folge)	z3
Zechstein 2 (Staßfurt-Folge)	**z2**
Zechstein 1 (Werra-Folge)	z1

Oberer Staßfurt-Ton	**z2STO**
Gebänderter Deckanhydrit	**z2DA**
Decksteinsalz	**z2DS**
Kaliflöz Staßfurt	**z2SF**
Kieseritische Übergangsschichten	**z2UE**
Tonliniensalz	**z2TS**
Polyhalitbänkchensalz	**z2PS**
Speisesalz	**z2SP**
Hangendsalz	**z2HG**
Hauptsalz	**z2HS**
Basissalz	**z2BS**
Basalanhydrit	**z2BA**
Staßfurt-Karbonat	**z2SK**
Staßfurt-Ton	**z2ST**

Stratigraphic table (details)

Kristallbrockensalz	z2HS3
Streifensalz	z2HS2
Knäuelsalz	z2HS1

Oberer Staßfurt-Ton	z2STO
Gebänderter Deckanhydrit	z2DA
Decksteinsalz	z2DS
Kaliflöz Staßfurt	z2SF
Kieseritische Übergangsschichten	z2UE
Tonliniensalz	z2TS
Polyhalitbänkchensalz	z2PS
Speisesalz	z2SP
Hangendsalz	z2HG
Hauptsalz	z2HS
Basissalz	z2BS
Basalanhydrit	z2BA
Staßfurt-Karbonat	z2SK
Staßfurt-Ton	z2ST

Stratigraphic table (details)

Zechstein 7 (Mölln-Folge)	z7
Zechstein 6 (Friesland-Folge)	z6
Zechstein 5 (Ohre-Folge)	z5
Zechstein 4 (Aller-Folge)	z4
Zechstein 3 (Leine-Folge)	**z3**
Zechstein 2 (Staßfurt-Folge)	z2
Zechstein 1 (Werra-Folge)	z1

Oberer Leine-Ton	z3TO
Grenzsalz	z3GS
Tonmittelsalz	z3TM
Kalflöz Riedel	z3RI
Schwadensalz	z3SS
Anhydritmittelsalz	z3AM
Buntes Salz	z3BT
Kaliflöz Bergmannssegen	z3BE
Bändersalz	z3BD
Banksalz	z3BK
Kaliflöz Ronnenberg	z3RO
Orangesalz	z3OS
Liniensalz	z3LS
Basissalz	z3BS
Hauptanhydrit	z3HA
Leine-Karbonat	z3LK
Grauer Salzton	z3GT
Leine-Sandstein	z3SD

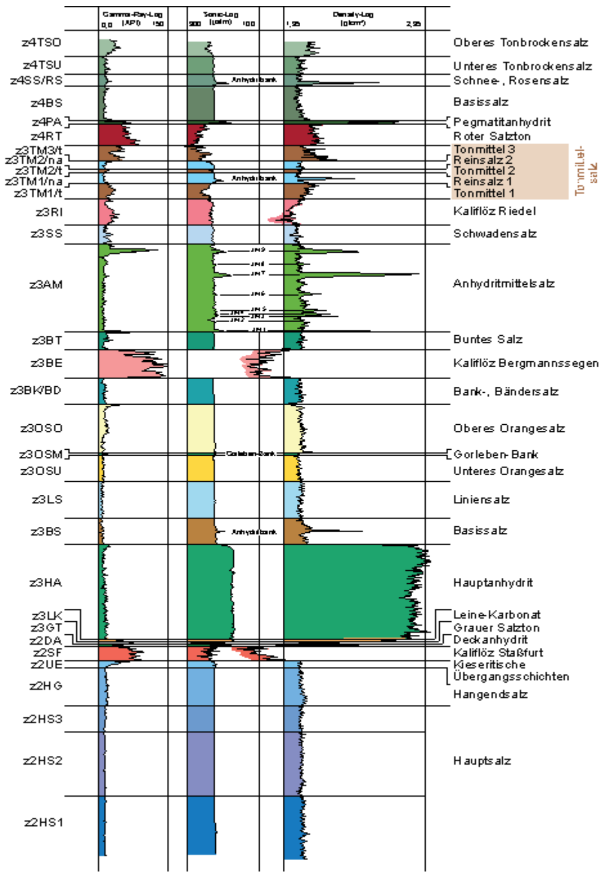
Stratigraphic table (details)

Zechstein 7 (Mölln-Folge)	z7
Zechstein 6 (Friesland-Folge)	z6
Zechstein 5 (Ohre-Folge)	z5
Zechstein 4 (Aller-Folge)	**z4**
Zechstein 3 (Leine-Folge)	z3
Zechstein 2 (Staßfurt-Folge)	z2
Zechstein 1 (Werra-Folge)	z1

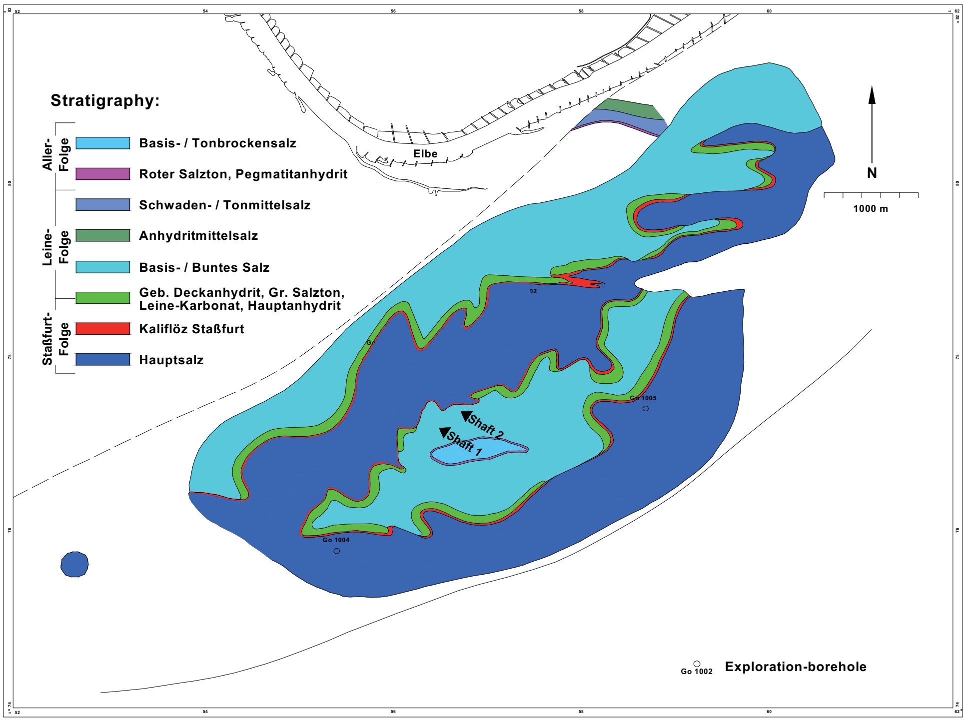
Oberer Aller-Ton	**z4TO**
Aller-Grenzanhydrit	**z4GA**
Tonbanksalz	**z4TB**
Tonbrockensalz	**z4TS**
Rosensalz	**z4RS**
Schneesalz	**z4SS**
Basissalz	**z4BS**
Pegmatitanhydrit	**z4PA**
Aller-Karbonat	**z4AK**
Roter Salzton	**z4RT**
Aller-Sandstein	**z4SD**

Synthetic Sequences of z2, z3 and z4

based on Log Interpretation



Geological map of the top of Gorleben salt dome



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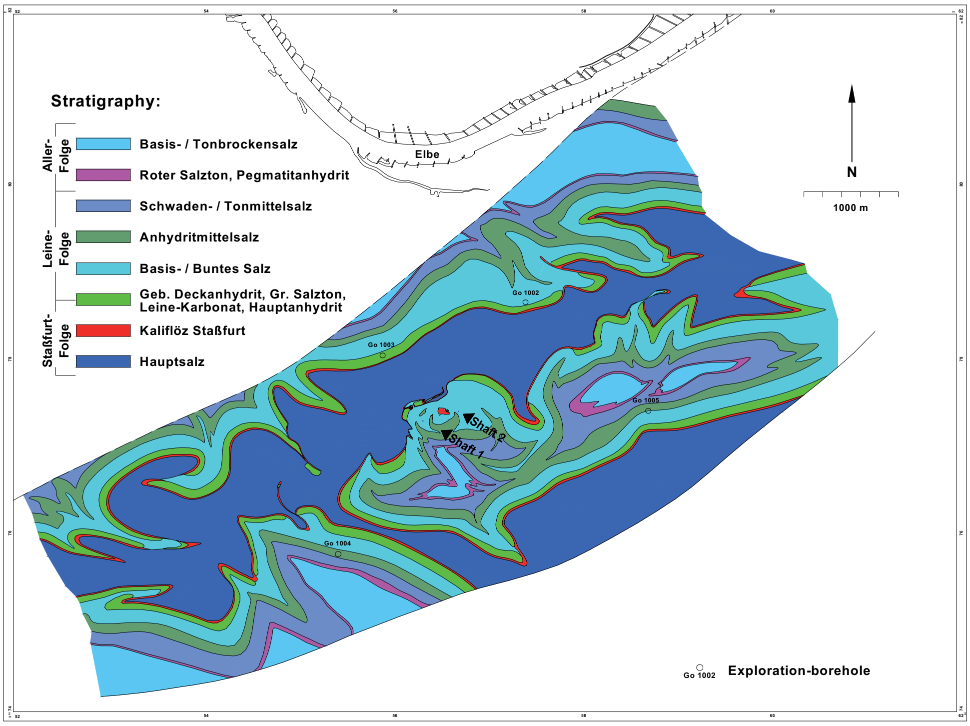
Prognostic geological map of 840 m level



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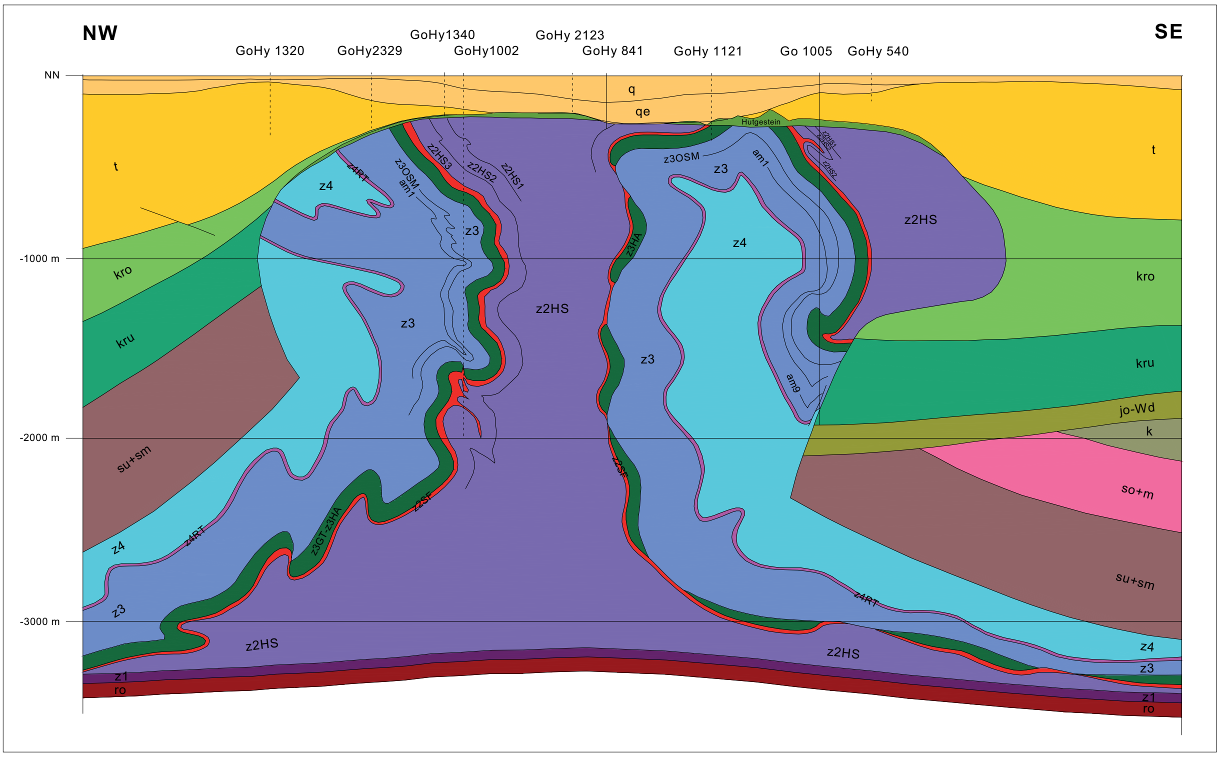
Geological cross-section of the Gorleben salt dome



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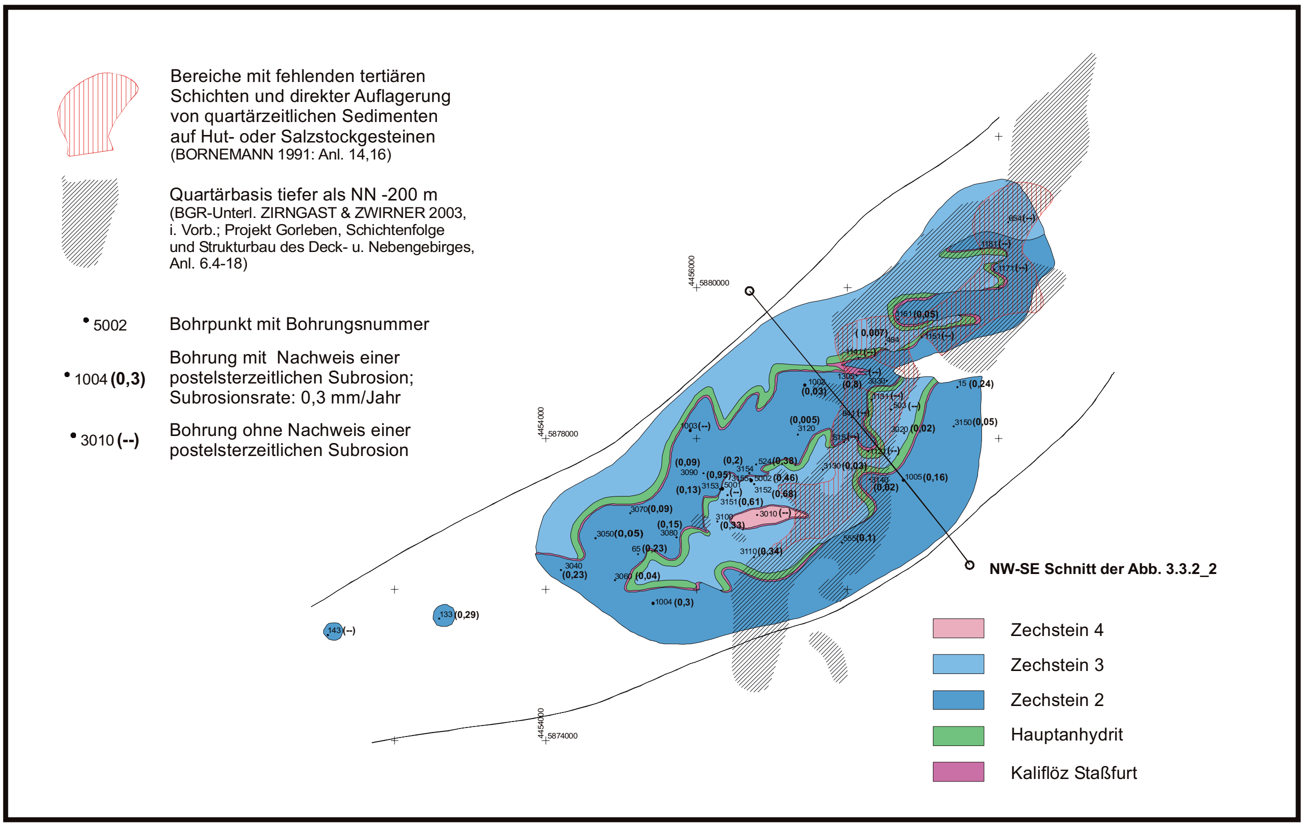
Subrosion at the Top of Gorleben Salt Dome



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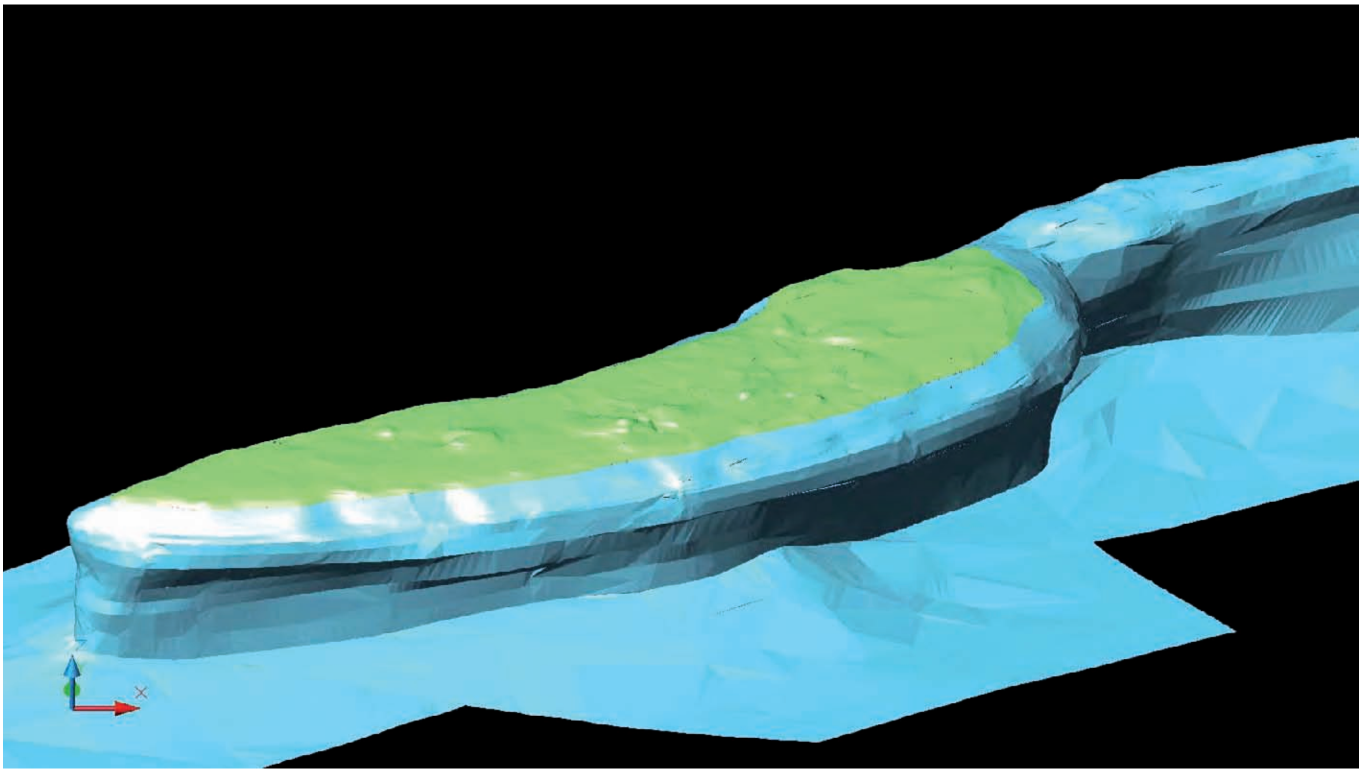
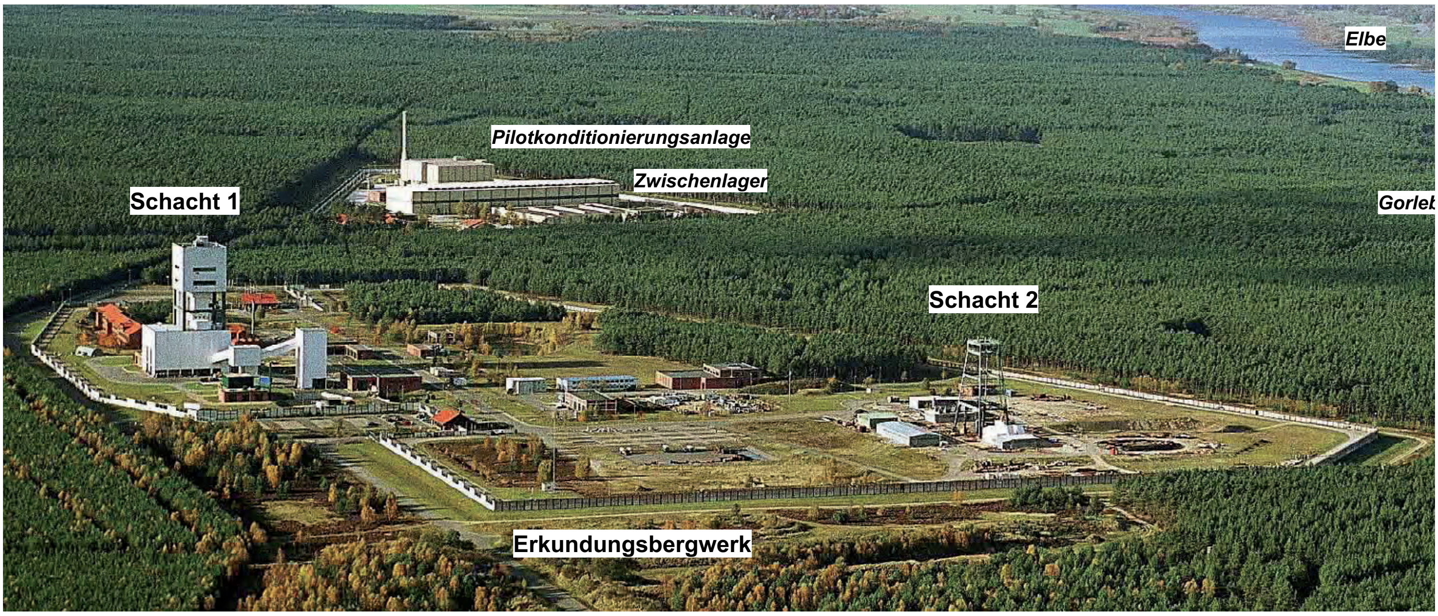
Subrosion at the Top of Gorleben Salt Dome



Underground exploration of Gorleben Salt Dome



Foto

Underground exploration

Main aims that have to be proved:

- Is there interconnection between Hauptanhydrit blocks in the southern border of the exploration area 1 (Zechstein 3/Zechstein 2) in the central part of the salt dome?
- Do the Hauptsalz member (EB1) occurr salt solutions and gas reservoirs ?
- Are there connections and flow paths for salt solutions between the exploration area and the aquifer (salt leaching surface) ?
- Is there interconnection between salt solution reservoirs in the Hauptanhydrit blocks over long distances ?

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Underground exploration

Geological works to be done:

- Exploration boreholes
- Detailed geological mapping
- GPR measurements in boreholes and drifts
- Geochemical investigation
- Construction of a geological 3D-model

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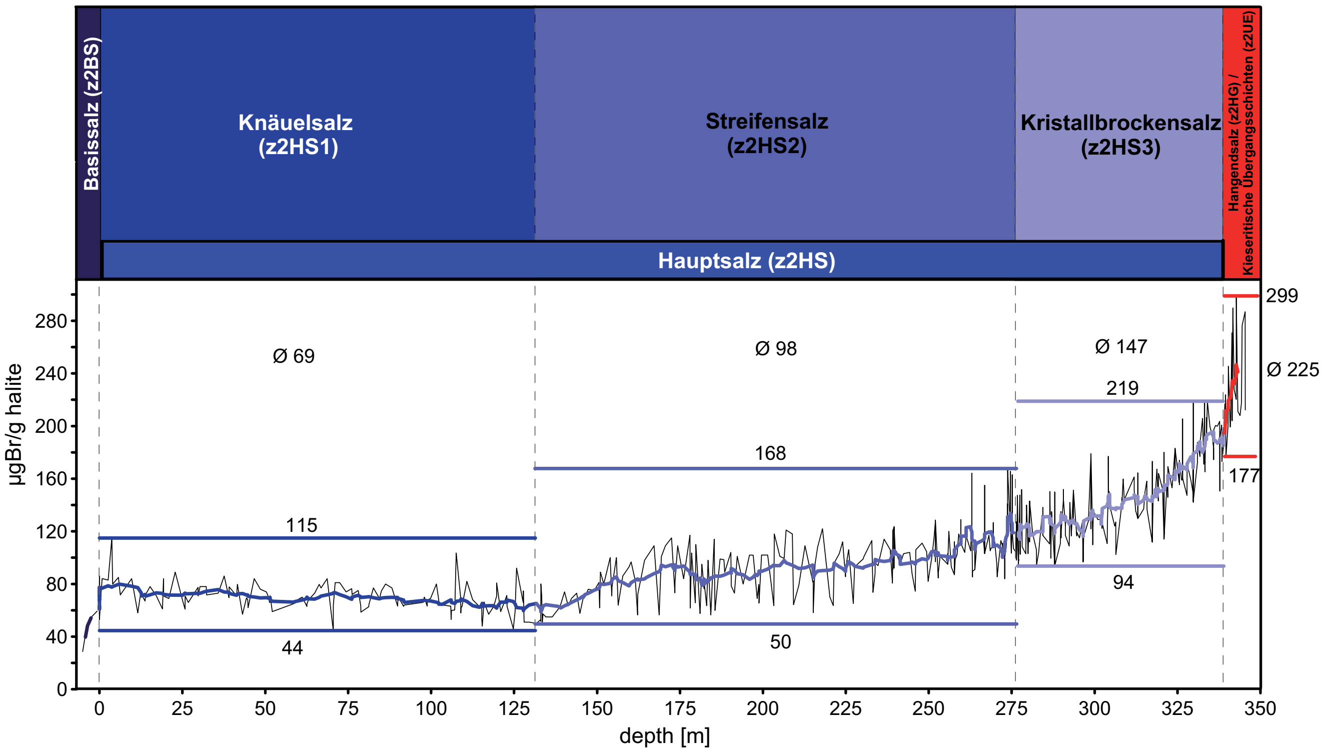
Standard Bromine Profile Zechstein 2



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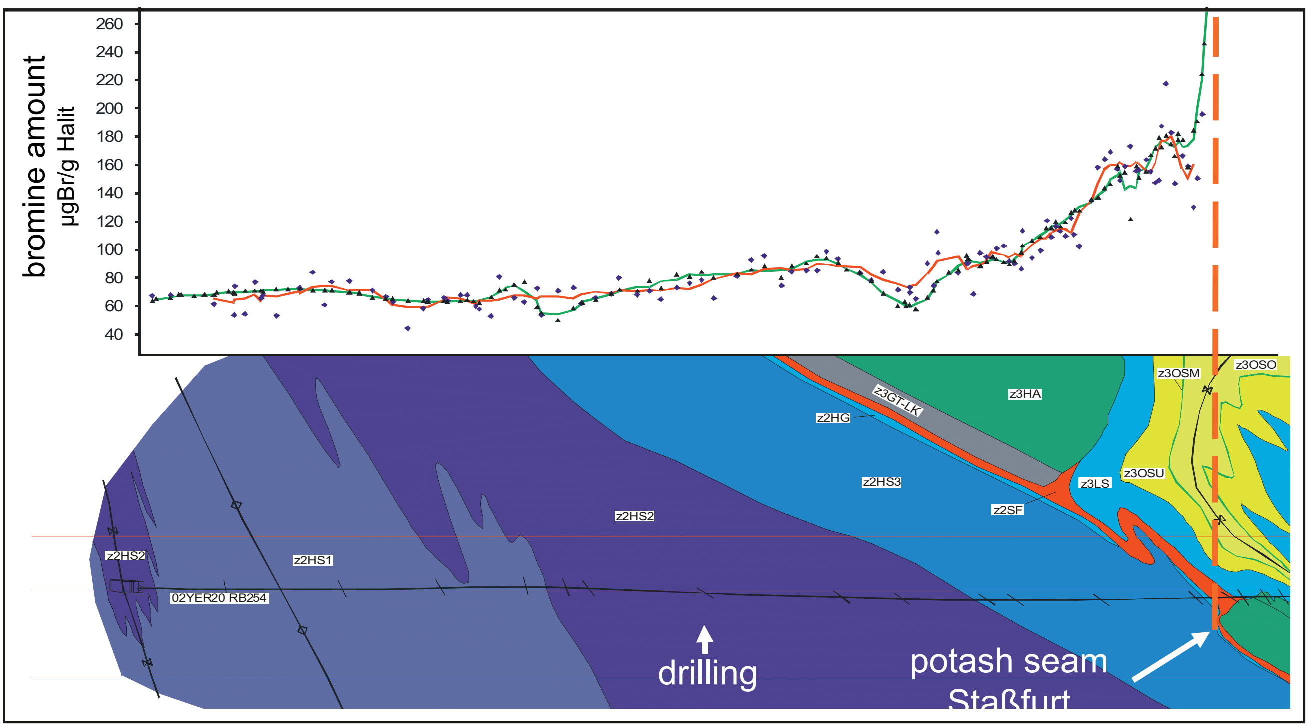
Underground exploration - bromine distribution in bore holes



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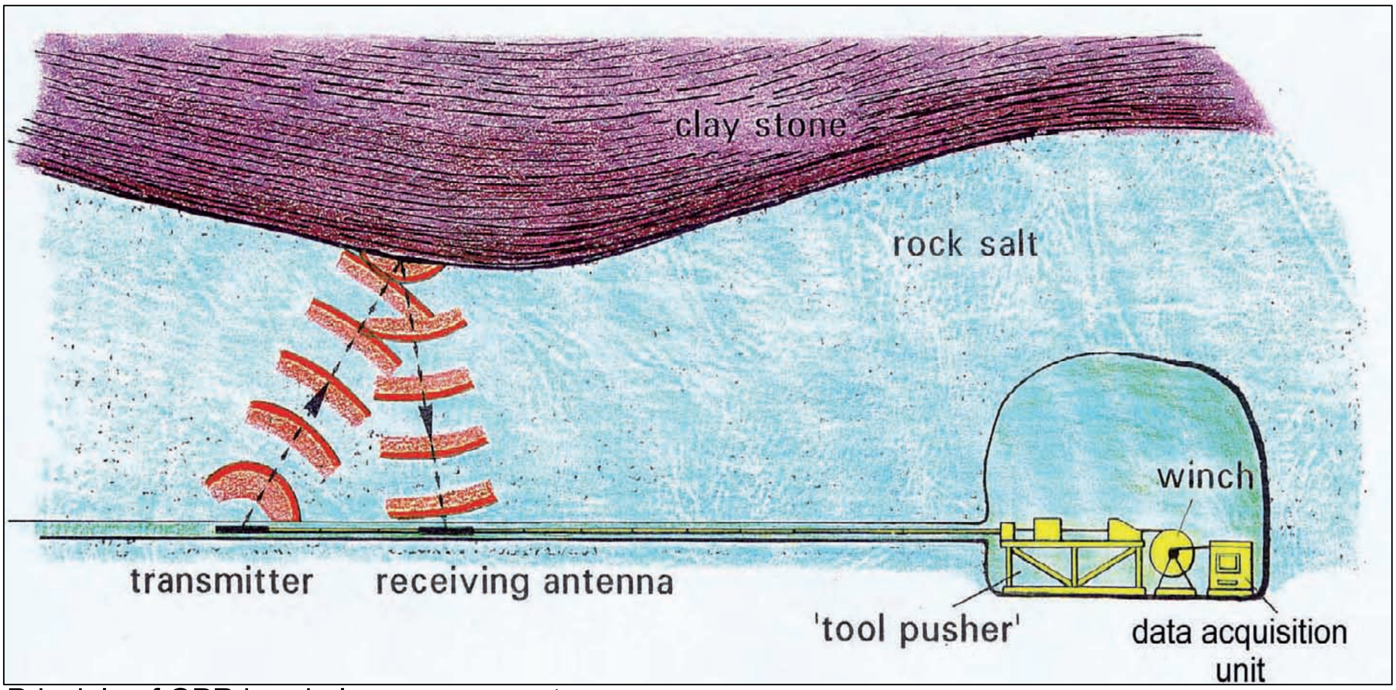
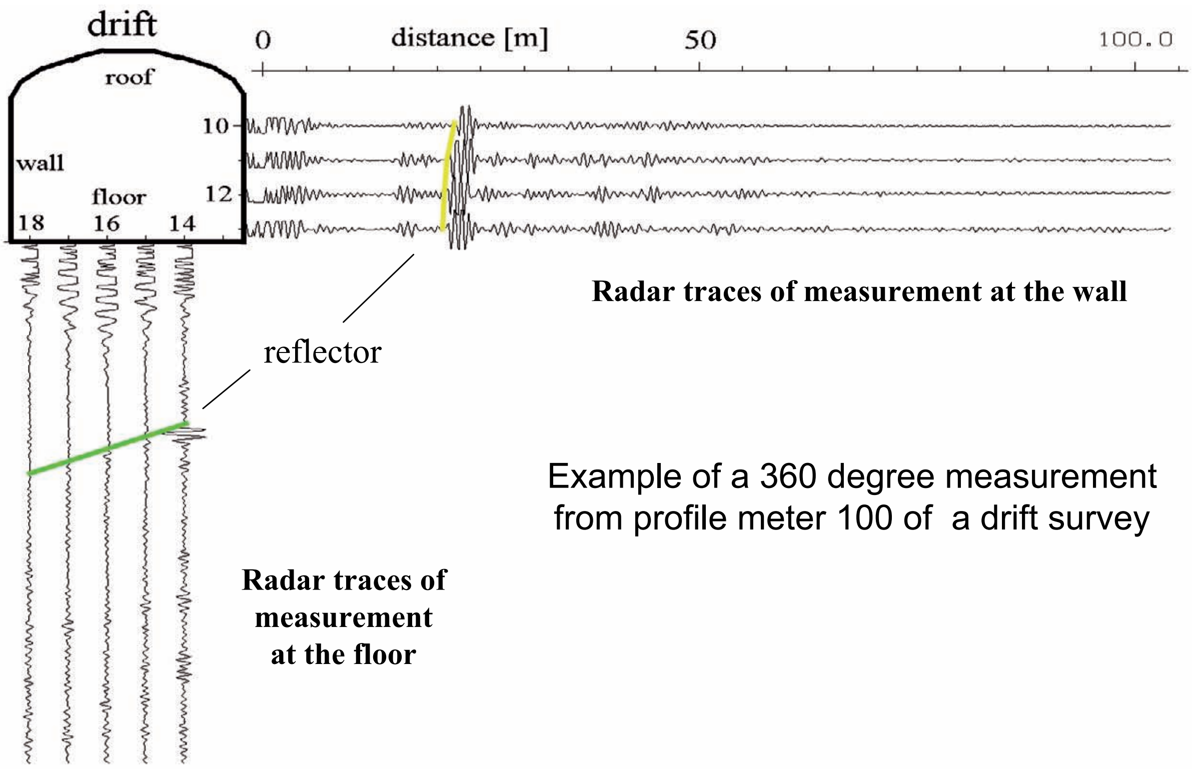
Geological Exploration of Gorleben Salt dome



Principle of GPR borehole measurements

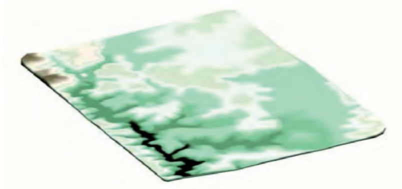
Geological Exploration of Gorleben Salt dome



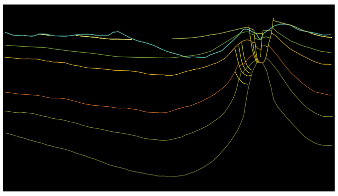
Example of a 360 degree measurement from profile meter 100 of a drift survey

Basic data for 3d modelization

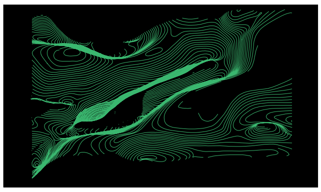
digital topology / terrain model

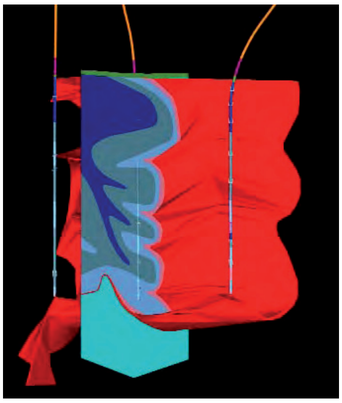


interpreted seismic data

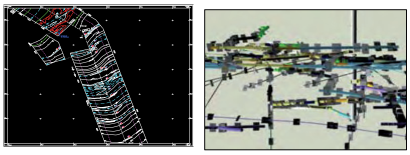


subsurface contour maps

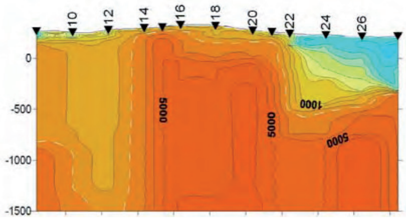




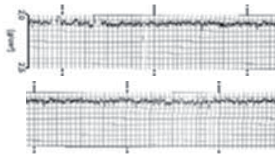
Mapping of drifts



geophysial data



Bore hole data



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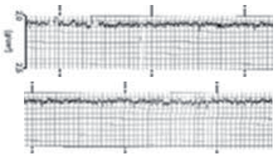
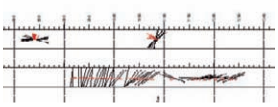
Basic data for 3d modelization
- bore hole and core data -

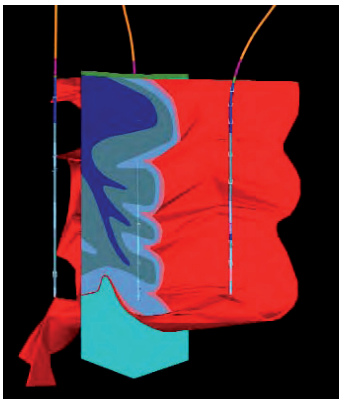
logging data



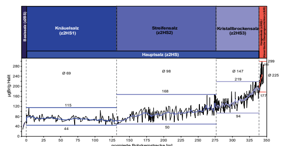
cores

measurements of orientations

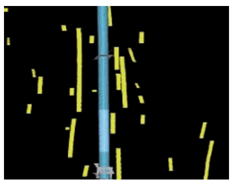




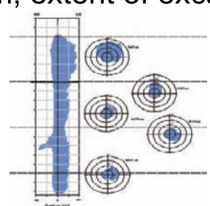
Bromide distribution



Georadar data



form, extent of excavation



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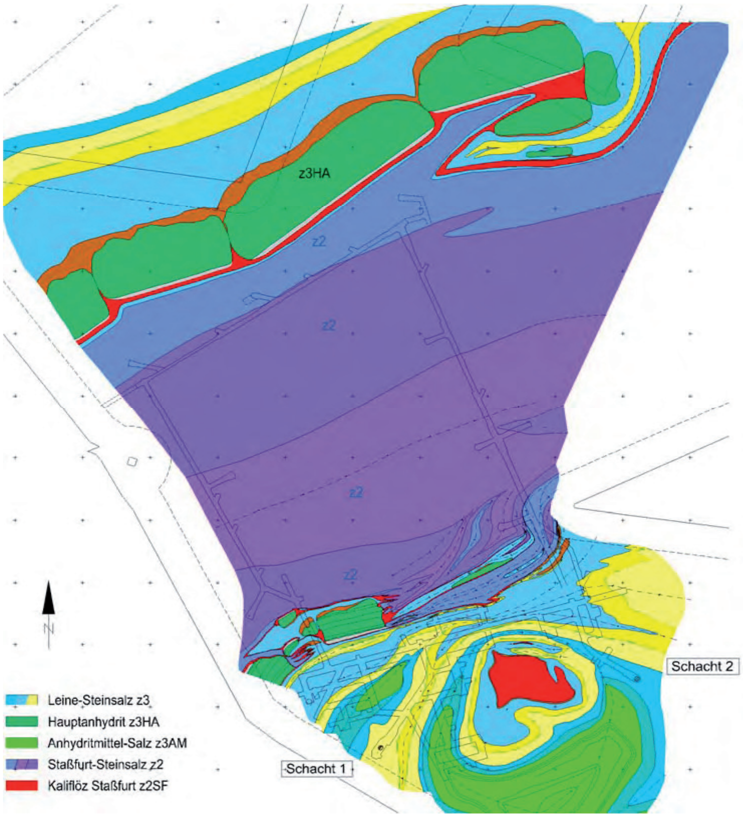
Underground geological exploration



Horizontalschnitt 840 m-Sohle, EB 1

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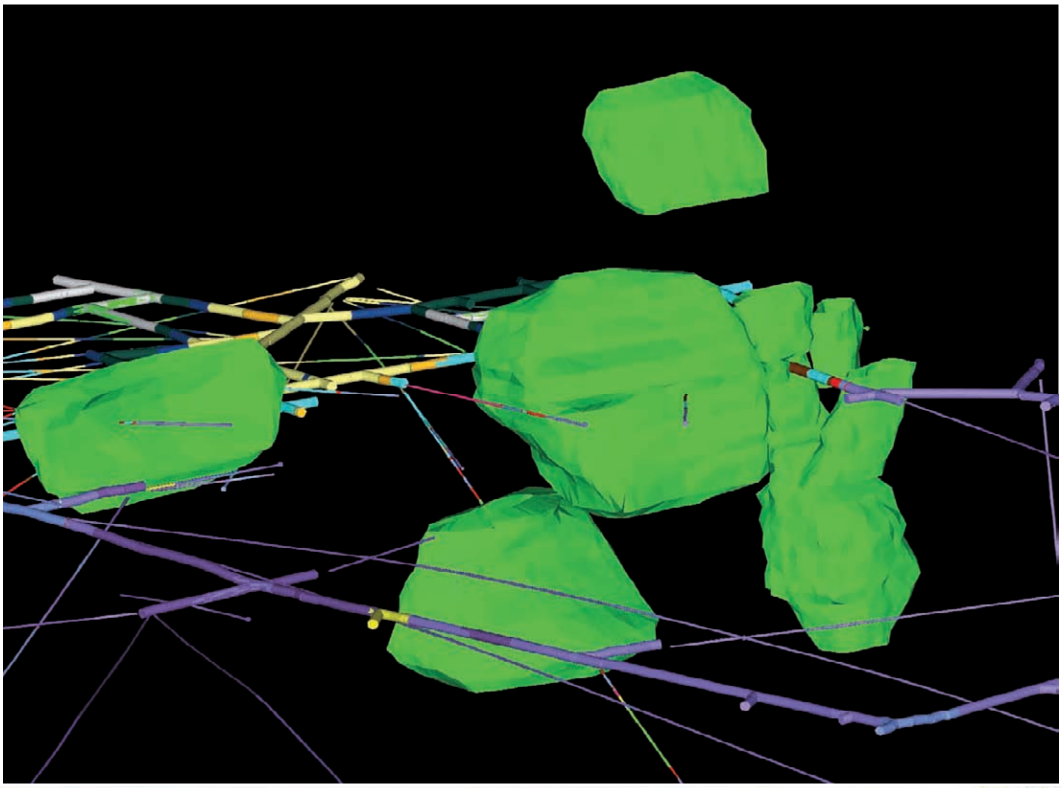
Boudinage of Hauptanhydrit Gorleben salt dome



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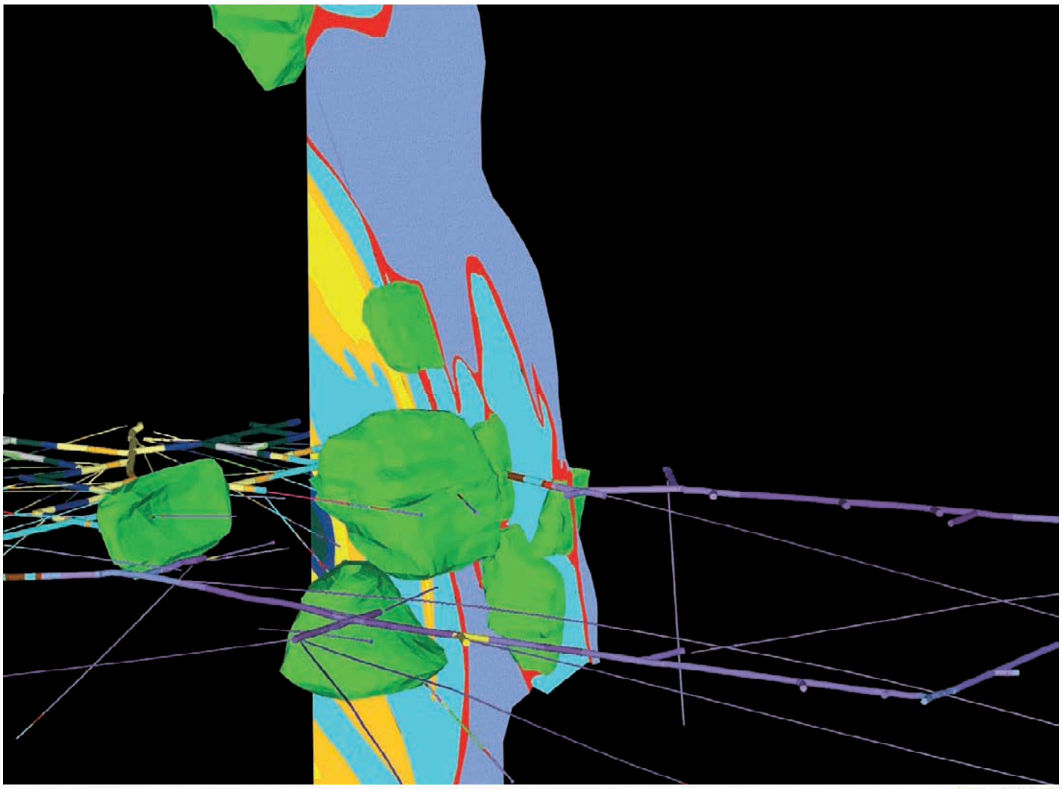
Boudinage of Hauptanhydrit Gorleben salt dome



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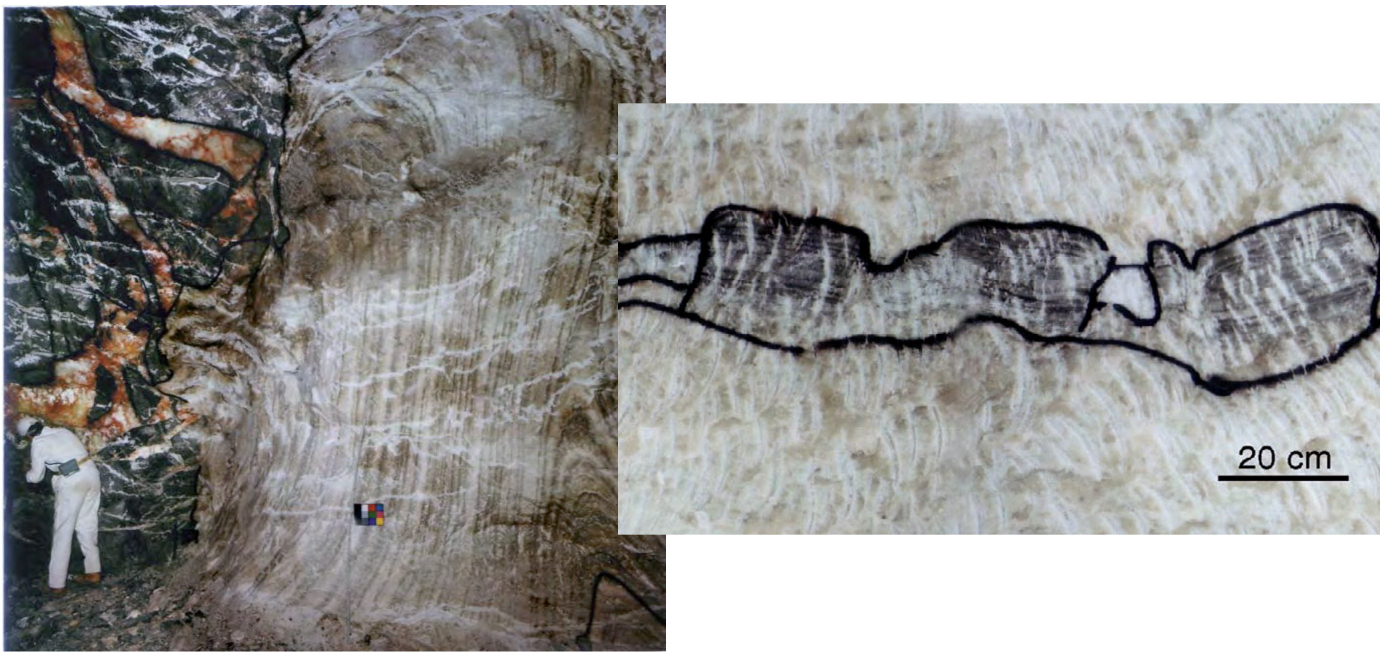
Boudinage of Hauptanhydrit/Anhydritmittelsalz Gorleben salt dome



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Results of geological exploration (1)

- No interconnection between anhydrite blocks in the central part of the salt dome
- No significant occurrence of salt solutions and gas reservoirs in the "Hauptsalz" Formation
- Occurrence of salt solutions and gas reservoirs only in anhydrite-bearing rocks (e.g. "Gorleben Bank")
- No connection and flow paths from salt solution reservoirs in the salt dome to the aquifer in overburden (salt leaching surface)
- No interconnection between salt solution reservoirs over long distances

Results of geological exploration (2)

- Between the two shafts the transition from z3 to z2 was encountered in complicated folds and shear structures
- The central zone of the salt dome consists of "Hauptsalz" in a simple anticline
- The Hauptsalz (Zechstein 2) with a primarily sedimentary thickness of 800 m is deformed to a breccia
- If there is intensive folding salt beds react by thinning or thickening
- Thicker anhydrite horizons are mostly torn into single isolated blocks
- The anhydrite units are often isolated reservoirs for brines, hydrocarbon gases and condensates because of fracturing

CONCLUSIONS

- The final suitability of the Gorleben salt dome is evaluated by a stepwise manner.
- Up to now, there are no indications for non-suitability.
- The experiences gained in the first exploration area (EB1) are determining the further exploration strategy in the following exploration areas.

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

FIELD AND EXPERIMENTAL R&D FOR SALT REPOSITORIES

David Holcomb
Sandia National Laboratories

Field and Experimental R&D for Salt Repositories

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Sandia National Laboratories

US-German Workshop on Salt Repository Research, Design and Operation
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Canton, MS

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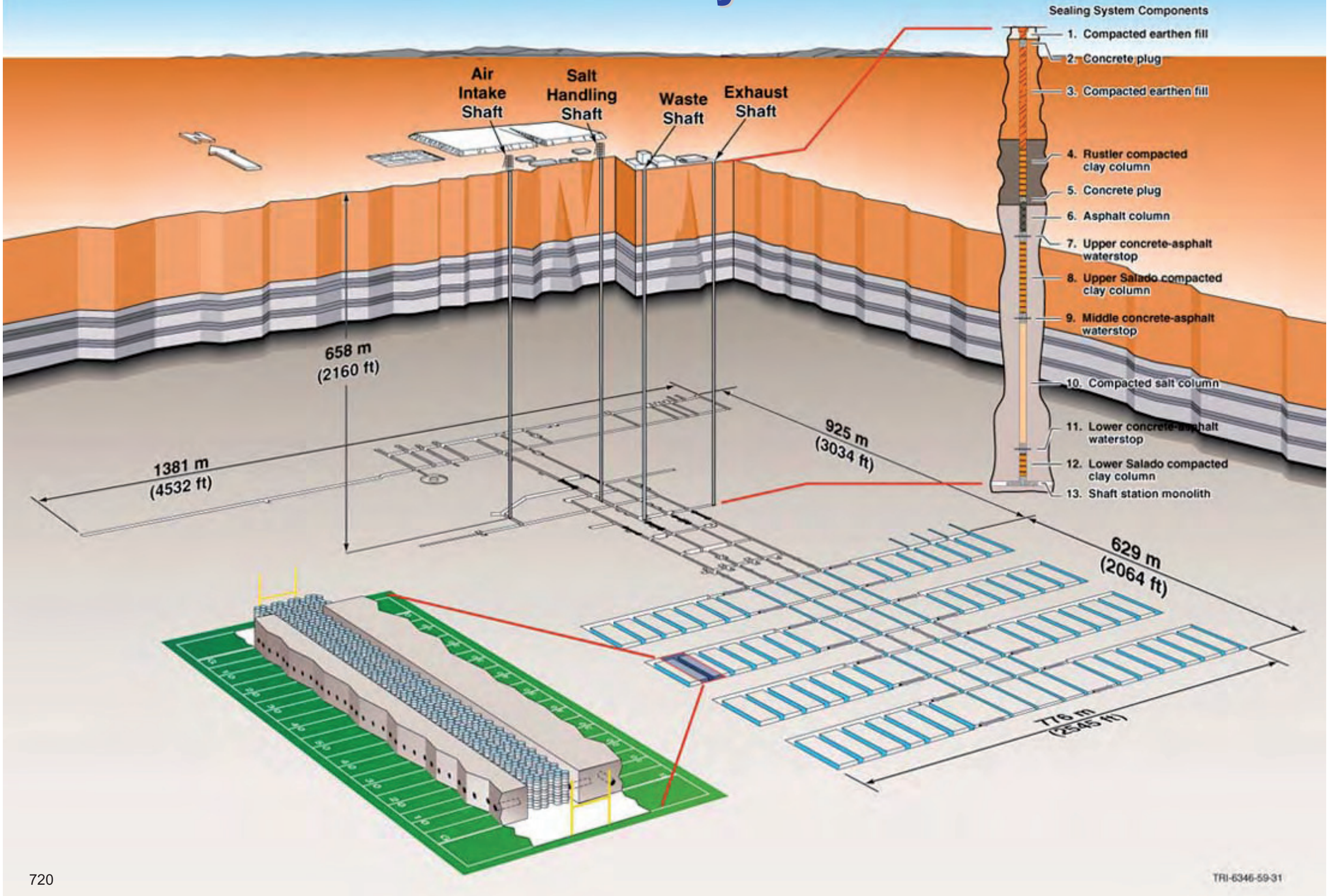
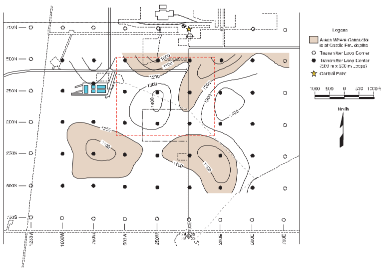
WIPP Layout



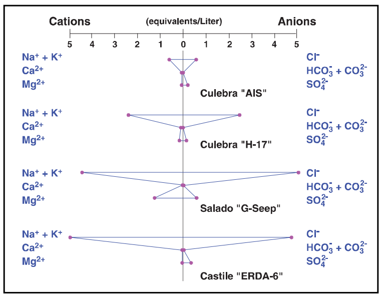
WIPP Site Characterization

Geologic studies



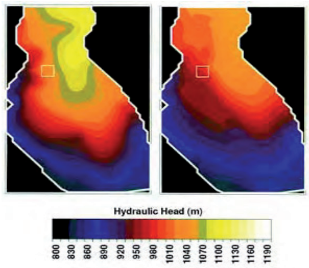
Geophysical surveys

Hydrologic testing



Geochemical sampling and analysis

Geomechanical testing



Numerical modeling

5.2-8.ppt

Recent Laboratory and Field Work

- DRZ (Disturbed Rock Zone) Investigations
- True Triax Lab Tests
- Hot Salt Reconsolidation

Understanding Changes in Permeability Motivates Investigations

- DRZ (Disturbed Rock Zone) Investigations
  - Field studies aim to quantify damage spatial and temporal variation because damage increases permeability
  - Some influence on closure rates and constitutive modeling
- High Temperature Salt Consolidation
  - Permeability of backfilled, mined salt
  - Material properties of backfilled salt control the closure and sealing properties of the host salt

DRZ Criterion in Halite

- D "damage" factor, is derived from the dilatancy criterion of Van Sambeek et al.
- This proposed criterion is linear in terms of stress invariants

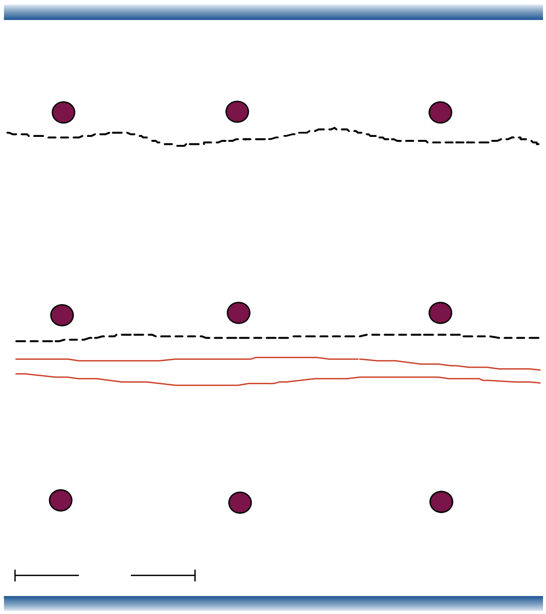
$$\sqrt{J_2} \geq 0.27 I_1 = 0.81 \sigma_m \quad (1)$$

- Eq. (1) was used to defined a damage factor D

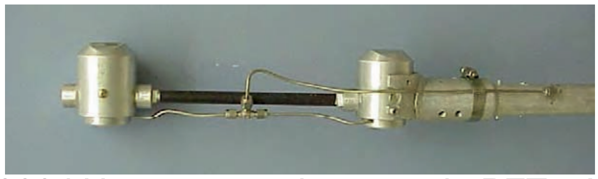
$$D = \frac{\sqrt{J_2}}{0.27 I_1} \quad (2)$$

- Where *D* < 1, No damage is expected
- Where *D*> 1, Damage is expected
- Where *D* > 1, the shear stresses in the salt (J_2) are large compared to the mean stress (I_1) resulting in dilatancy and damage

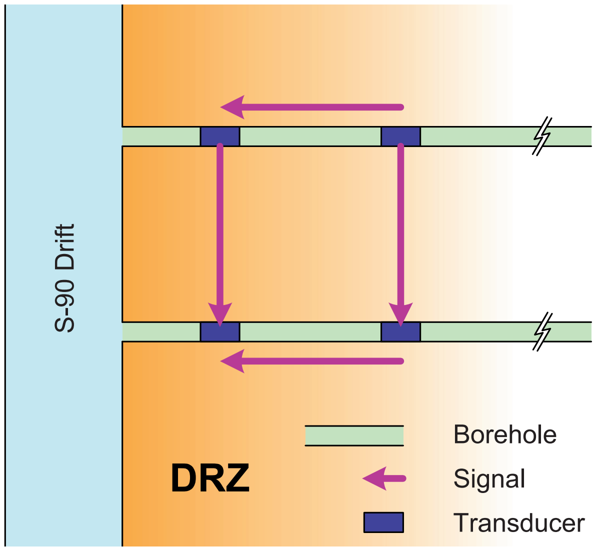
S-90 Drift Experimental Configuration



Borehole geometry in S-90 rib face

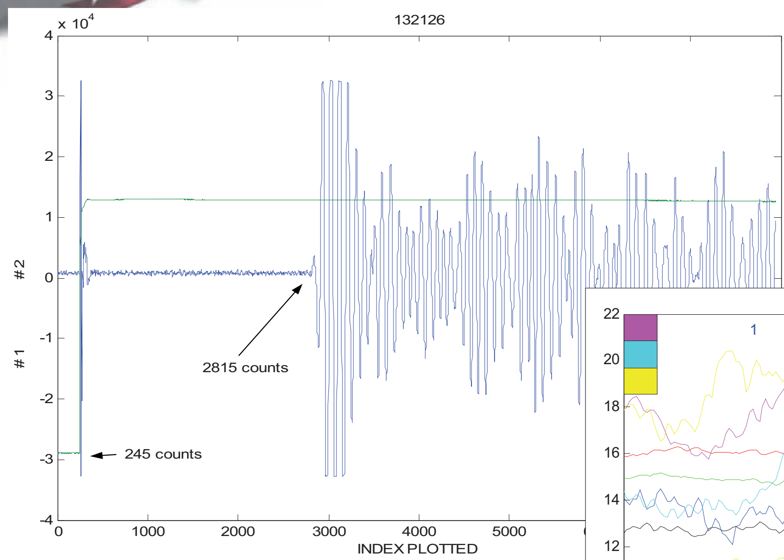


300 kHz, compressional mode PZT-5A



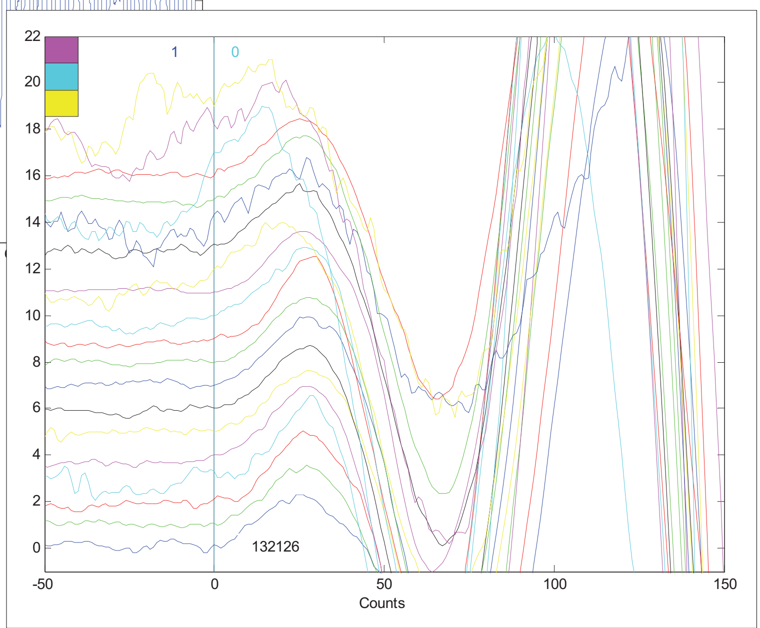
Plan view (schematic)

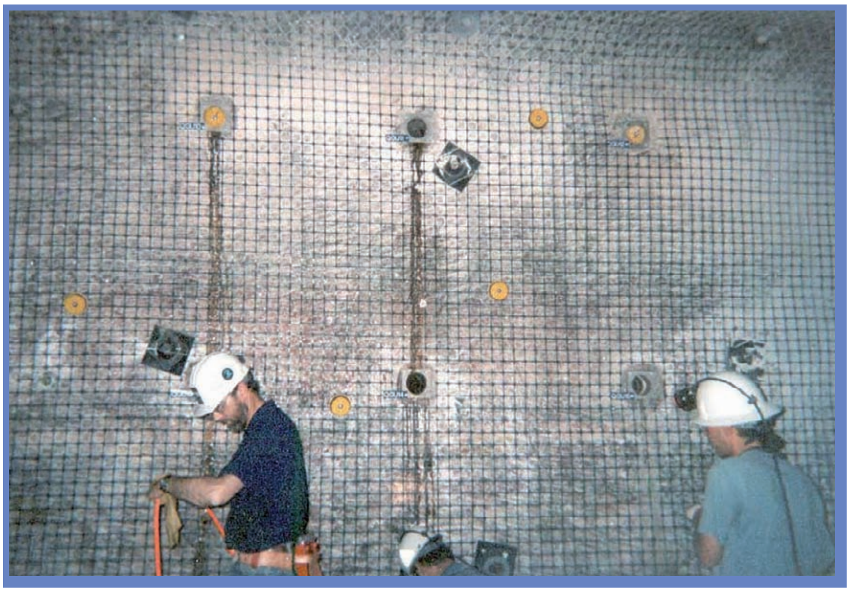
Arrival Time Picking Process



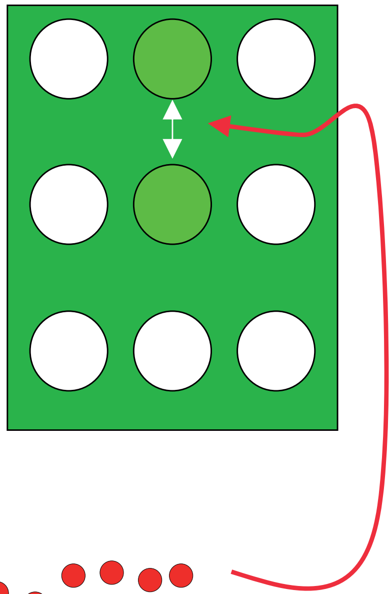
Superimposed signal traces from all measurements within a borehole.

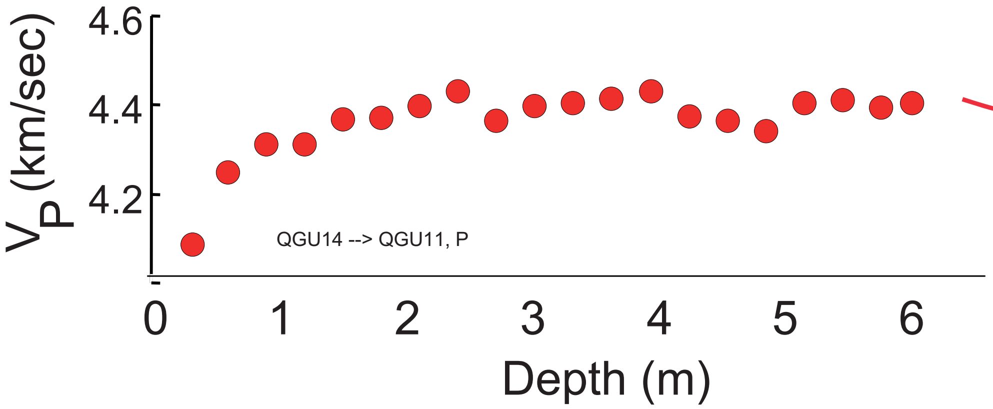
Transmitted signal and received signal plotted as a function of sample counts and scaled amplitude.





Hole Pattern





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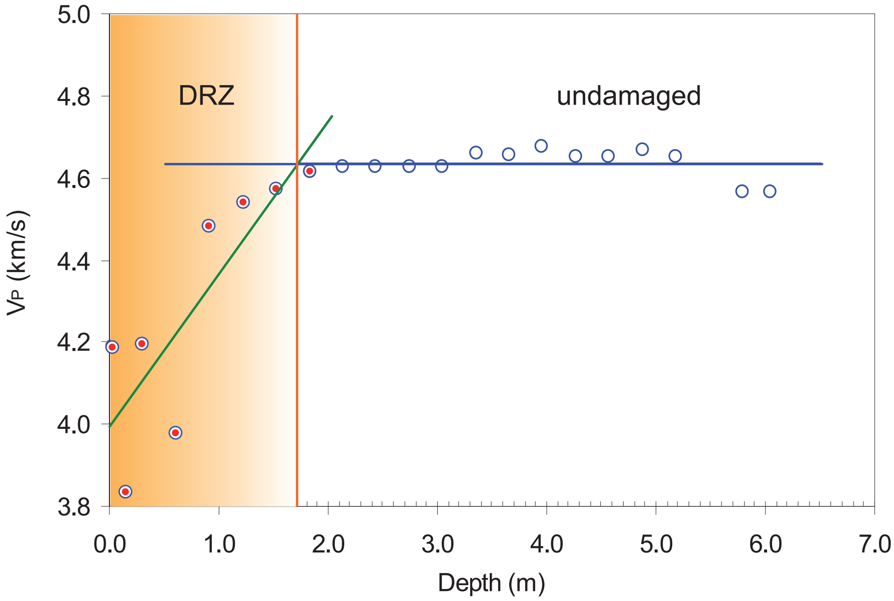
Ultrasonic Velocity with Depth

DRZ

- **Non-constant velocity region, changing with depth**

Undamaged zone

- **Constant velocity region**



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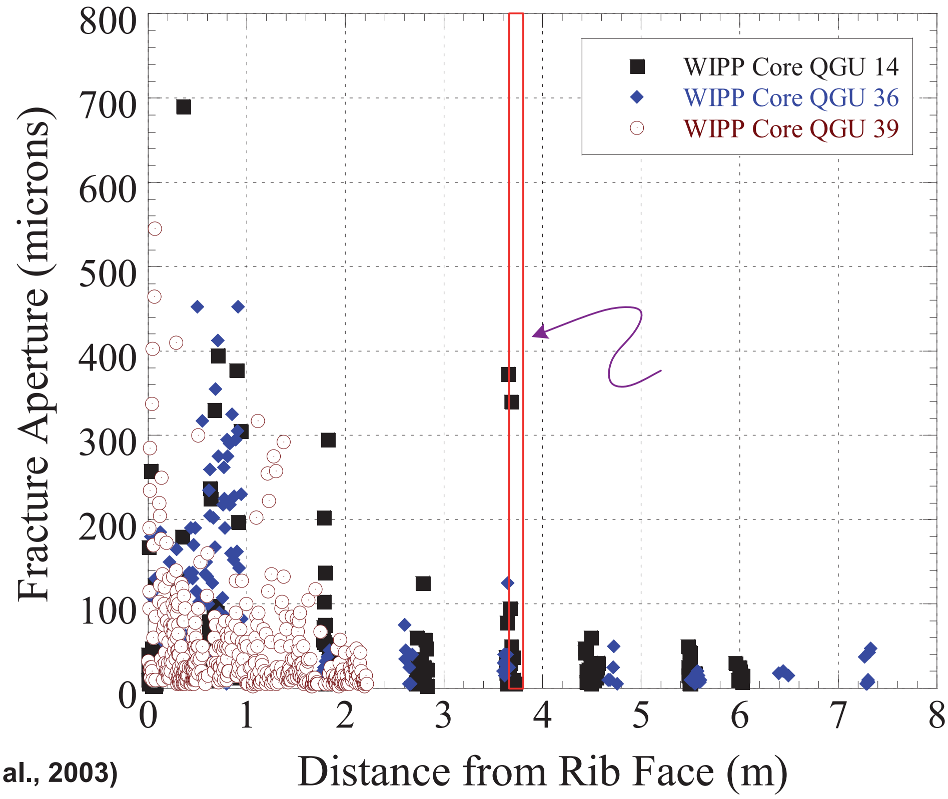
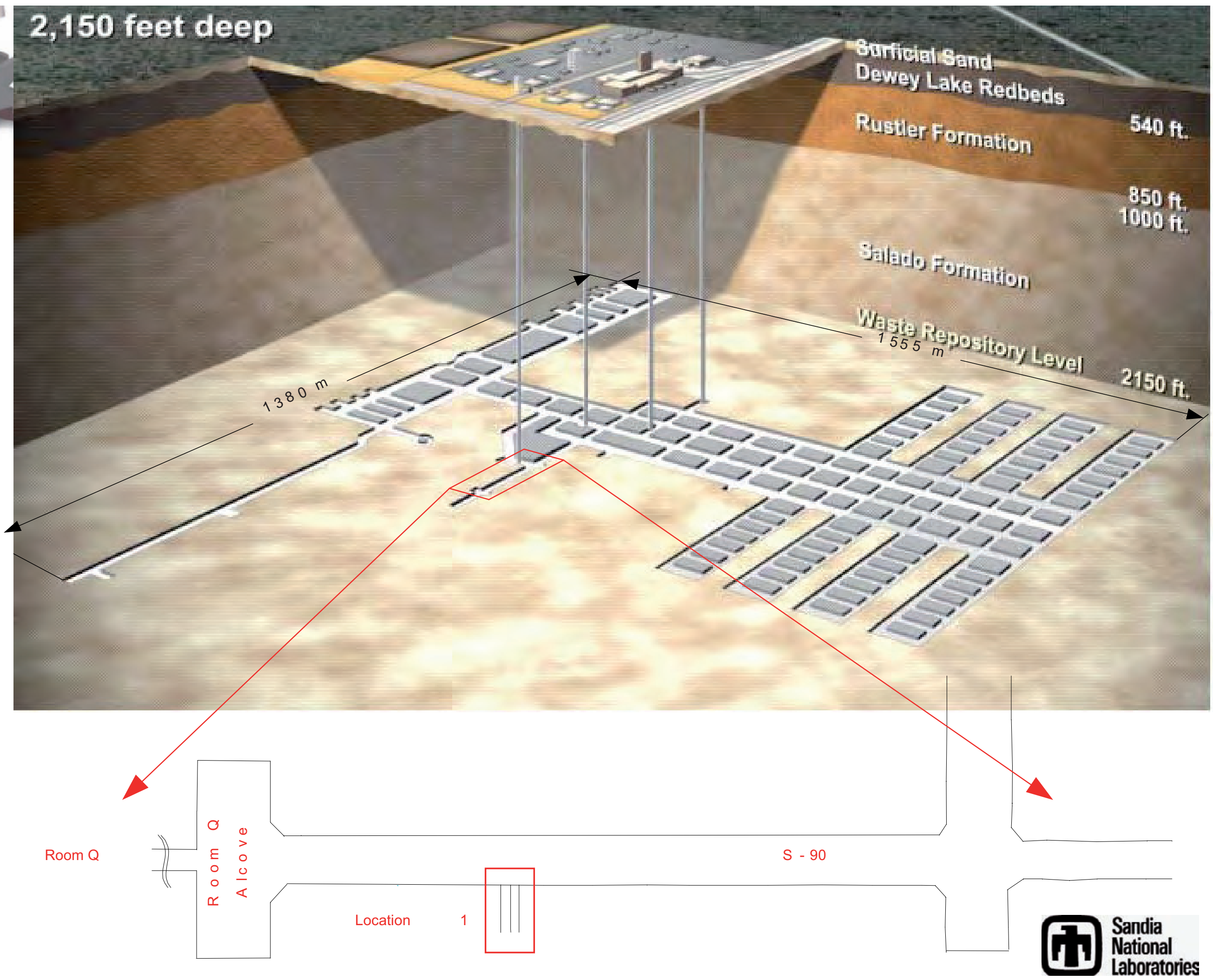
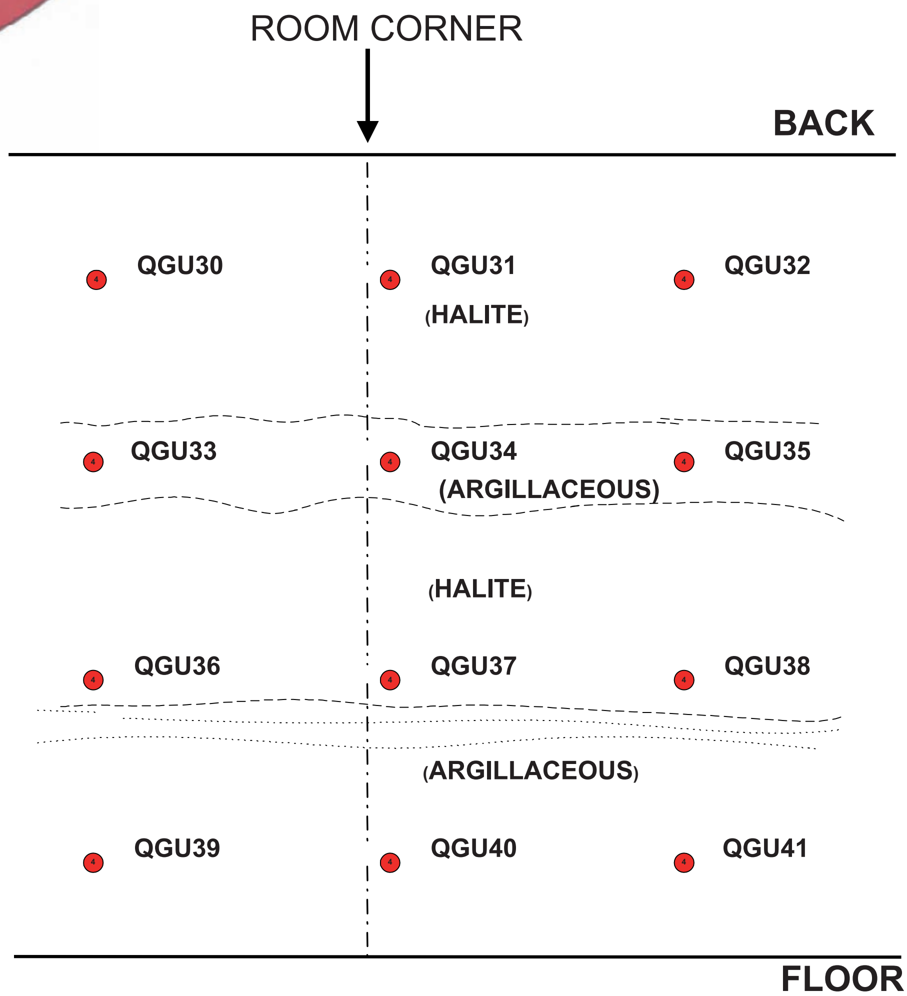
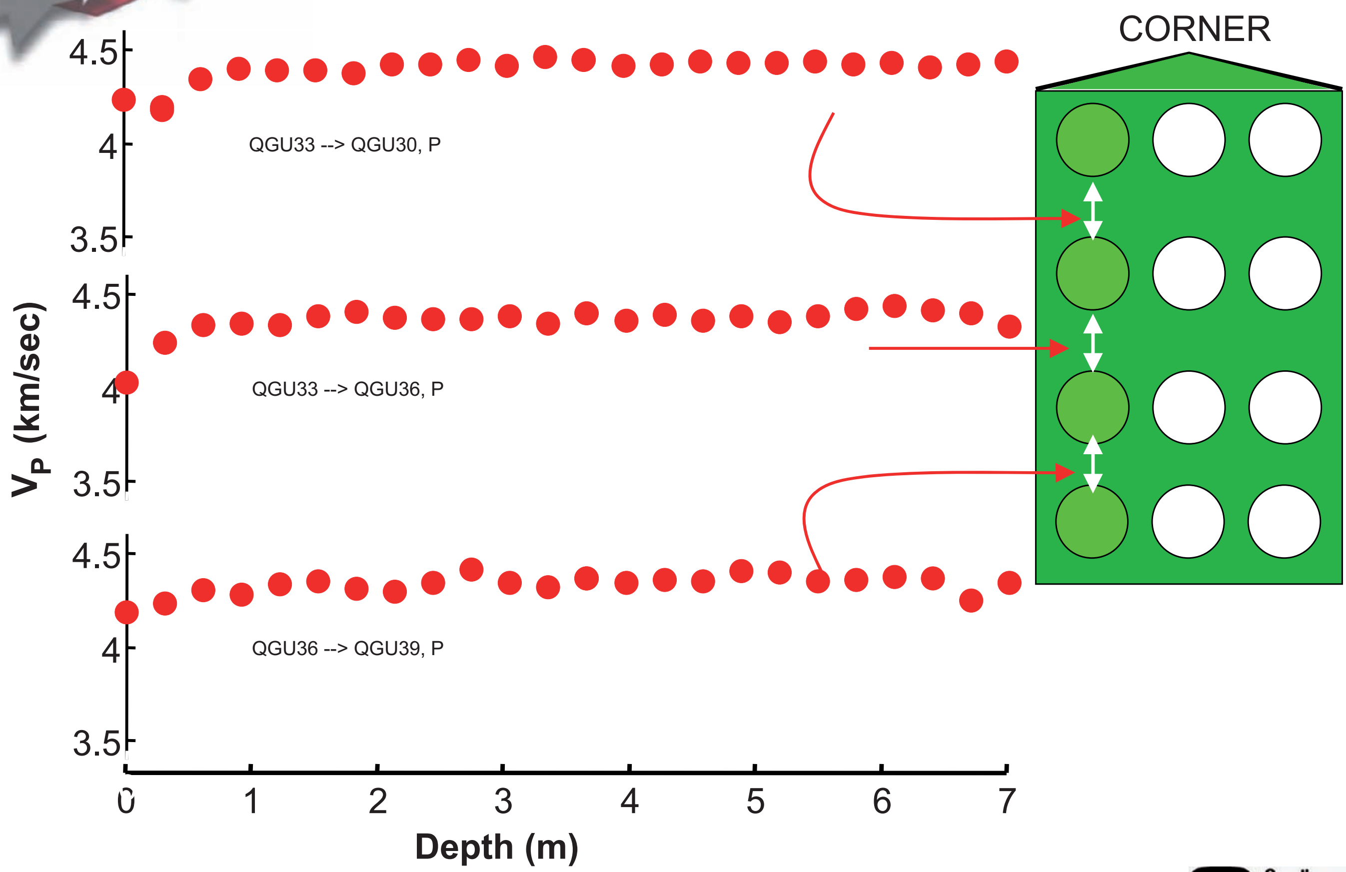
Fracture Apertures in Core from S-90 drift

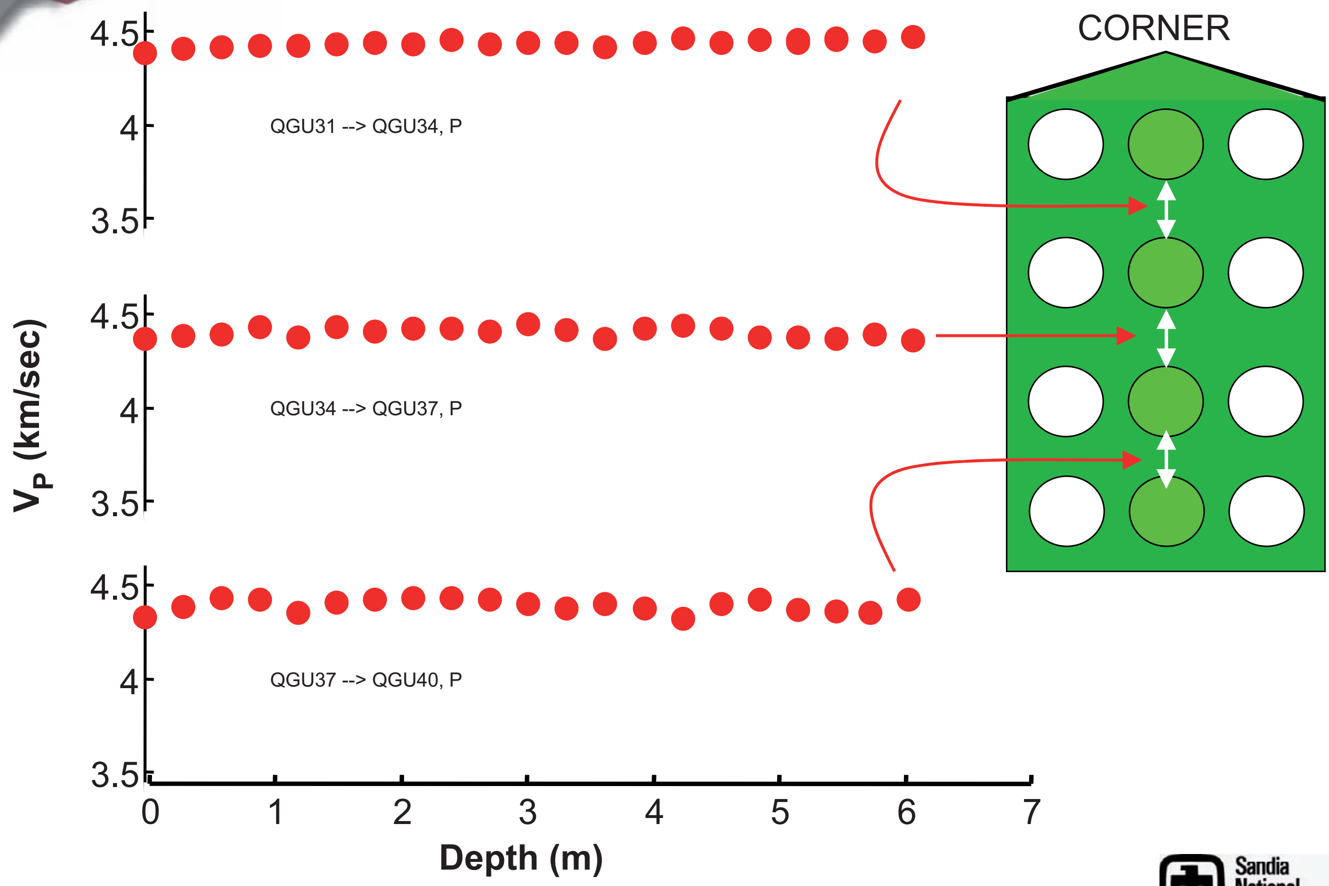


From (Bryan et al., 2003)



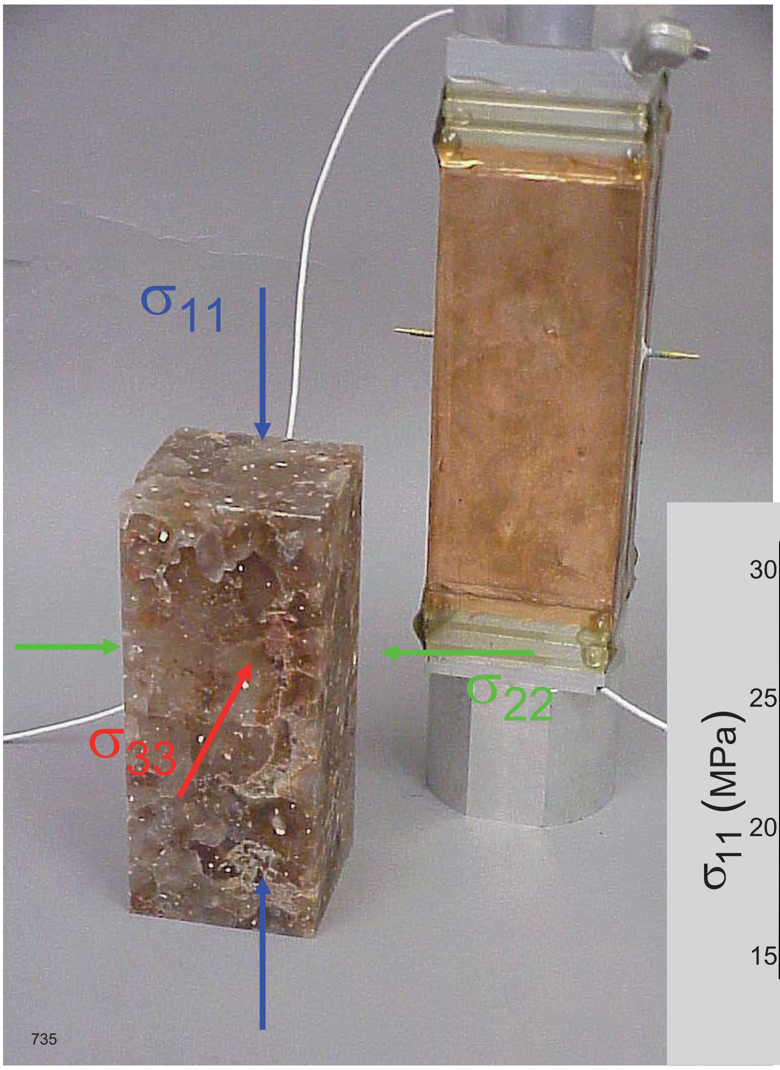

ROOM CORNER
BACK
QGU30
QGU31
QGU32
(HALITE)
QGU33
QGU34
QGU35
(ARGILLACEOUS)
(HALITE)
QGU36
QGU37
QGU38
(ARGILLACEOUS)
QGU39
QGU40
QGU41
FLOOR


CORNER
4.5
4
3.5
QGU33 --> QGU30, P
QGU33 --> QGU36, P
QGU36 --> QGU39, P
V_P (km/sec)
0
1
2
3
4
5
6
7
Depth (m)



Comparison of Laboratory and In Situ Results

- Quasistatic, 3-D stress -vs- in situ creep under the influence of an evolving 3-D stress state
- Relative effectiveness of creep and quasistatic stress in generating anisotropic damage



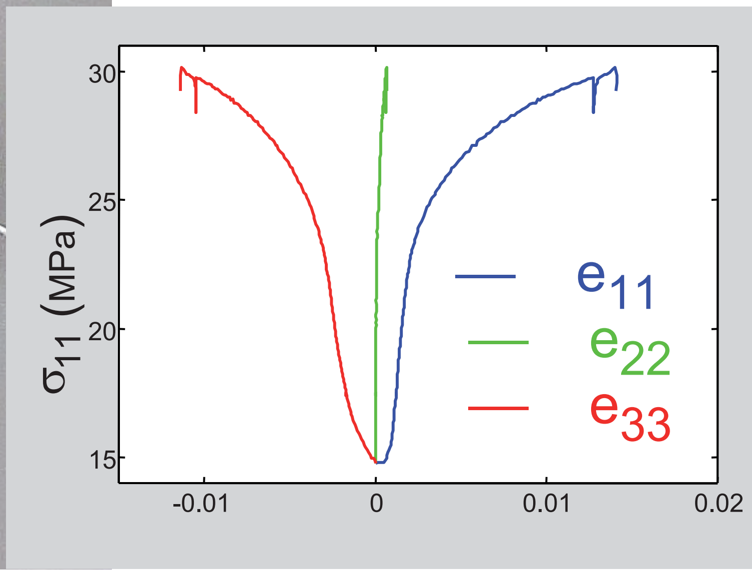
True Triaxial Testing

Simulate Changing Stress During Mining

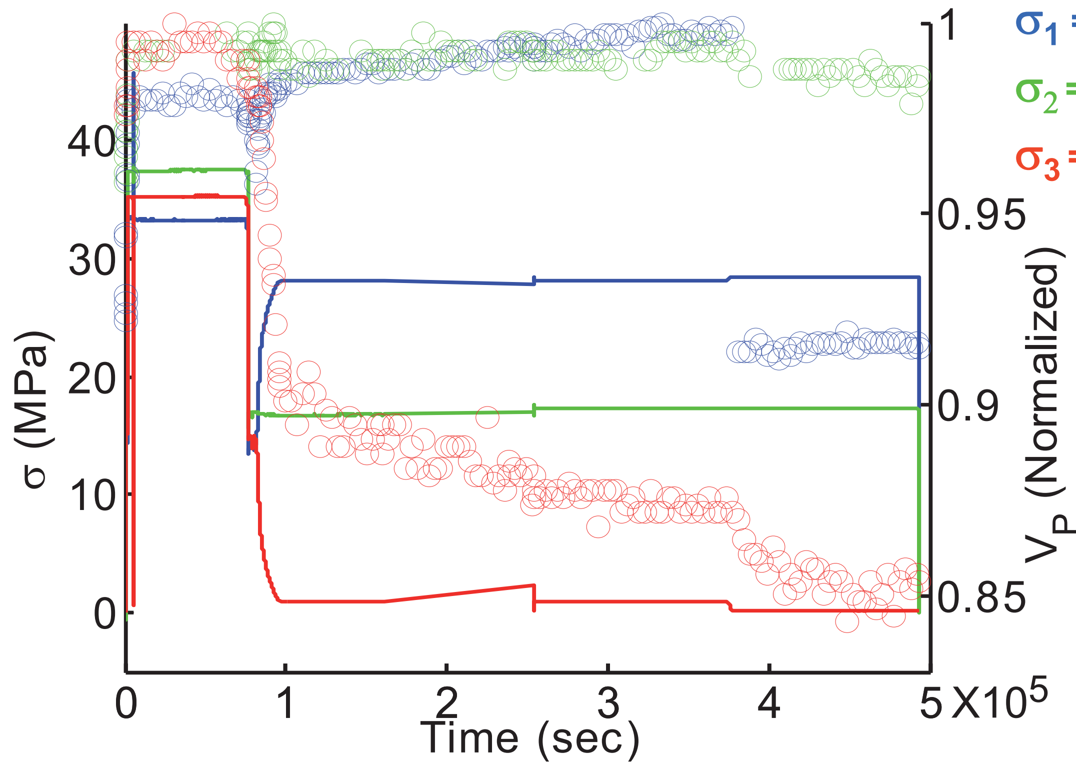
σ_1 = 15 → 30 MPa

σ_2 = 15 MPa

σ_3 = 15 → 0 MPa



Changes in V_p for Simulated Drift Mining



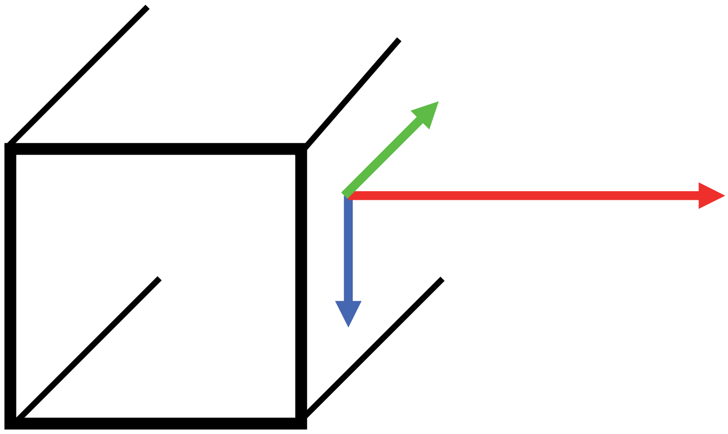
σ_1 = 15→ 30 MPa

σ_2 = 15 MPa

σ_3 = 15→ 0 MPa

Field vs Lab DRZ Effects on V_p

- Vertical (σ_1)
  - In situ -7 %
  - *Lab 0 %*
- *Parallel to drift (σ_2)*
  - In situ -7 %
  - Lab 0 %
- Perpendicular to drift(σ_3)
  - In situ -20 %
  - Lab -15 %



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SUMMARY

- Lab and in situ results differ because of creep
- Time- hours -vs- years
- Different effects of in situ and laboratory 3-D stress emphasizes the importance of creep in generating anisotropic damage, even in directions that might be expected to have low damage (parallel to wall of drift)

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Salt Reconsolidation for Higher Temperatures

- Available data were acquired under WIPP-appropriate conditions (< 100 C)
- High level waste will impose higher heat loads and higher temperatures
- Technological issues in conducting hydrostatic creep tests at high temperatures on initially low porosity mined salt
- Water behavior is difficult to simulate in small samples. Vented, sealed, partially dried?

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Stages of sample preparation

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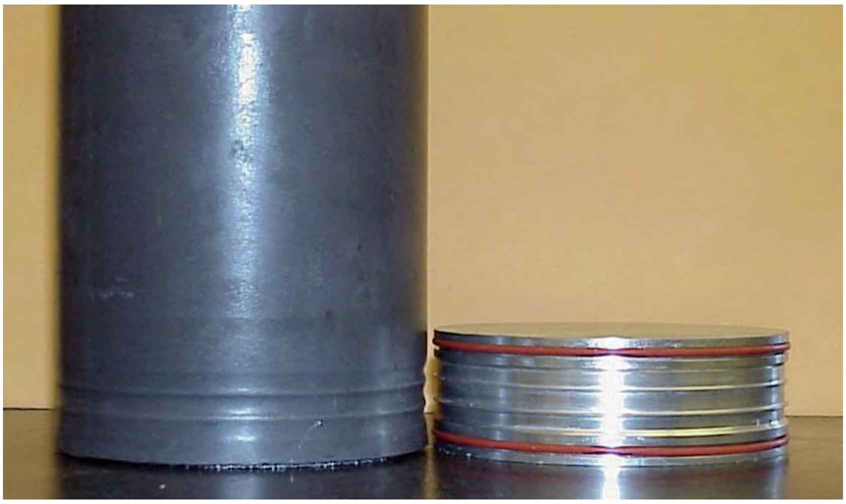
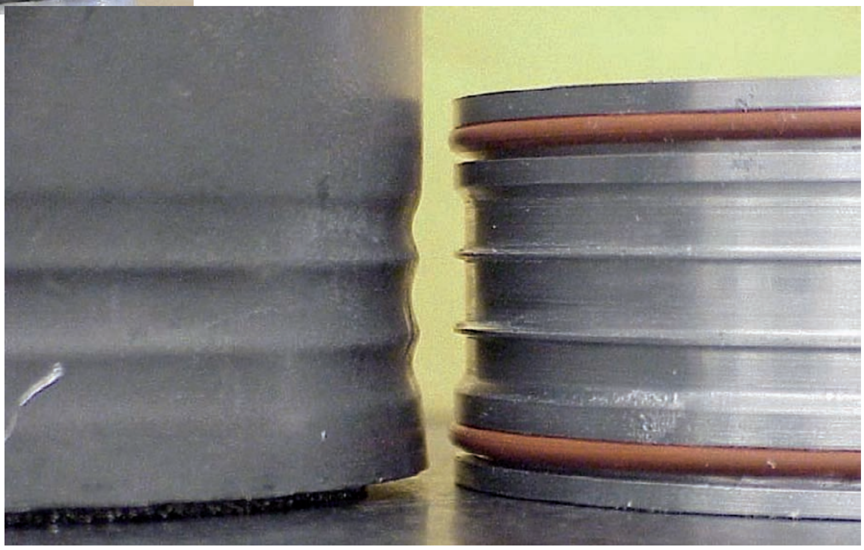


Elastomer jackets always failed.

Metal-metal seal with lead jacket was key to success



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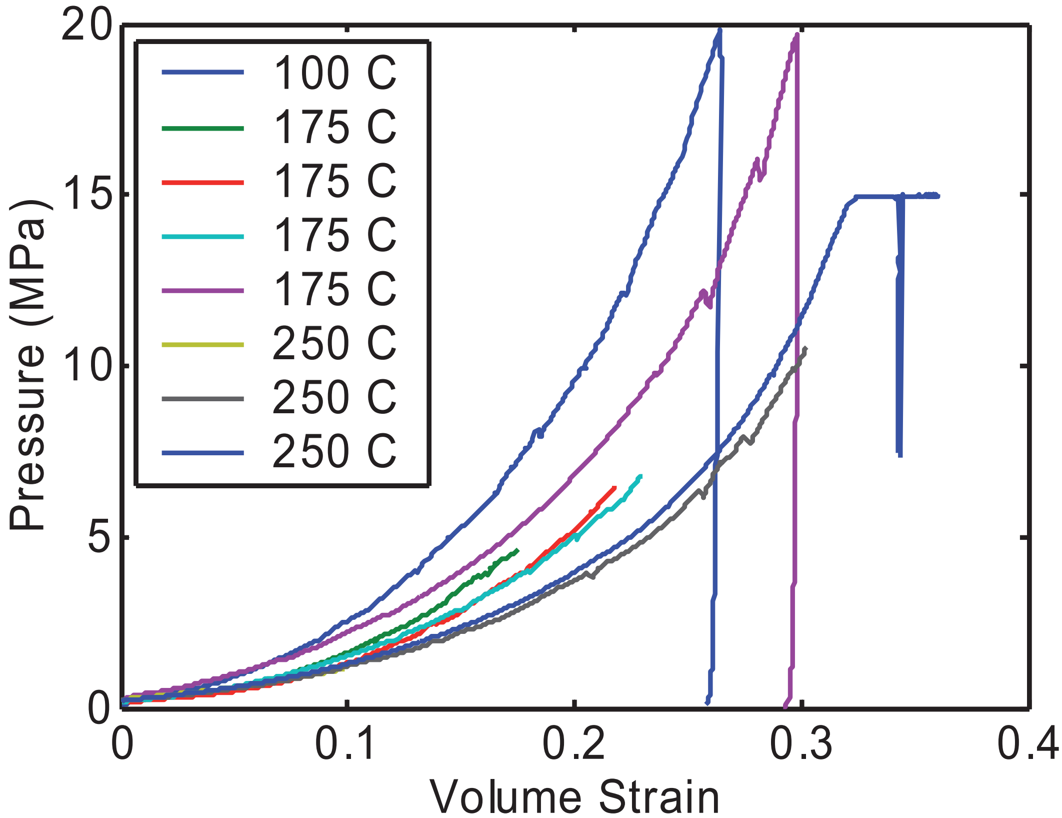
High Temperature Consolidation of Mined Salt



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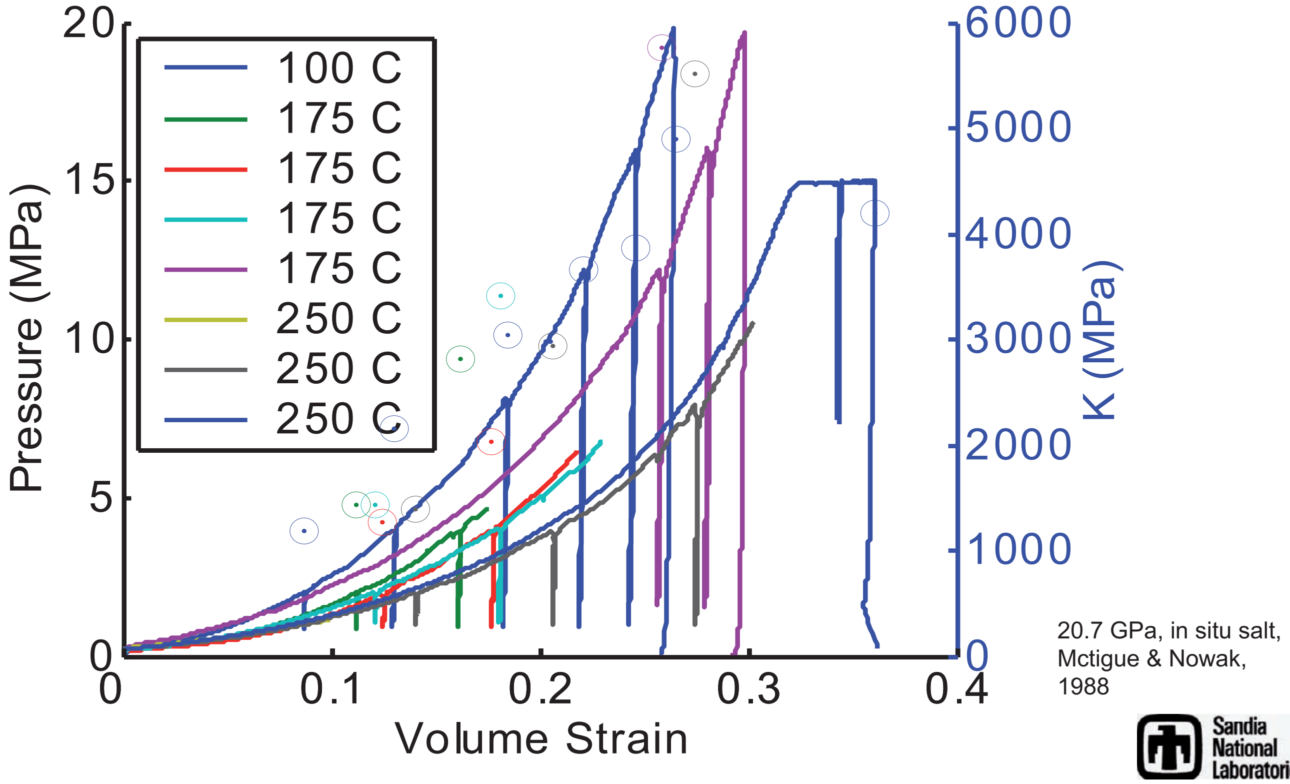
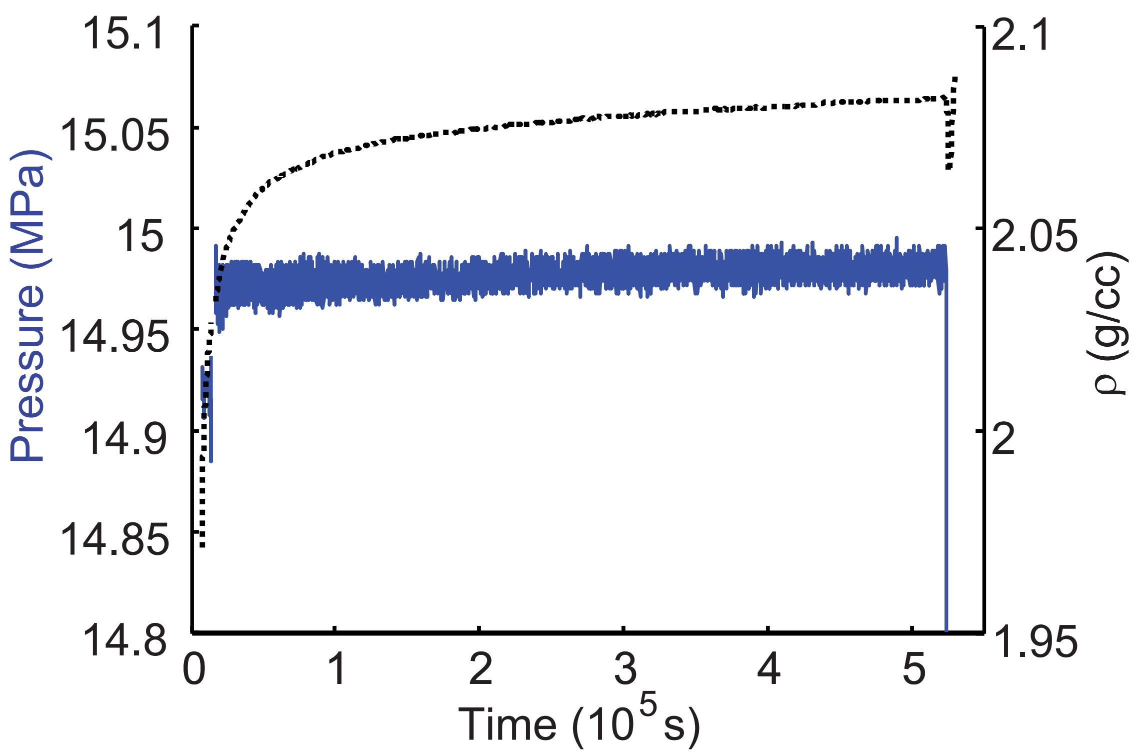
Evolution of Bulk Modulus



Density increased throughout creep test, 2.082 g/cc = 97% of theoretical after 145 hours.



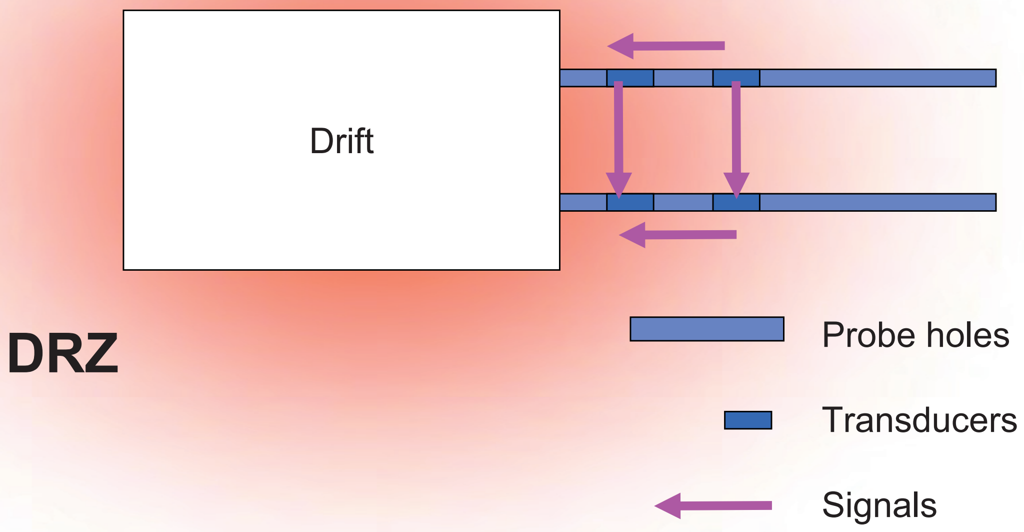
Summary of High Temperature Consolidation Results

Type	Quasi	Quasi	Quasi	Creep 145 hrs
P_{max} (MPa)	20	19.68	14.92	14.98
T (°C)	100	175	250	250
ΔV_{direct} (cc)	-286	-364	unknown	-447
ρ_f (g/cc) % theoretical	1.922 90%	1.940 91%	1.969 92%	2.082 97%

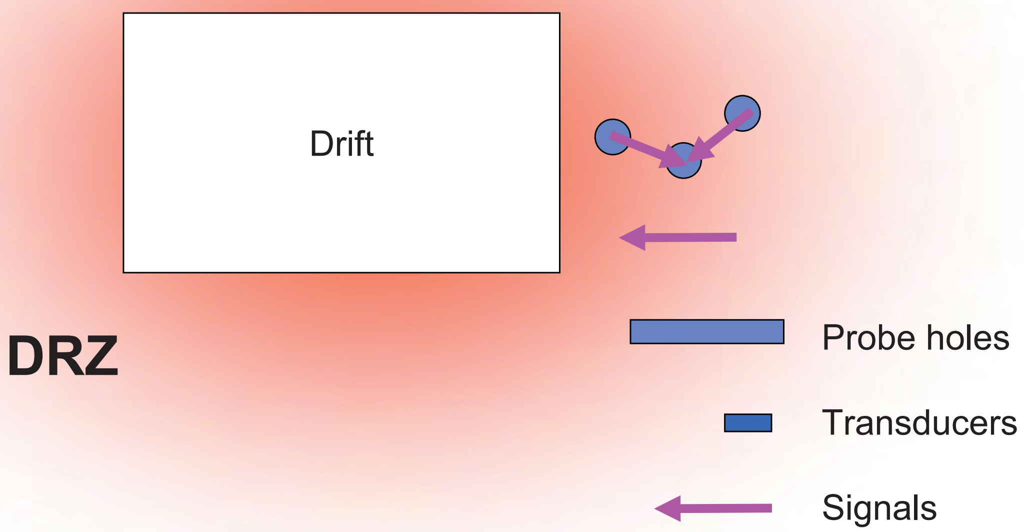
Geomechanics Issues for the Future

- Temperature is an important difference between current state of knowledge and future needs
- Constitutive laws will need to be validated, and possibly modified
- Experimental difficulties should not be underestimated when doing high temperature, long duration creep tests
- Include effects of 3-D geometry, corners, finite openings
- Interaction between heat and water transport : What happens to the native water under the effects of high temperature, higher thermal gradient?
- Healing versus damage in the DRZ? Higher temperatures speed healing, cause water to move, increase creep rate.
- Mineby experiments are needed to understand the temporal evolution of DRZ

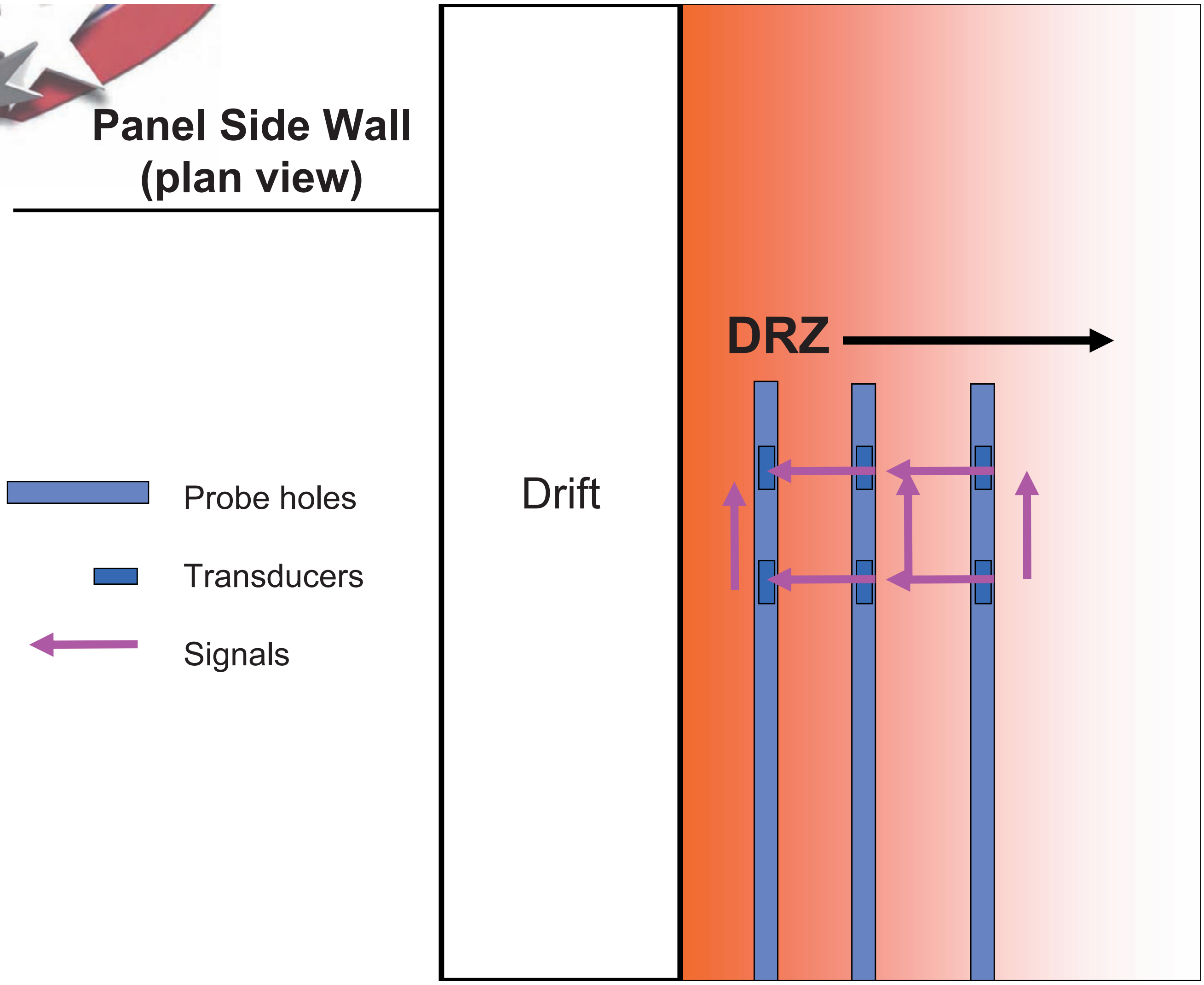
Basic Layout (cross section)



Panel side wall (cross section)



Panel Side Wall (plan view)



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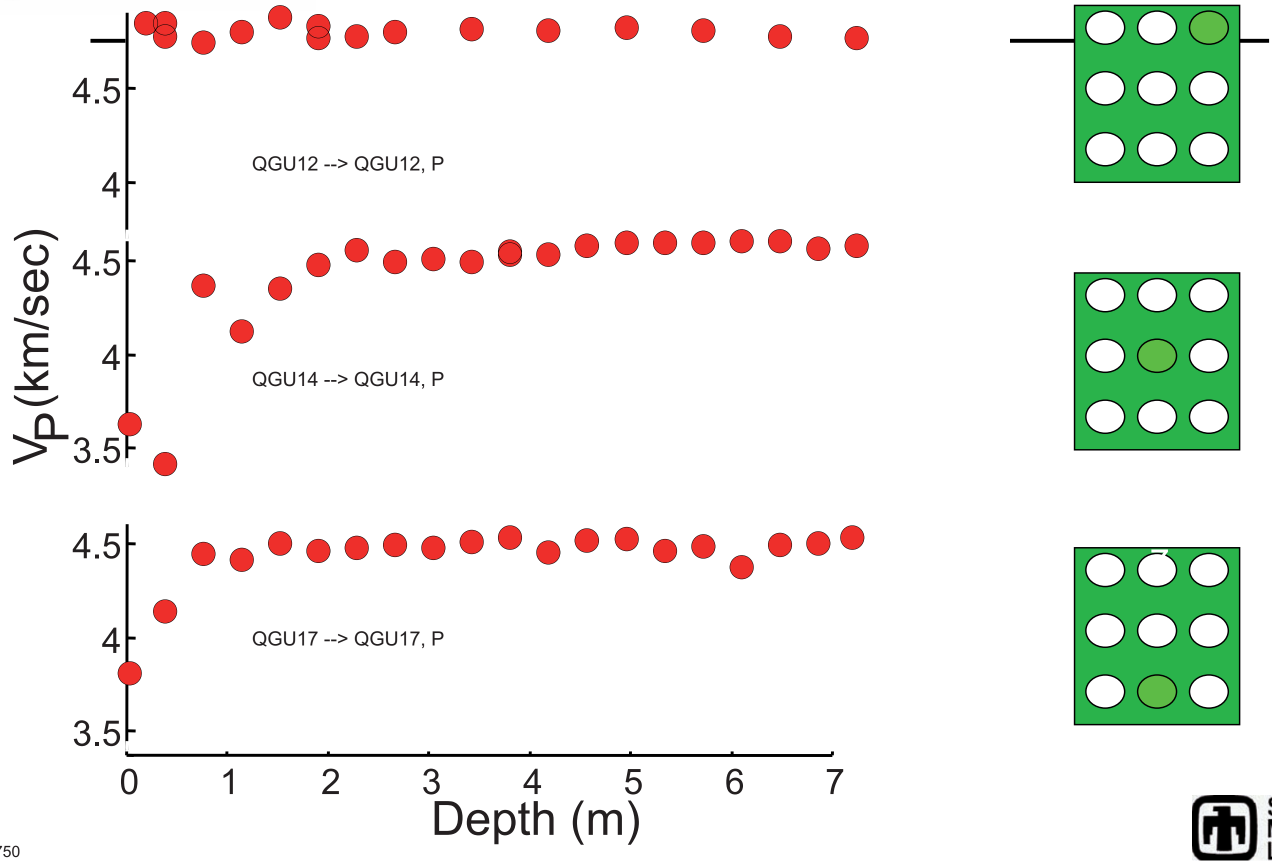

Sandia National Laboratories

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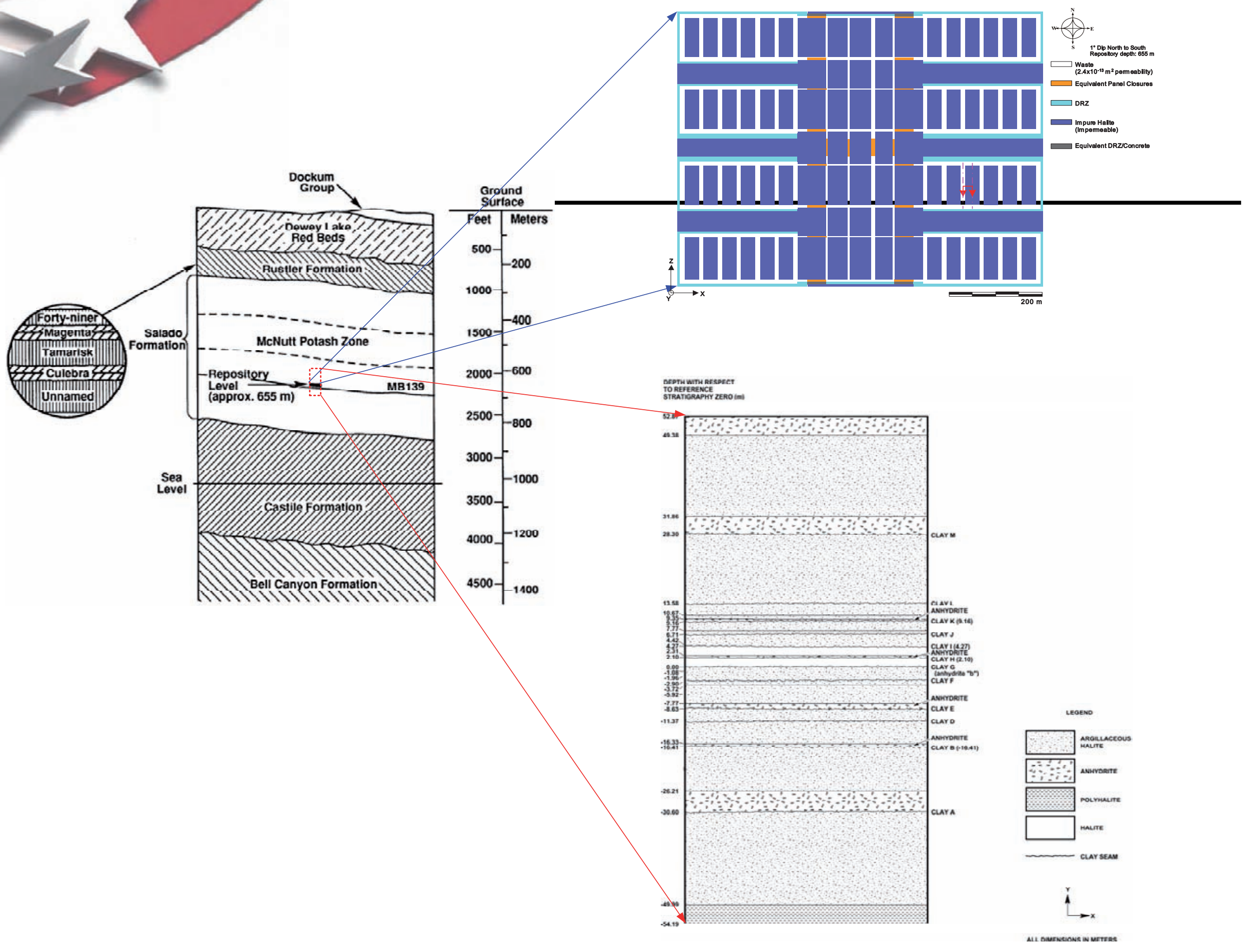

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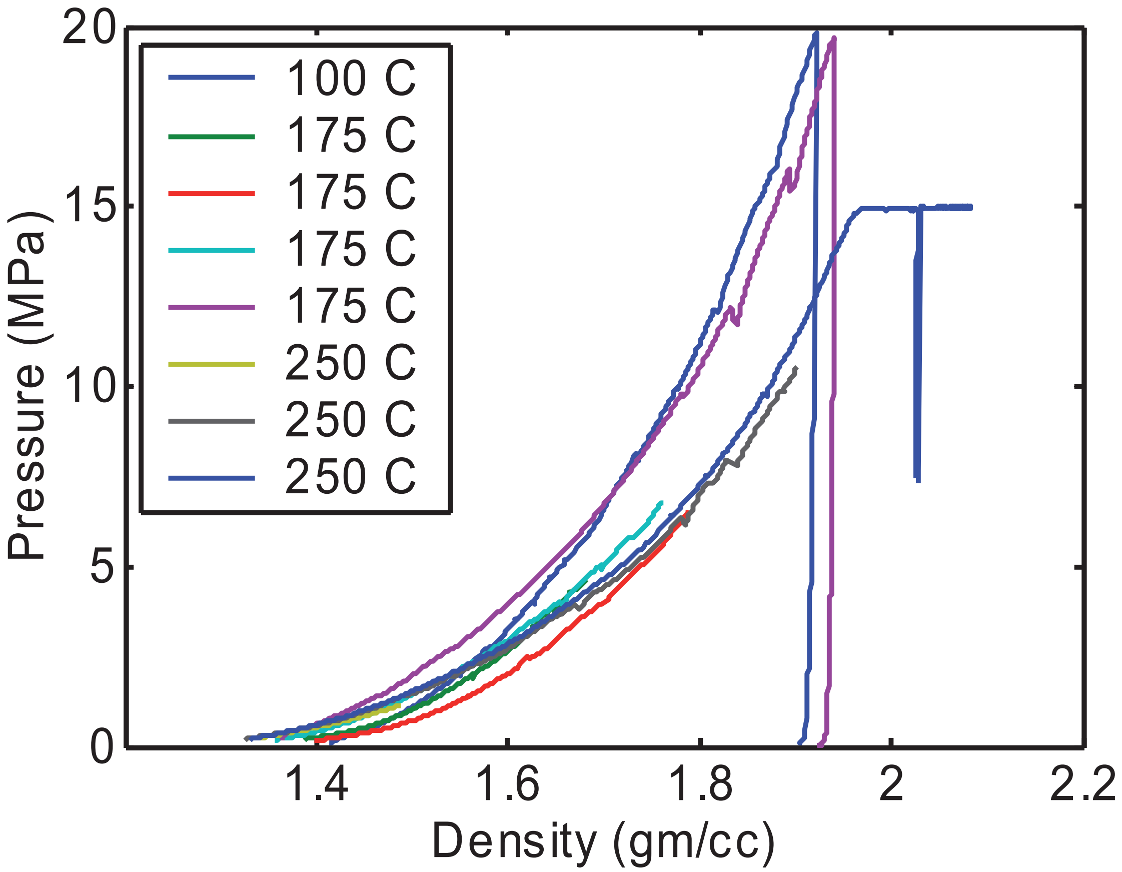
Densities



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GEOMECHANICAL LAYOUT AND BARRIER INTEGRITY OF A ROCK SALT REPOSITORY

Peter Kamlot, Wolfgang Minkley, Ralf-Michael Günther, Ulrich Wüste
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

Abstract

The presentation of IfG deals with the two topics: First, the dimensioning of drifts and panels in a radioactive waste repository in rock salt for the drift disposal concept in such a way that the safe containment of the waste within the Isolating Rock Zone (IRZ) and the barrier integrity around the IRZ can be predicted. Second, the discussion of the special features of the former salt extraction mine Asse II, which was later used as repository for LAW and MAW, to clarify the differences to the reference concept of a German HAW-repository in rock salt.

A substantial progress was reached in the last years regarding the development of constitutive laws for simulation of softening, dilatancy and damaging (in combination with creep) as typical processes in the EDZ. For instance, in the THERESA-project [1] laboratory benchmark tests were modelled and the constitutive laws could be validated against the measured dilatancy and permeability course under temperature increase. This interpretation modelling was vital for the understanding of THM-coupled processes on a laboratory scale.

In the project BAMBUS-II [2] investigations on an in-situ scale were carried out for completion of the TSDE (Thermal Simulation of Drift Emplacement) in which two simulated emplacement drifts had been electrically heated to 170 - 200°C by disposal cask mock-ups over more than eight years. The thermo-mechanical computational studies helped to refine the models and codes regarding the long-term repository predictions.

After validation, a visco-elasto-plastic constitutive law which describes softening, dilatancy and creep [3] was used in thermo-mechanical coupled simulations aiming at the evaluation of potential HAW repository-sites in rock salt. These theoretical case studies for the two reference-sites "Salt dome" and "Bedded salt" [4] revealed that temperature-induced effects of stress redistribution in the host rock and overburden must be assessed by use of the dilatancy and minimal stress criterion and, following, that a complex optimization of the repository layout (regarding geology, drift design, heat impact, barrier dimensions…) is necessary. The aim of the studies was to demonstrate the applicability of the used tools. After that, recommendations for the integrity guaranteeing barrier thicknesses around an IRZ in comparison to other German proposals [5] to [7] were summarized. These dimensions should be used for the preliminary site evaluation, but, at the end, a site-dependent long-term assessment is indispensible.

Further laboratory investigations should aim to complete the database on dilatancy and to understand the brine influence on EDZ recompaction. The further development of process-level models must lead to validation of their suitability for in-situ application. Regarding the use of thermo-mechanical coupled model calculations the sensitivity of the minimal stress criterion and, in case of violation, the consequences on fluid-flow calculations for simulation of the long lasting penetration processes through the geological barrier are to investigate.

In the Asse II salt mine's southern flank an array with relatively small pillars and stopes was excavated between 1916 and 1964 in the course of halite extraction [8]. Most of the volume of the chambers (in total approx. 3.4 Mio. m^3) was exposed to free convergence until 1995, when a backfilling campaign by pneumatic transportation of a granular salt material started, which lasted until 2004. The barrier to the overburden rocks is formed by rock salt with a minimal thickness of minimal 10 m in the upper part. The flank dips by approx. 70° in SW direction. The rock mechanical evolution has been monitored for decades by displacement observations, stress and strain measurements in the pillars, and recording of the backfill pressure built-up in the chambers.

Furthermore, micro-seismic activity in the mine and the adjacent overburden has been recorded. Softening and damaging in the pillars and stopes of the mining horizon have led to stress redistributions into the overburden rocks, where fracturing processes were generated as well. Hence, because of the small dimensions of the bearing elements on the southern flank and the close distance to the overburden, far reaching geomechanical interactions exist.

The recent geomechanical and hydrological situation of the mining system at the southern flank can be assessed as follows:

- With the horizontal overburden displacement in direction to the mine, in the pillars, stopes and the adjacent overburden rocks damaging and fracturing processes continue.
- Because of the rock salt backfill in the chambers the convergence leads to a backfill pressure increase (measured at approx. 1 MPa in maximum). As a geomechanical positive consequence, the rates of overburden displacement drop down for several years.
- The miners try to catch (as complete as possible) all brine from the overburden in local drainage equipments. The order of brine inflow is more or less constant in a range of 12 m^3 per day.
- The not caught brine is currently penetrating through discrete pathways (open boreholes, backfill, fractures in salt) down to the level of 750 m, in which the Low Radioactive Waste is embedded.
- The prediction of an inflow trend from the overburden is not possible. A strong increase cannot be excluded.
- The residual load bearing capacity of the broken pillars and stopes can be predicted on basis of model calculations only for a limited time range (supported by intensive mine surveying), if the brine inflow not rises dramatically.

Since January 2009 BfS (Federal Office for Radiation Protection) as new operator of the mine Asse II has the order to close immediately the mine under Atomic Law. The urgent necessary action results from the unclear hydrological situation and the limited time range for load bearing capacity. For the closure, three options were considered and stipulating long-term security of underground isolation with highest priority the decision was made for complete retrieval as best option.

This decision for retrieval is under several reservations: contour stability and amount of brine in the emplacement chambers, condition of the barrels, consequences on radiology, stability of the southern flank and inflow rate. The potential uncertainties are able to prevent the removing. So far, the decision is not final.

The further work complies the stabilization of the southern flank on basis of cap filling in the rooms and backfilling of drifts. The stabilization is of decisive importance and doesn't prevent the removal. On account of the permanent risk of brine inflow escalation an emergency concept with included provision measures is developed. The provision measures mustn't prevent a later safety-case, if the waste cannot be replaced completely. The relevance to the safety-case is investigated.

As accepted by the most people involved, the radioactive waste should not have been imbedded in this old mineral extraction mine. But it must be emphasized: The Asse II mine has nothing to do with a new rock salt mine, especially constructed for repository reasons. A comparison with the recent requirements for radioactive waste repositories reveals that numerous criteria at the Asse II site are violated and that the underground embedding couldn't be licensed nowadays.

References

[1] Wieczorek, K., Rothfuchs, T., Förster, B., Heemann, U., Olivella, S., Lerch, C., Pudewills, A., Kamlot, P., Grupa, J., Herchen, K. (2009): Coupled Processes in Salt Host-Rock Repositories, Final Report of Work Package 3, THERESA project, Deliverable D9, Commission of the European Communities, Brussels

[2] Bechthold, W., Smailos, E., Heusermann, S., Bollingerfehr, W., Bazargan Sabet, B., Rothfuchs, T., Kamlot, P., Grupa, L, Olivella, S., Hansen, F.D. (2004): Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS-II Project), EUR 20621, Commission of the European Communities

[3] Minkley, W., Mühlbauer, J. (2007): Constitutive models to describe the mechanical behavior of salt rocks and the imbedded weakness planes, 6th Conference on the Mechanical Behaviour of Salt (SaltMech6) - Understanding of THMC Processes in Salt Rocks, Hannover, May 2007

[4] Minkley, W. (2009): Final Disposal in Rock Salt and Barrier Integrity, Keynote on salt formations, Conference "Impact of THMC-processes on the safety of underground radioactive waste repositories", Luxembourg, September 2009

[5] AkEnd (2002): Recommendations of the AkEnd-Committee on a Site Selection Procedure for Repository Sites, Final Report, December 2002

[6] BGR (2006): Endlagerung radioaktiver Abfälle in Deutschland - Untersuchung und Bewertung von Regionen mit potenziell geeigneten Wirtsgesteinsformationen, Hannover/Berlin, August 2006

[7] GRS, BGR, DBE TEC (2008): Überprüfung und Bewertung des Instrumentariums für eine sicherheitliche Bewertung von Endlagern für HAW - Projekt ISIBEL, Final Report, April 2008

[8] Kamlot, P., Günther, R.-M., Stockmann, N., Gärtner, G. (2007): Modelling of strain softening and dilatancy in the mining system of the southern flank of the Asse II salt mine, 6th Conference on the Mechanical Behaviour of Salt (SaltMech6) - Understanding of THMC Processes in Salt Rocks, Hannover, May 2007

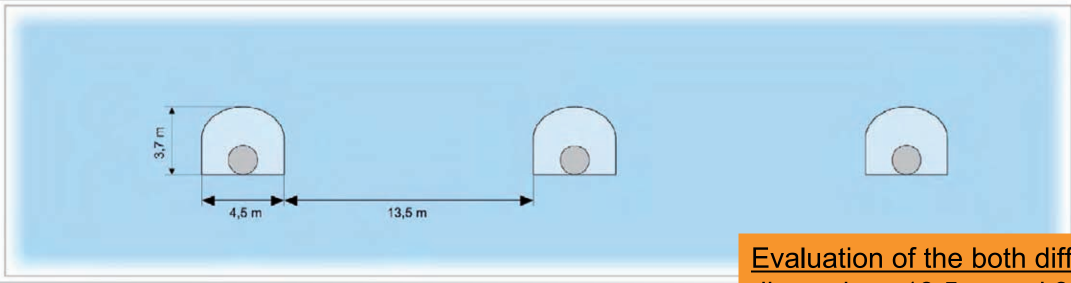
Geomechanical Layout and Barrier Integrity of a Rock Salt Repository

Dr. Peter Kamlot, IfG Leipzig

IfG

- Layout of emplacement drifts and panels
- T-M coupled model calculations of two different stratifications and barrier thickness recommendations for a repository in rock salt
- Current geomechanical situation in the Asse II mine, assessment on the basis of numerical modeling
- Prognosis and work to be done in Asse II in the next years

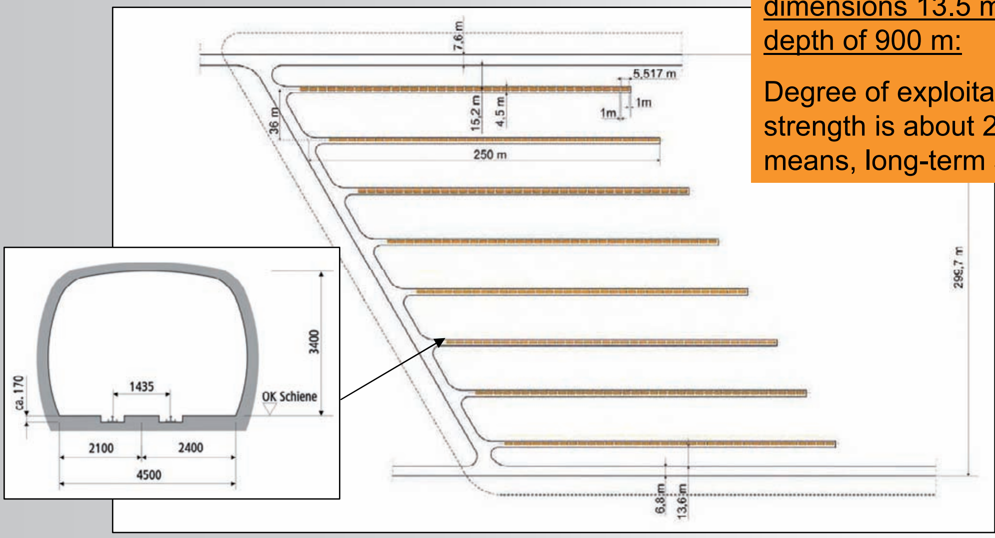
IfG



Reference:
DBE 2005

Evaluation of the both different pillar dimensions 13.5 m and 31.5 m in depth of 900 m:

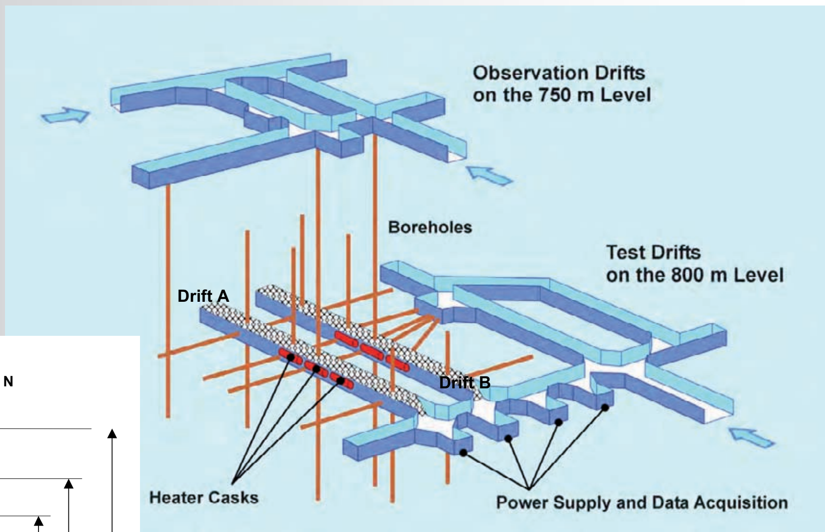
Degree of exploitation of pillar strength is about 20 % and lower. It means, long-term stability is given.

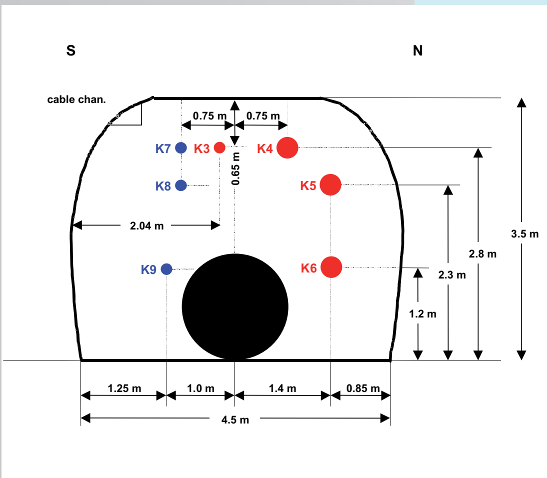


Reference:
"ISIBEL", GRS, BGR, DBE-Tec, 2008

Recommendations for layout of emplacement drifts in rock salt

Reference:
"BAMBUS II", 2004





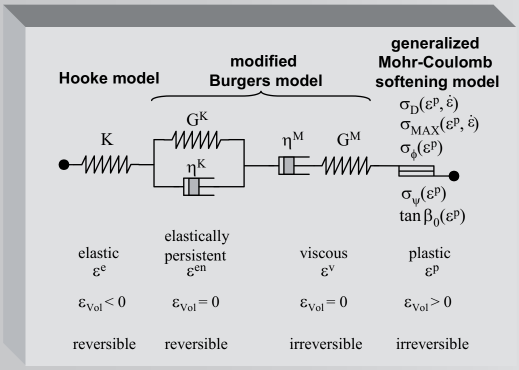
Assessment of thermo-mechanical coupled model calculations, supported by in-situ measurements:

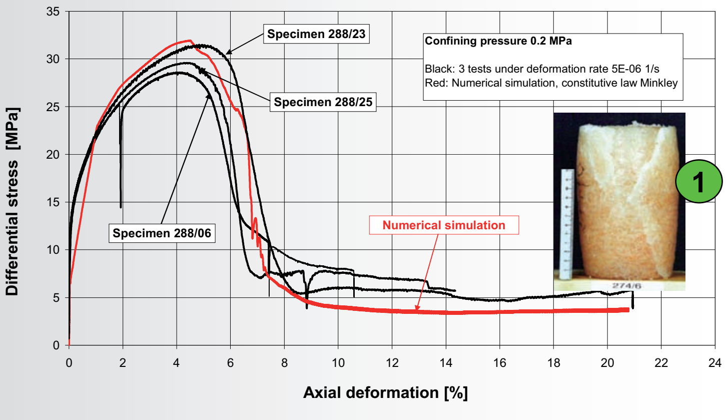
Even after 9 years of heating the degree of exploitation of pillar strength is about 20 %. Long-term stability is given.

Experiences from the BAMBUS-Project

- Layout of emplacement drifts and panels
- **T-M coupled model calculations of two different stratifications and barrier thickness recommendation for a repository in rock salt**
- Current geomechanical situation in the Asse II mine, assessment on basis of numerical modeling
- Prognosis and work to be done in Asse II in the next years

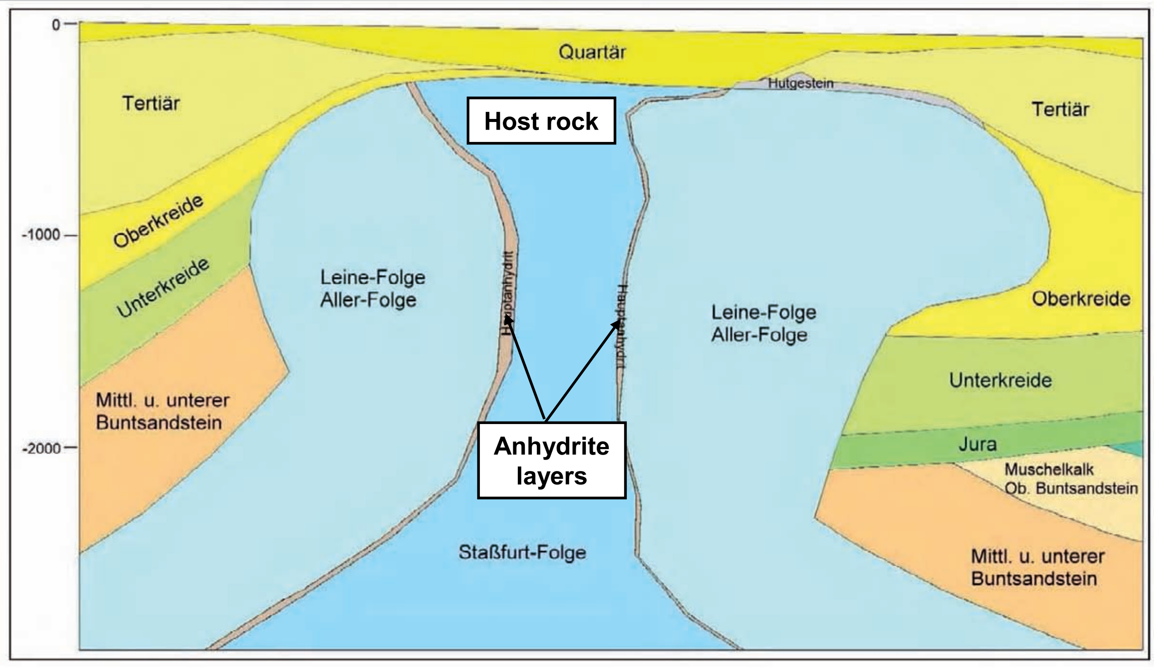
(1) Elasto-plastic softening model with dilatancy and creep



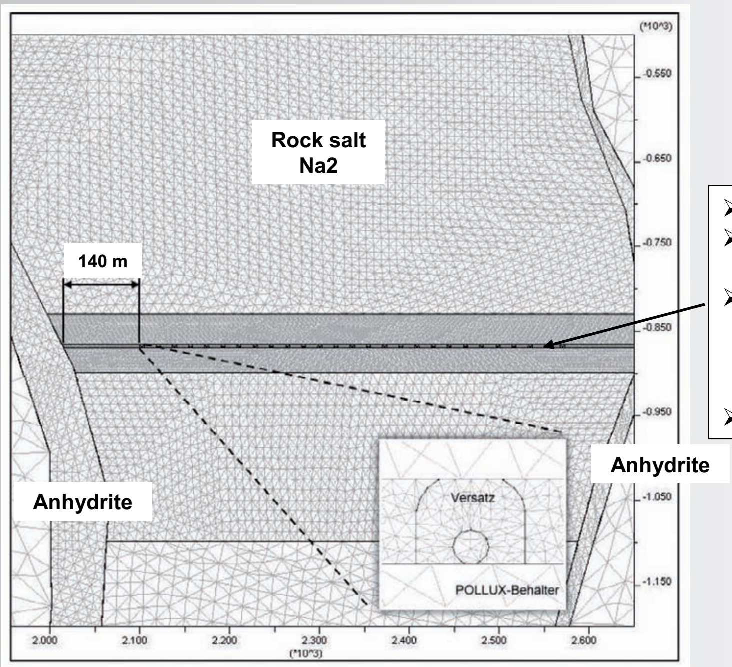


(2) Shear model for discontinuities and bedding planes with displacement/ velocity-dependent softening

Constitutive models for salt rocks and imbedded weakness planes

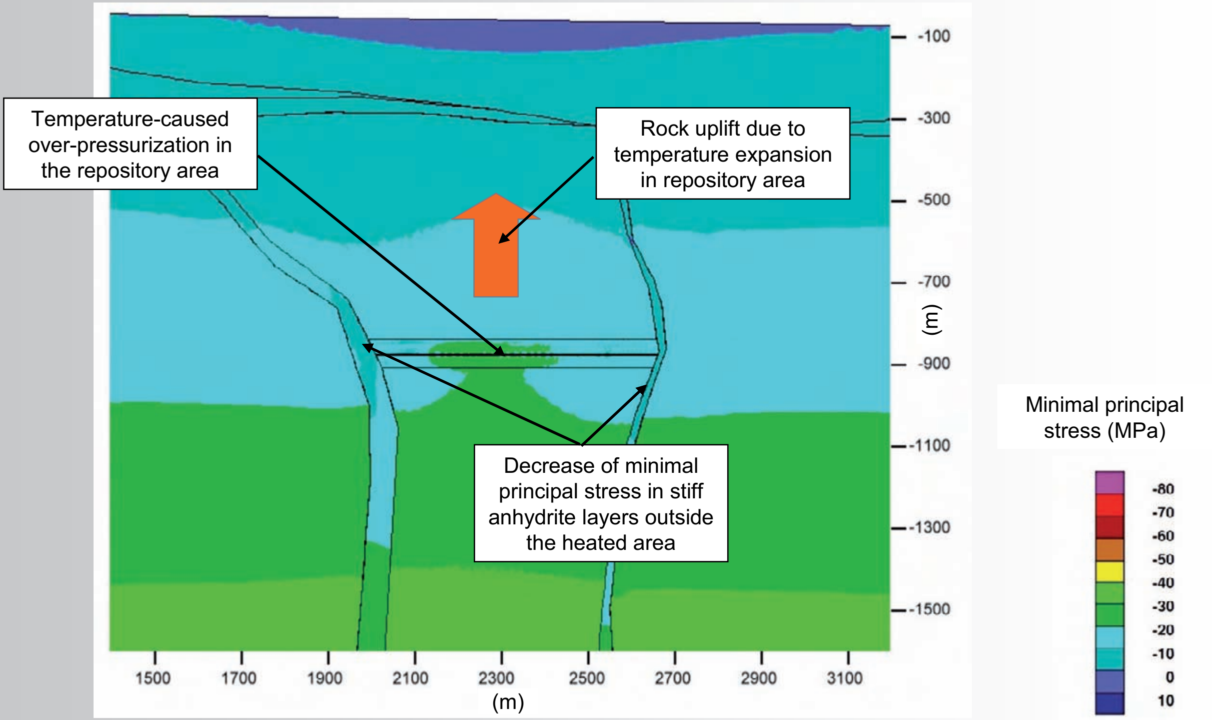


Geological cross-section through the reference-site "Salt dome" (Gorleben)



- Depth of emplacement horizon 870 m
- 22 backfilled drifts (perp. to model plane), height 3.7 m, width 4.5 m, pillar 13.5 m
- Material parameters and temperature boundary condition at POLLUX-containers in reference to project BAMBUS II
- Distance to anhydrite 140 m

Layout for T-M coupled model calculation ("Salt dome")



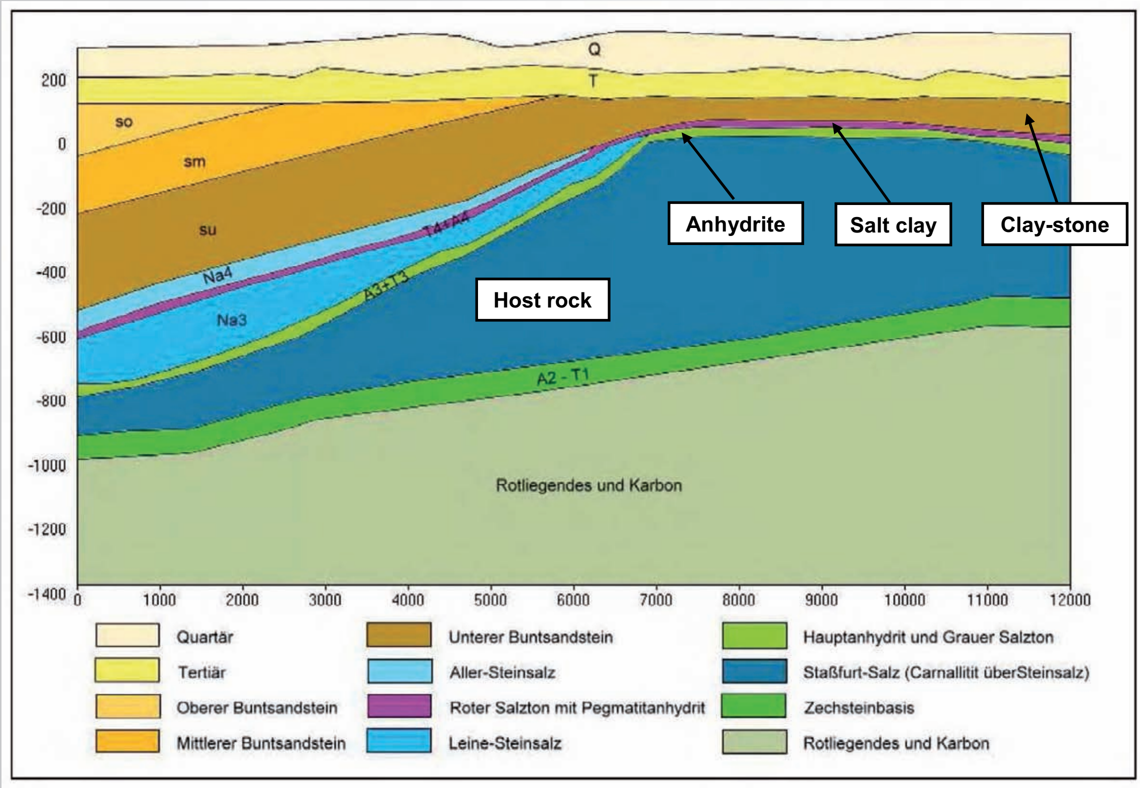
T-M coupled model calculation ("Salt dome"):
σ_{min} immediately after embedding

765

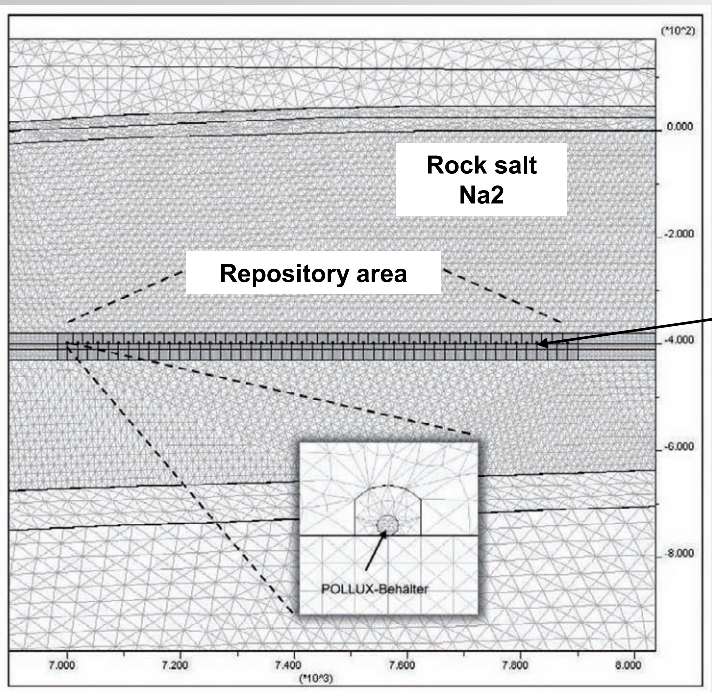
- **The thermo-mechanical coupled model calculations for the reference case "Salt dome" reveal a drop down of σ_{min} in neighbored anhydrite layers.**
- **Reason: The uplift of the heated rock salt leads in the model in the non-heated surrounding area to a slight stress decrease in the stiff anhydrite (there are no ability for creep).**
- **The stress and deformation state must be assessed by use of dilatancy and minimal stress criterion. Because of the high sensitivity the minimal stress criterion can reach the threshold.**
- **If anhydrite layers are separated into different blocks and cannot generate potential fluid flow pathways to the biosphere, the barrier integrity could be given nevertheless. A complex optimization of the repository layout (reg. geology, drift design, heat impact, barrier dimensions…) is necessary.**

Conclusions for reference-site "Salt dome"

766

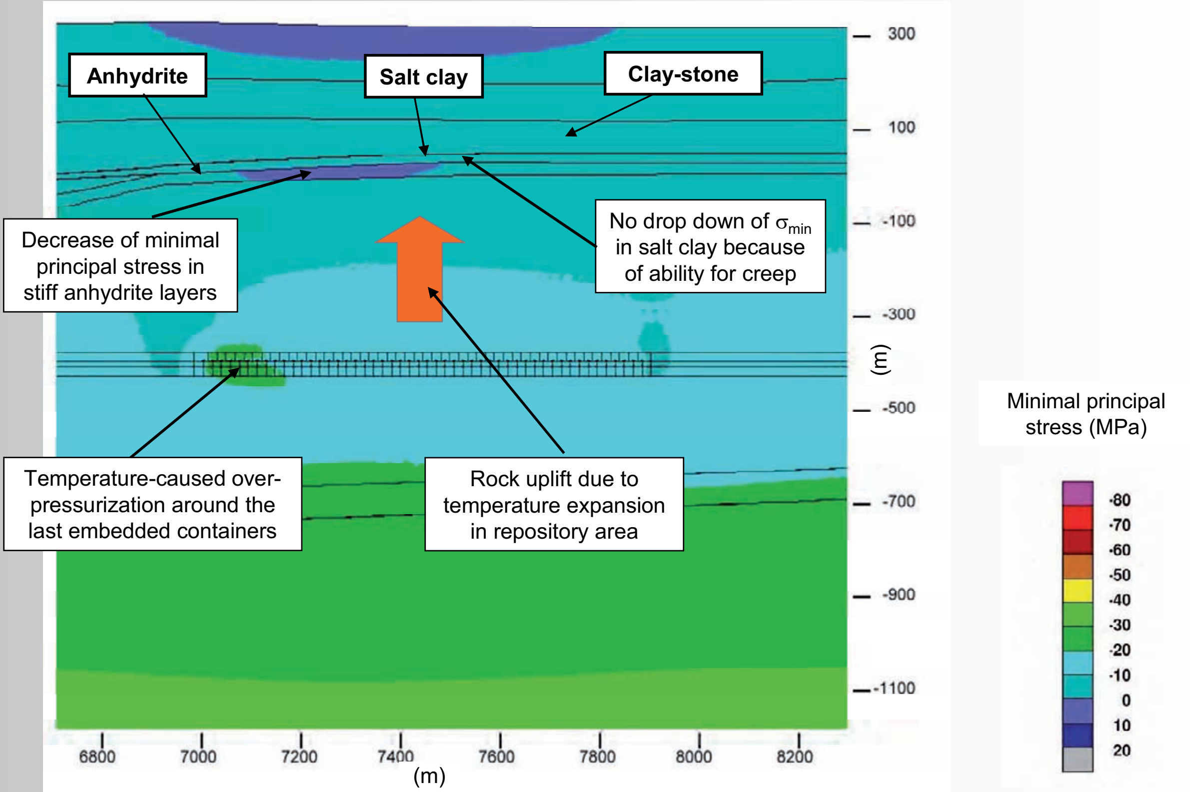


Geological cross-section through the reference-site
“Bedded salt” formation



- Depth of emplacement horizon 700 m
- 50 backfilled drifts (perp. to model plane), height 3.7 m, width 4.5 m, pillar 13.5 m
- Material parameters and temperature boundary condition at POLLUX-containers in reference to project BAMBUS II

Layout for T-M coupled model calculation (“Bedded salt”)



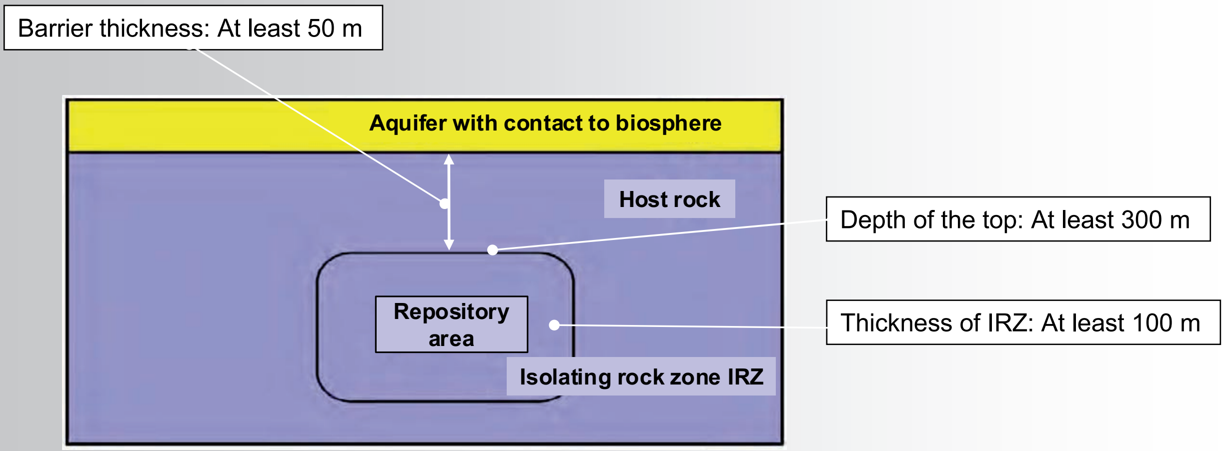
T-M coupled model calculation ("Bedded salt"):
σ_{min} immediately after embedding

769

- **The thermo-mechanical coupled model calculations for the reference case "Bedded salt" reveal a drop down of σ_{min} in the anhydrite layers above the repository.**
- **This follows from the rock uplift above the heated area.**
- **In anhydrite, due to the high sensitivity, the minimal stress criterion can reach the threshold.**
- **But, in the overlaying salt clay layers, a decrease of σ_{min} is not calculated because of creep behavior. If undisturbed, the clay layers could cover and protect the anhydrite.**
- **Again, for long-term assessment, a complex optimization of the repository layout (reg. geology, drift design, heat impact, barrier dimensions…) is necessary.**

Conclusions for reference-site "Bedded salt"

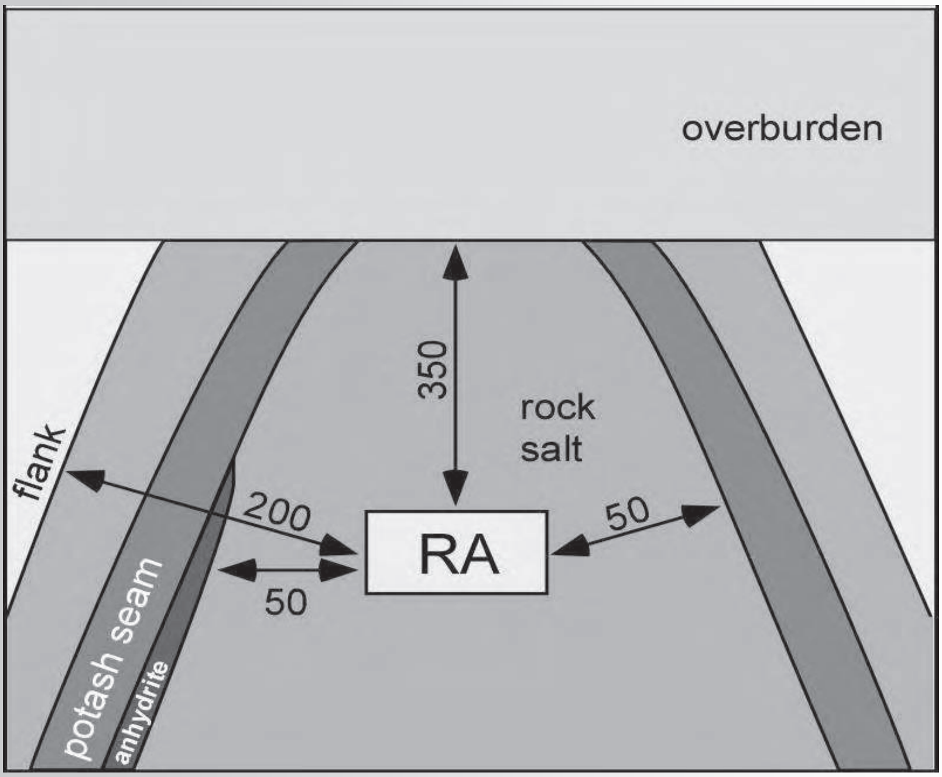
770



Reference: "Recommendations of the AkEnd – Committee on a Site Selection Procedure for Repository Sites", December 2002

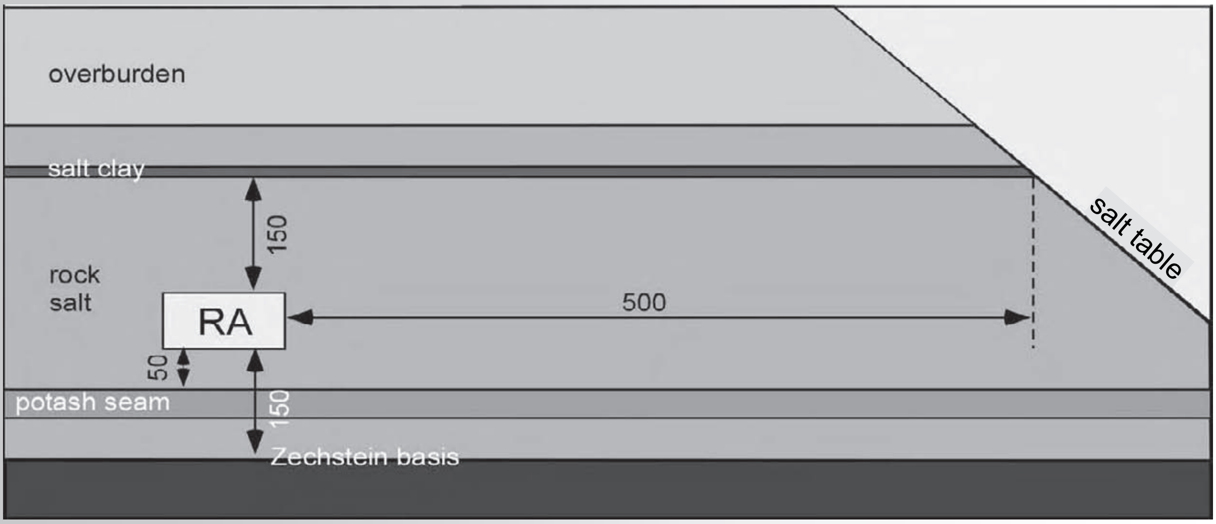
Recommendations of AkEnd regarding minimum requirements for the isolating rock zone (IRZ)

771



IfG-proposals for reference case "Salt dome" regarding distance to salt top, flanks, anhydrite/potash layers

772



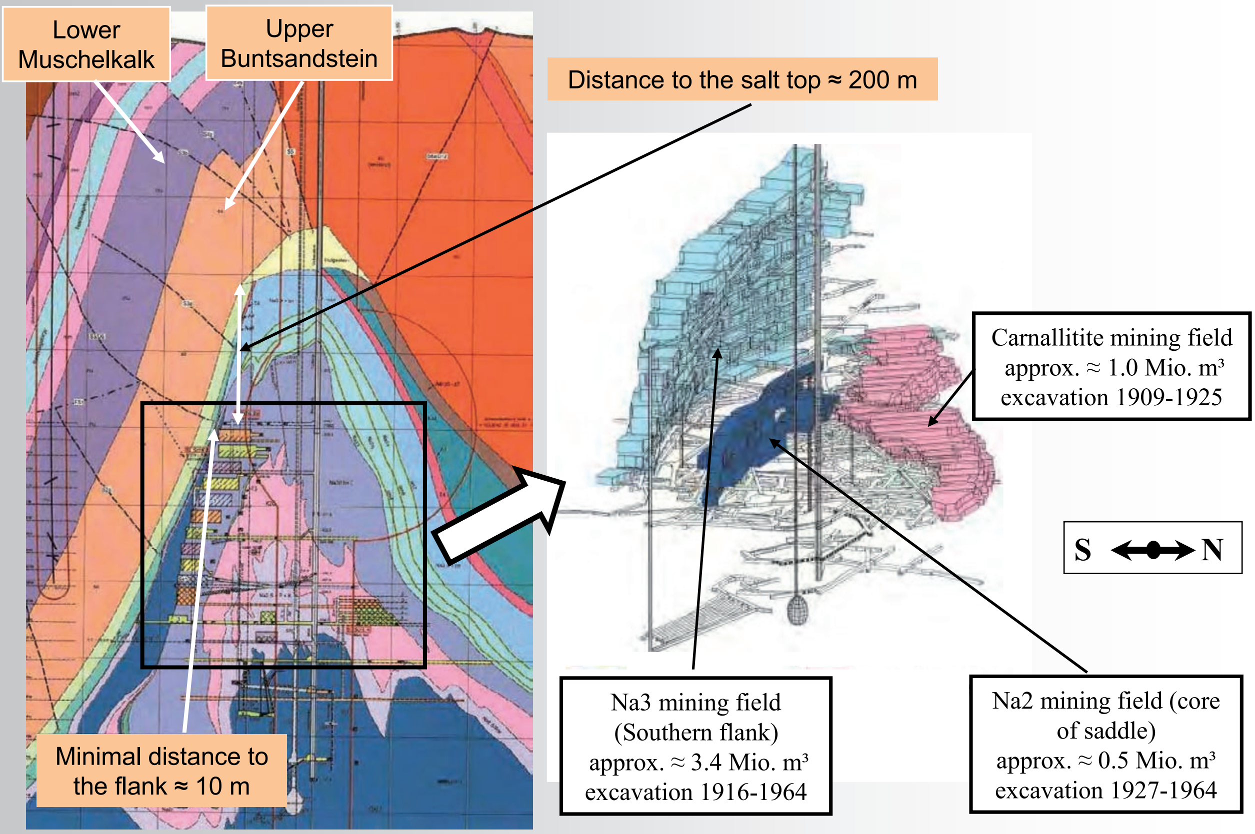
IfG-proposals for reference case "Bedded salt" regarding distance to top and basis of Zechstein, potash layers, salt table

- There are several recommendations and proposals for the barrier thickness in HAW-repositories (e.g. AkEnd, BGR, GRS, DBE-Tec, IfG …)
- These dimensions should be used for the preliminary site evaluation.
- An assessment must be elaborated in model calculations on basis of the dilatancy and minimal stress criterion.
- Site-dependent long-term assessment is indispensible.

Conclusions for barrier thickness

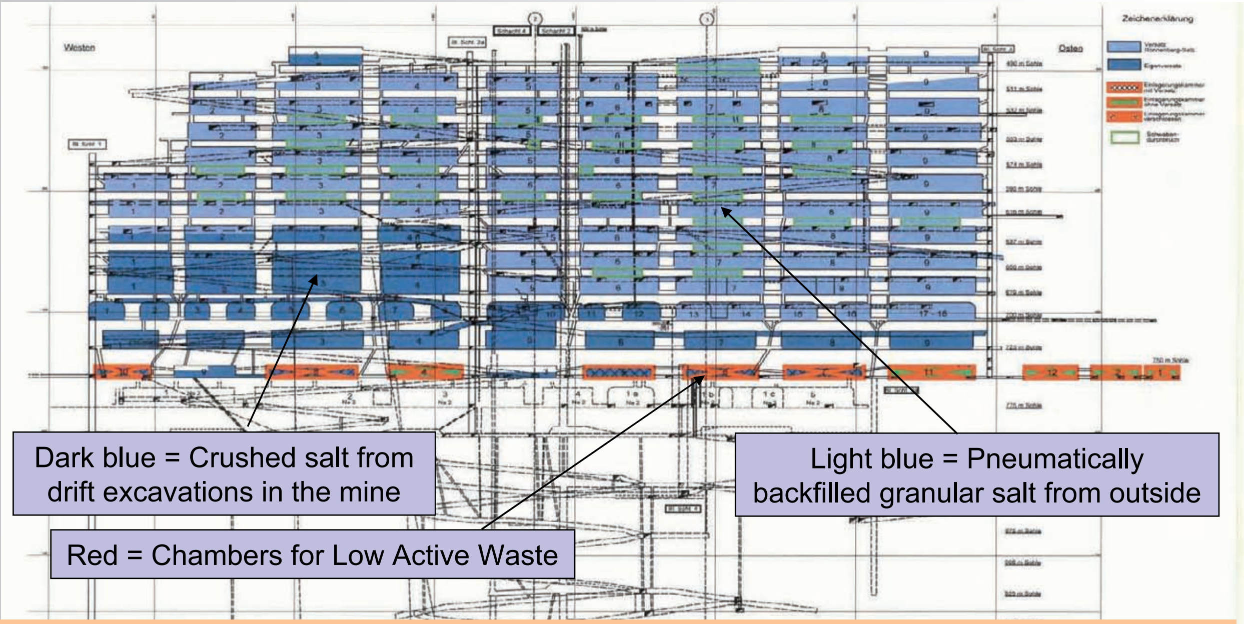
- Layout of emplacement drifts and panels
- T-M coupled model calculations of two different stratifications and barrier thickness recommendation for a repository in rock salt
- **Current geomechanical situation in the Asse II mine, assessment on basis of numerical modeling**
- Prognosis and work to be done in Asse II in the next years

775



Geological structure and mining fields in Asse II

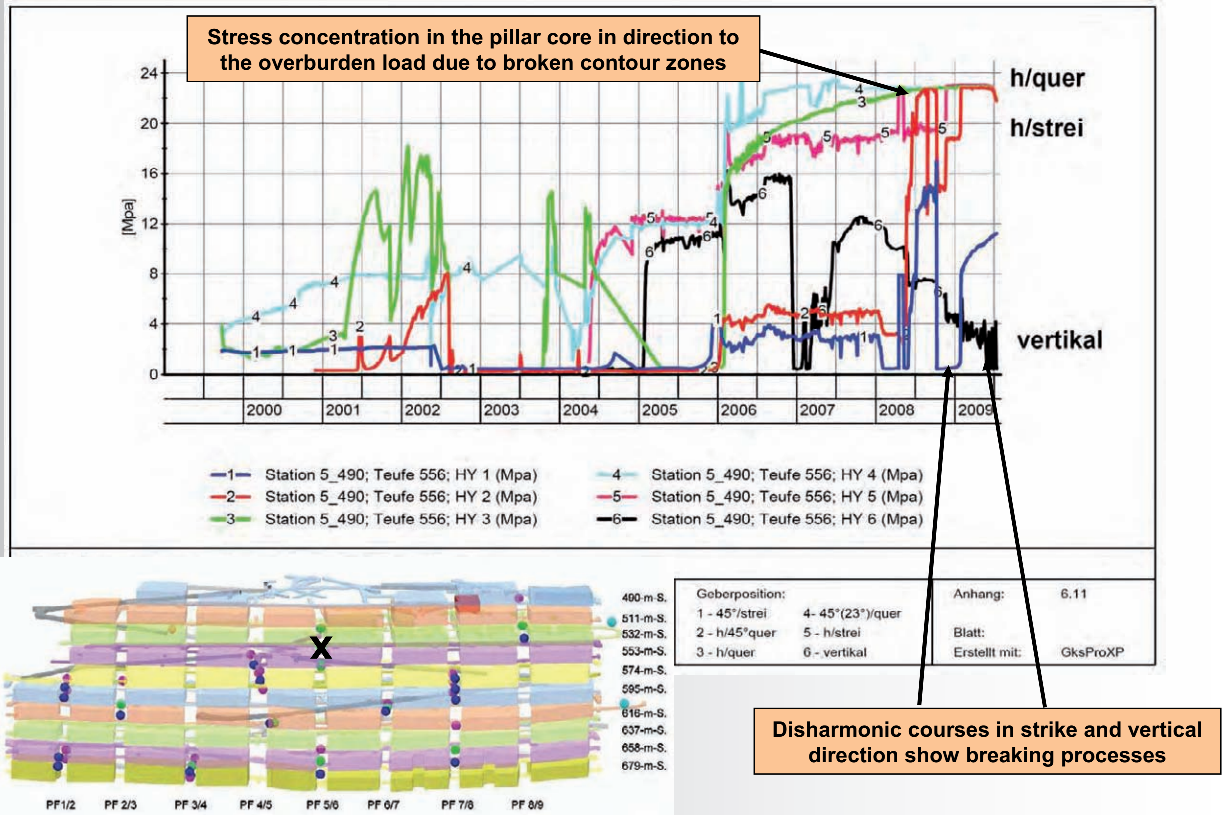
776



Evaluation of pillar dimensions (width 12 m, horizontal length against overburden load = 40 m):

The pillar strength (short-term strength) is exploited in the upper part and exceeded in the deeper levels. The system of pillars and stopes wasn't mined long-term stable. It was dimensioned only for a short phase of mineral extraction.

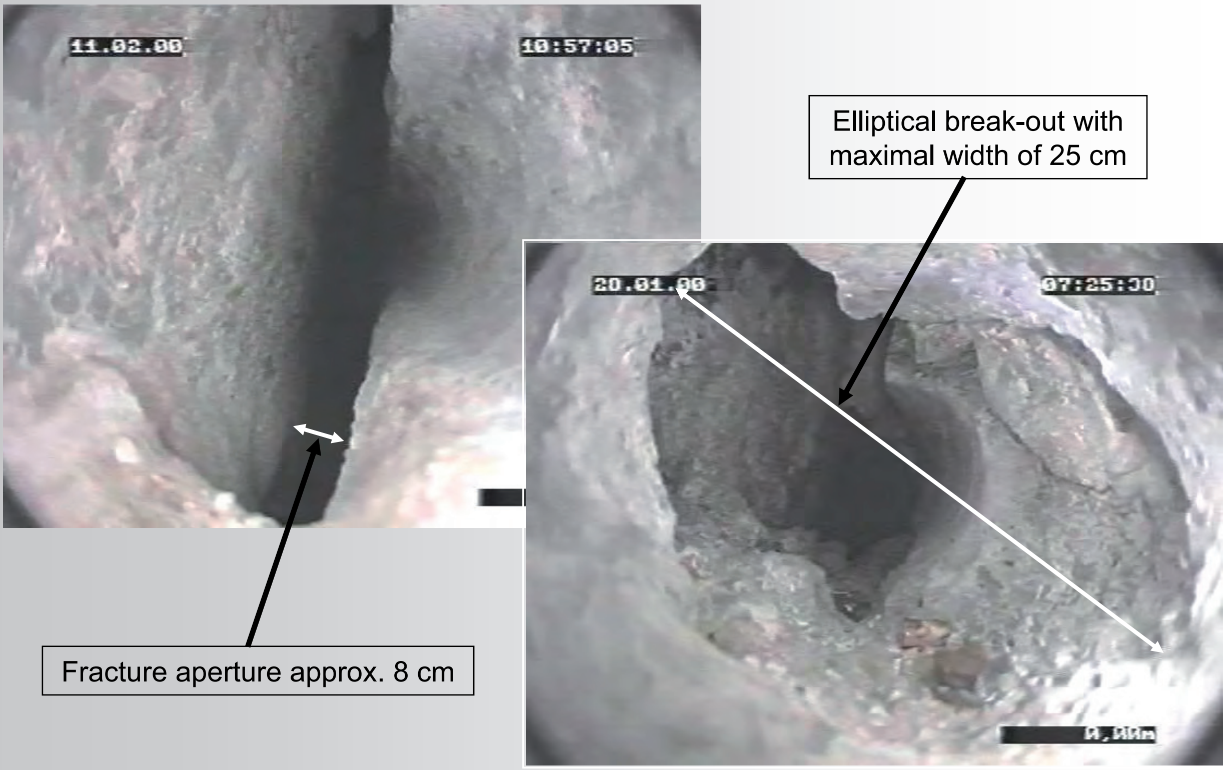
Geomechanical design of the Na3 mining field at the southern flank



Stress monitoring in different directions reveals pillar splitting: Pillar 5/6 in depth 556 m, middle of pillar across to strike, half height of stopes

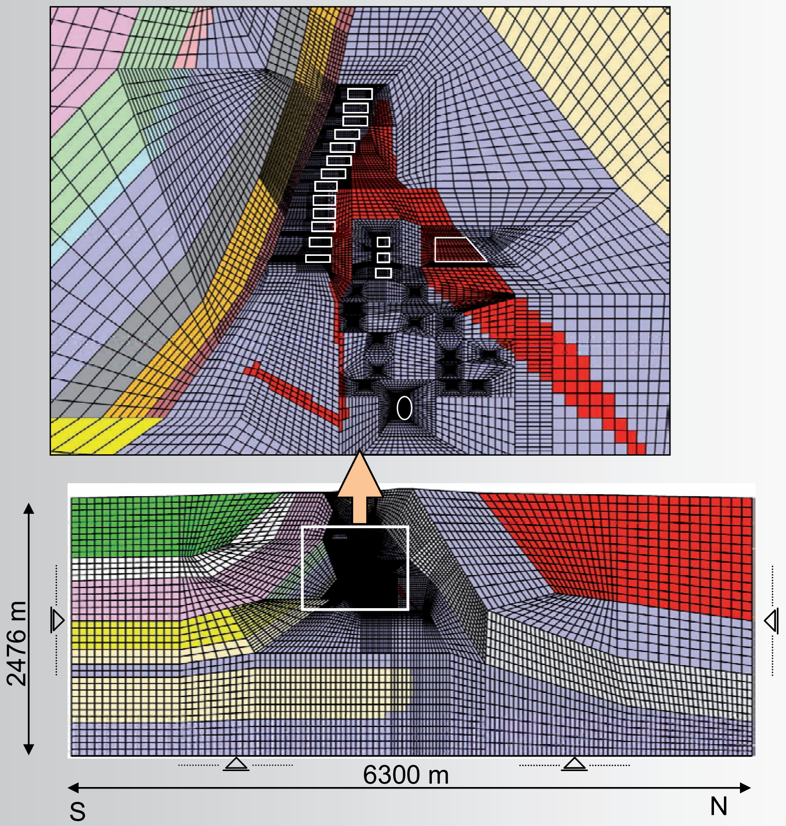
Broken stope between level 490 m and 511 m in pillar row 7, photo taken at 27.08.2003

779

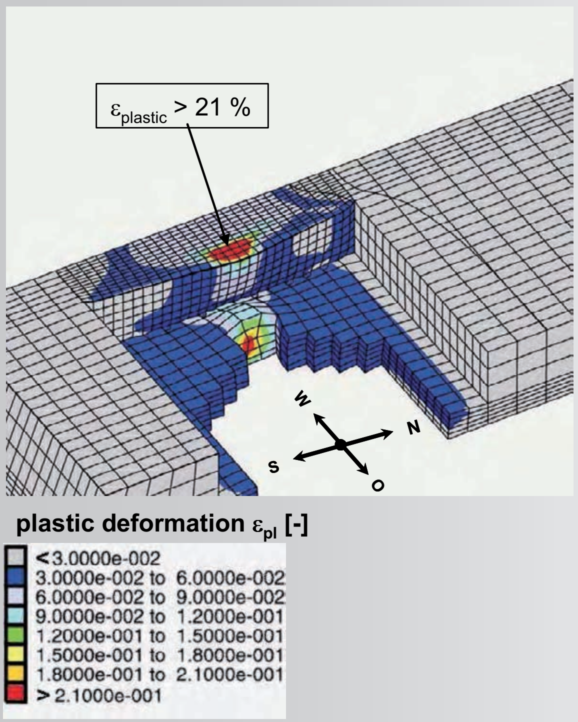


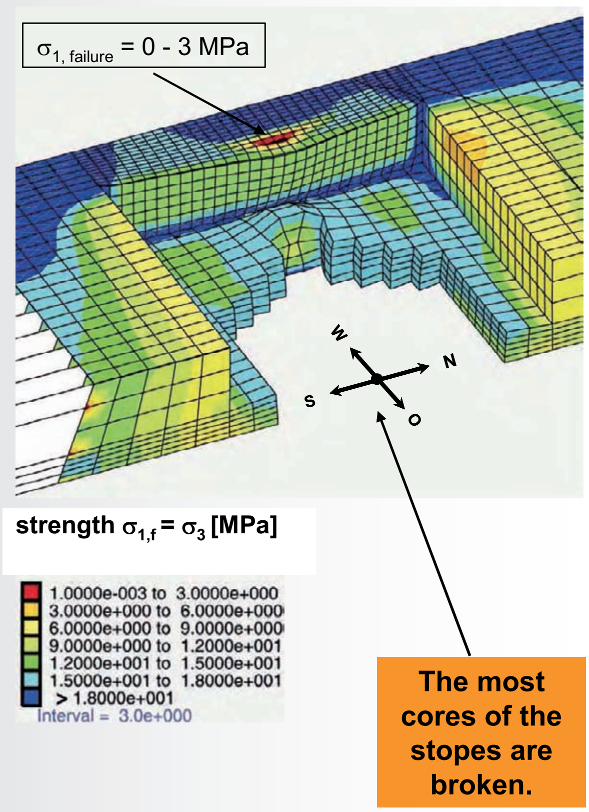
Open fractures and break-outs in pillar 3/4, depth 658 m, video inspection from January 2000

780

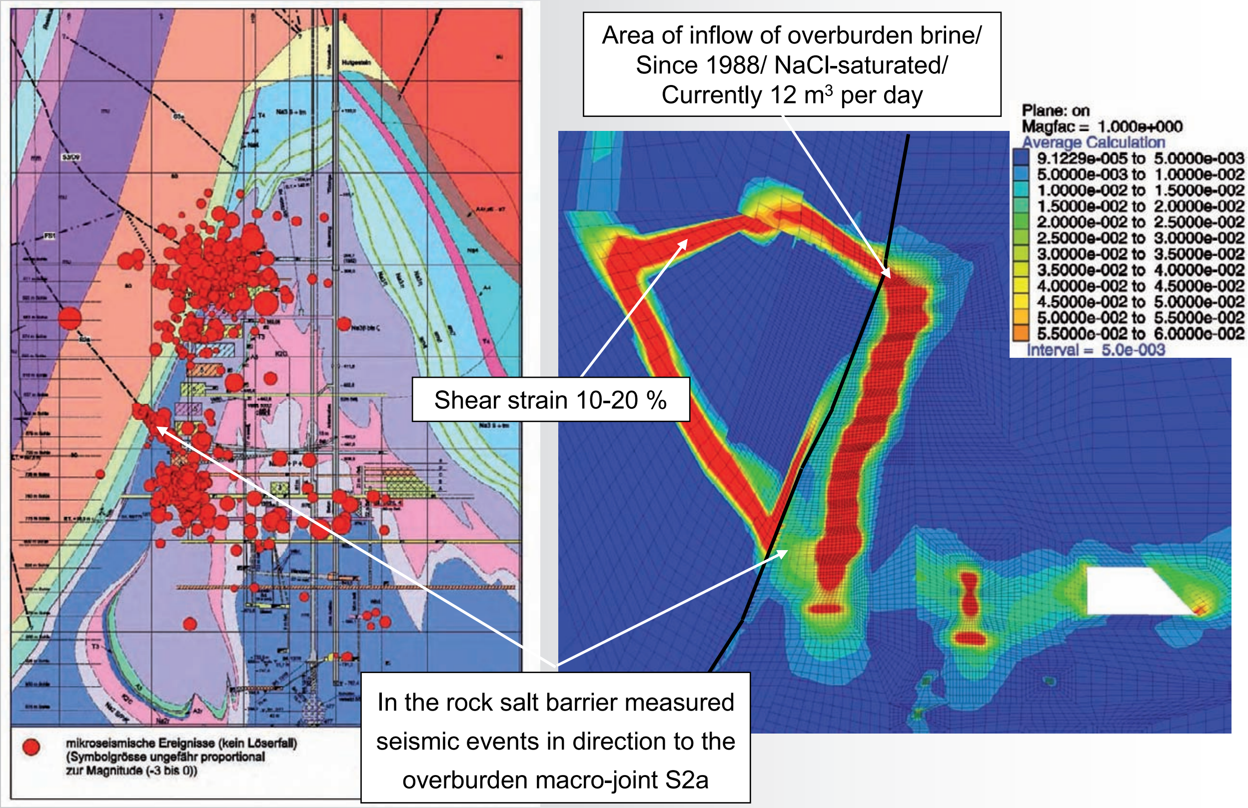


3D-calculation model: Location in the middle of the E-W extension of the mine. The dimension perp. to the sketch is 36 m





Recent plastic shear deformation (left) and strain softening (right) in the pillar-stope system. Horizontal cut in half height at level 574 m.



Left: Measured micro-seismic activity 2008 with magnitudes from -3 to 0, right: Calculated visco-plastic shear strain

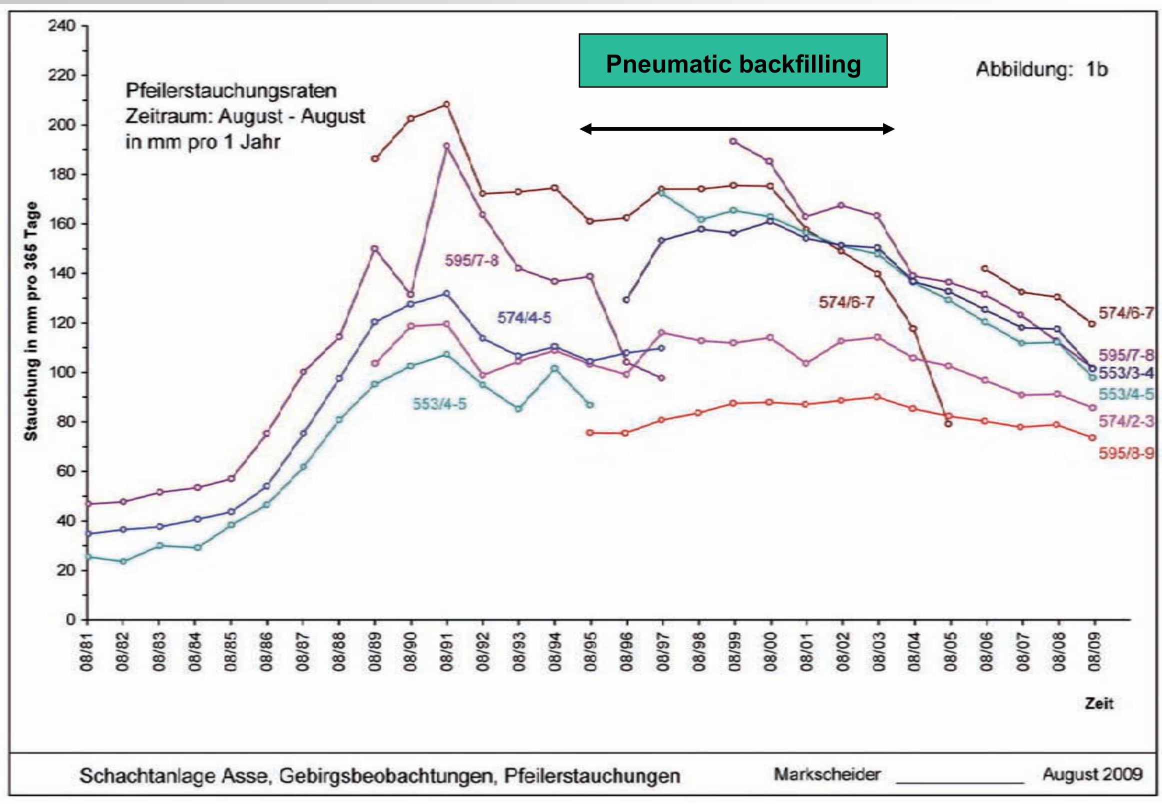
- **The contour fractures in pillars and stopes some decades after mining were assessed as usual. The convergences were assumed as regressively. No complex mine surveying was done.**
- **Higher bearing capacity of the southern overburden rocks and dry clay-stone rocks were presupposed.**
- **The high degree of separation in the Lower Muschelkalk and the aquifer-function were unknown.**
- **Source of brine inflow was seen in isolated reservoirs.**

With the current knowledge the Asse II mine would not get the certification for waste emplacement.

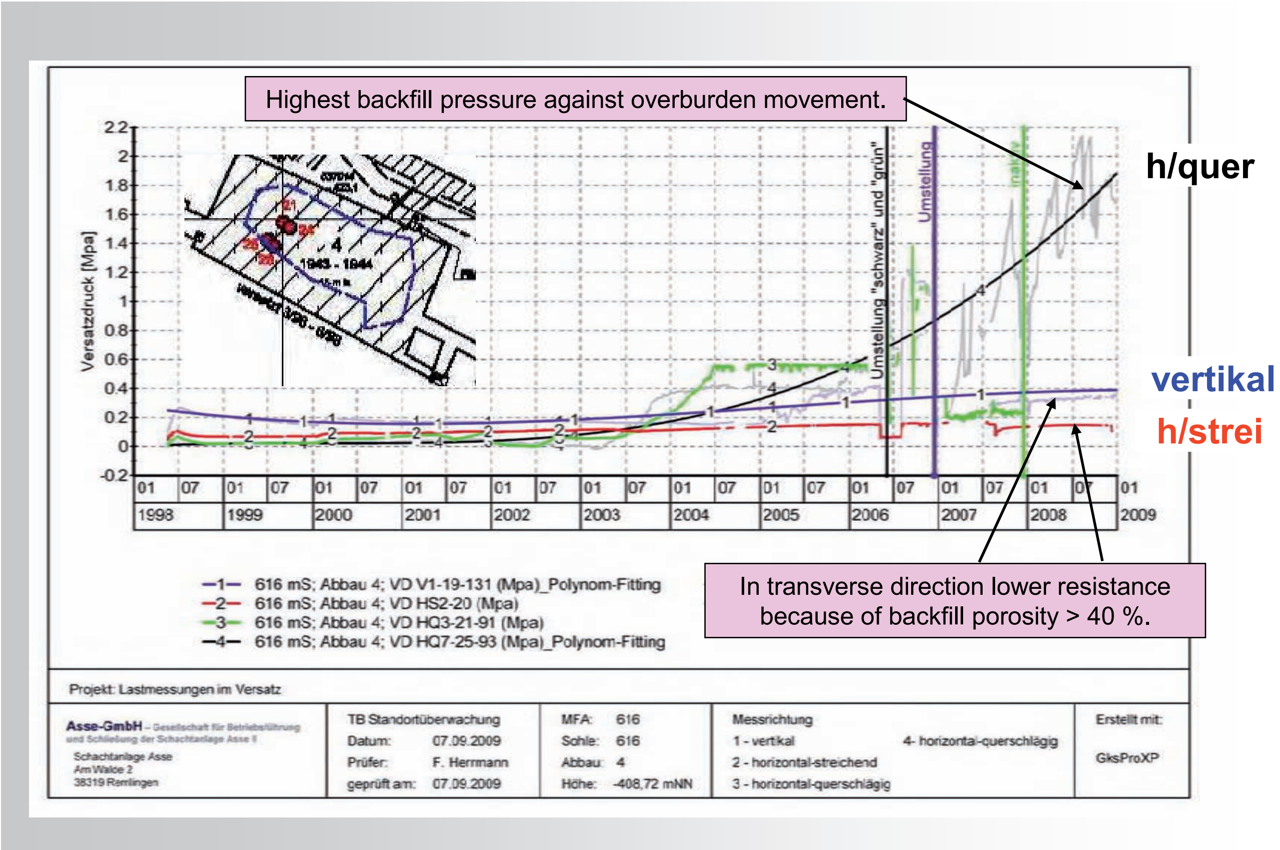
Asse II has nothing to do with a planned repository in rock salt in Germany.

State of knowledge (or assumptions) before permission of waste emplacement in the 1960s

- Layout of emplacement drifts and panels
- T-M coupled model calculations of two different stratifications and barrier thickness recommendation for a repository in rock salt
- Current geomechanical situation in the Asse II mine, assessment on basis of numerical modeling
- **Prognosis and work to be done in Asse II in the next years**

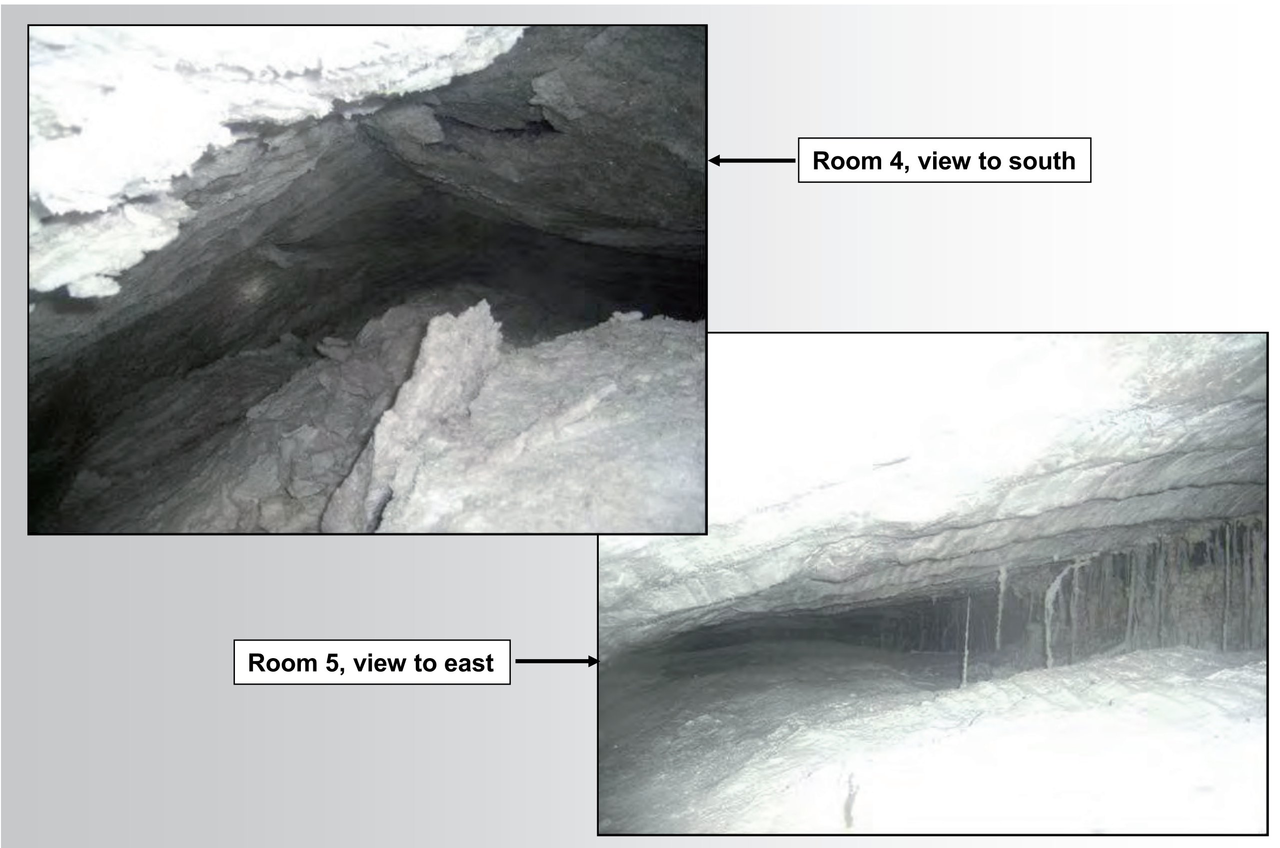


Decrease of pillar deformation rates due to backfilling, valid for pillars thickness of 40 m, levels from 553 m to 595 m



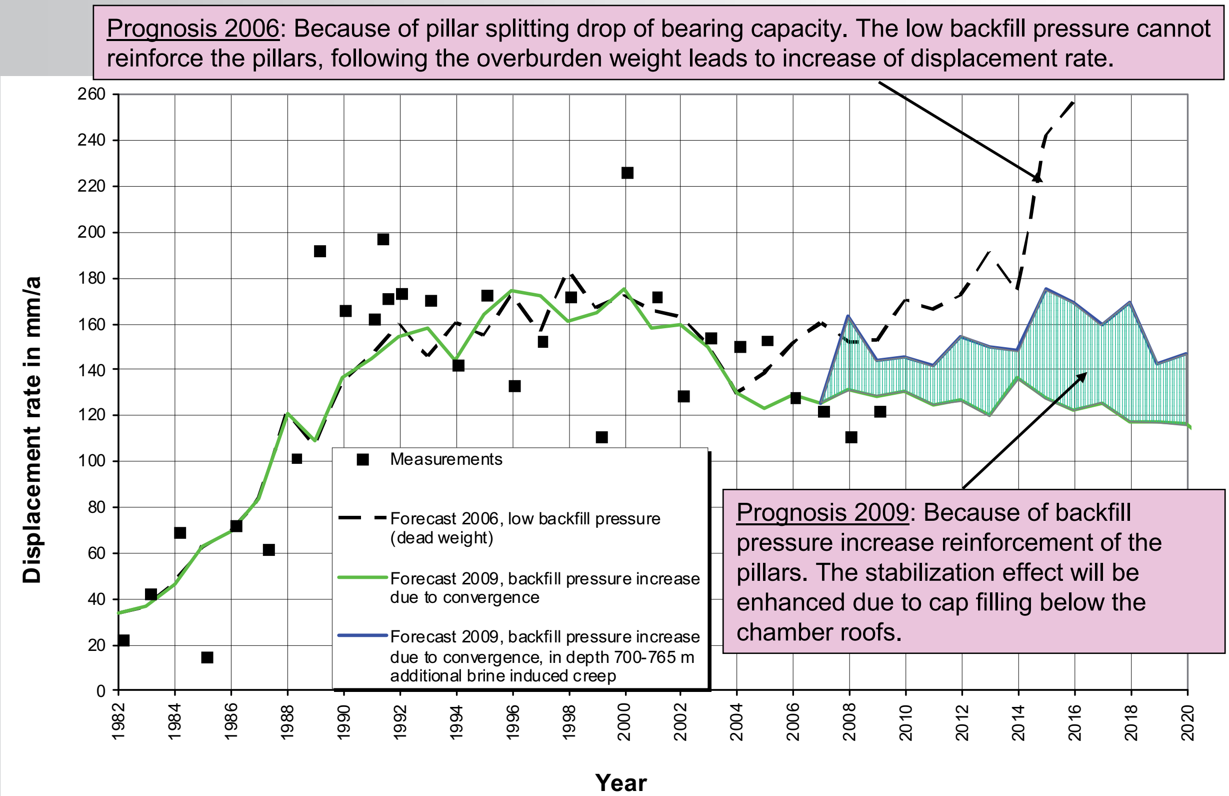
Backfill pressure increase due convergence, room 4 at 616-m-level

787



Open gaps below the roof at 700-m-level, photos taken at 04.12.2008

788



Model calculation of horizontal displacement rate
of southern overburden, depth level 553 m

789

- ➢ **The decision for retrieval was made as the best option in comparison to two others, but there are some reservations. It was not declared as final one.**
- ➢ **In 2 exemplary chambers the conditions of the barrels and in the emplacement rooms will be investigated using boreholes and later by opening. Only if the conditions let expect a safe removal and if the fracturing processes and brine inflow allow, all rooms will be opened.**
- ➢ **In every case, the stabilization of the southern flank on basis of cap filling in the rooms and backfilling of drifts proceeds. The stabilization is of vital importance and doesn't prevent the removal.**
- ➢ **On account of the permanent risk of brine inflow escalation an emergency concept with included provision measures is developed.**
- ➢ **The provision measures mustn't prevent a later safety-case, if the waste cannot be replaced completely. The relevance to the safety-case is investigated.**

Work to be done in the Asse II mine regarding
geomechanics and long-term safety

790

- The tools for assessment of geomechanical layout and barrier integrity are well developed. Now, in Germany it’s time for a site-dependent application.
- The Asse II is an old mineral extraction mine and has regarding to layout and barrier dimensions nothing to do with a new repository in rock salt.
- Therefore, the general conclusion that “*the disposal in salt is unsafe”* cannot be drawn.

Summary

THE GAS ISSUE IN SALT FORMATIONS – STATUS OF LABORATORY INVESTIGATIONS AND FIELD STUDIES

T. Popp & W. Minkley
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

Abstract

Understanding the transport properties of rock salt and their relationship to its mechanical behaviour is of vital importance for the design and safety analysis of underground cavities, in particular with respect to the long-term storage of heat-generating radioactive waste. The integrity of the geological barrier requires a sufficient tightness against fluids and gases which has to be guaranteed during the various stages relevant for performance assessment as schematically depicted in Figure 1, i.e. construction, operation and in the post-closure phase of a repository.

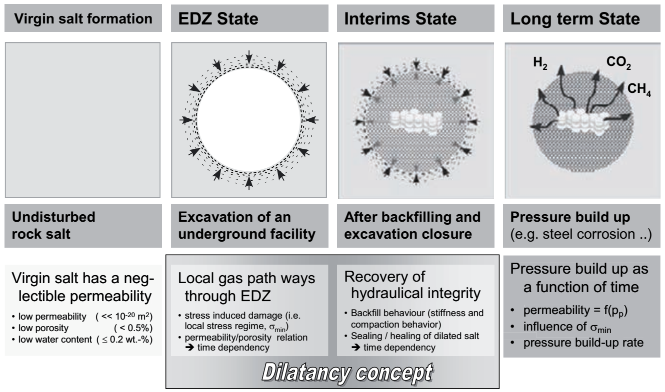


Figure 1: Gas transport issues in a salt repository related to the dilatancy concept. Note, that the dilatancy concept covers as well dilatant and sealing/healing processes inside salt as quantified by different permeability/ porosity relations depending on time and stress.

It becomes clear, that the competing processes of damage respectively compaction and healing affect not only damage-related near-field processes but also long-term effects, i.e. recovery of hydraulic integrity and subsequent gas transport as reviewed in [1, 2, 3], mainly basing on laboratory and field works:

(1) Rock salt in an undisturbed state is attributed to be impermeable for gases and fluids due to its low porosity and low permeability. During construction of underground openings in a rock salt formation, the change of stress state in the vicinity of these openings will affect the mechanical and hydraulic integrity of the surrounding rock salt by initiating local damage.

(2) Fluid flow through rock salt is mainly restricted to the excavation damaged zone (EDZ) (e.g. [1]). During the excavation of an underground opening, dilatancy and EDZ evolution start to take place without delay related to stress dependent property changes due to deformation induced stress re-distribution, i.e. onset of dilatancy, as it was demonstrated through permeability measurements in field tests and under laboratory conditions. From a geomechanical point of view the EDZ is well understood.
   - Based on sophisticated laboratory investigations with syn-deformational monitoring of various physical crack-sensitive parameters (e.g. permeability, volumetric strain, ultrasonic wave velocities) a comprehensive data base is available;
   - Verified rock mechanical models for predicting its initiation and evolution exist;
   - Permeability-porosity relationships depending on σ_{min} are available.

(3) In the post-closure phase (i.e. interim state) of the repository, when the loading conditions will change to non-dilatant, subsequent healing (probably due to fluid assisted compaction creep) will take place restoring at least the initial gas tightness of the salt. Recently the postulated healing capacity of salt was experimentally proven (e.g. [3]) but its time dependence and the relevant influence parameters (i.e. humidity) are actually not well understood.

(4) In the long term state, if the salt tightness is restored, it is usually assumed that due to the subsequent gas production a time dependent pressure build-up may occur until a level that may exceed the fracturing pressure of the rock (generally discussed as gasfrac-scenario). Therefore, the fundamental questions referring to a pressure build up in underground openings in salt are:

- How the host rock salt reacts on the gas pressure build-up, i.e. what is the influence of the pressure build-up rate and the minor principal stress?
- If a gas-frac becomes likely is there a potential self healing capacity, i.e. how efficient are such processes?

Regarding to these topics considerable progress has been obtained during the last 5 years as it is summarized in [4, 5]. For an assessment of the provable impact of increasing gas pressures on the integrity of rock salt new results from extensive lab and long term field testing are available (i.e. two long-term multi-stage injection - test duration up to five years – which were performed in the Bernburg salt mine (D) in gas-tight sealed boreholes, respectively hosted in the Stassfurt (representing domal salt) and the Leine salt formation (representing bedded salt);.

As outcome the general processes of pressure driven gas transport in salt rocks have been convincingly enlightened, whereby in lab and field tests qualitatively the same phenomena are observed but scale effect are obvious. The outstanding observation is that if the gas pressure approaches σ_{min} the further pressure increase is diminished for a wide range of gas injection rates, due to the coeval permeability increase at the gas threshold. This permeation process is independently from the amplitude of σ_{min}. The relevant incident is the order of permeability increase during the gas threshold, whereby the relationship k vs. differential stress $\Delta p = \sigma_{min} - p_i$ is empirically described with a hyperbolic tangent function. Only if the enhanced gas transport capacity of the surrounding salt is exceeded a further increase of pressure becomes likely (as confirmed by numerical simulations of the field tests) which could result in pneumatic fracturing if overpressures in the order of several MPa are reached.

However, in the field tests no pressure induced micro-seismic activity was observed during the gas-breakthrough which clearly contradicts the pneumatic gas-frac scenario at realistic pressurisation rates. We believe that only local widening of bottle-necks or linking-up of pre-existing pathways such as grain boundaries, causes the observed increase of permeability during the pressure threshold as may inferred from microstructural observations. This mechanism is generally described as “secondary permeability” which is not accompanied with a measurable increase in porosity.

Coevally with the permeability increase a pressure decay will occur in the reservoir resulting in a quasi-elastic closure of the prior opened path ways and thus to a recovery of hydraulic integrity. Because the observed permeability reversibility can be understood as “self sealing” this process may act as a “safety valve” if a gas pressure increase in salt occurs.

Beyond this, the self-healing capacity of rock salt is also convincingly demonstrated in the macro-scale of a natural analogue by the analyses of the post-gas-frac situation at the Merkers site (D) [4, 5]. After the disastrous event of barrier fracturisation due to CO_2-expulsion a time dependent recovery of the mechanical and hydraulical barrier integrity is demonstrated, at least partly during a short period of only 18 years. In addition, it has to be mentioned that as well the rock burst itself and the associated event of a gas-frac, and the subsequent healing could be simulated by the performed rock mechanical back-analysis of this scenario.

Evaluating the new experimental findings we can conclude that the gas-frac scenario resulting from an absolute tightness of rock salt becomes unlikely, which requires a new handling of gas pressure build-up in long-term assessments of a radioactive waste repository in salt formations. However, is pressurized fluids can permeate into the salt, for future proof of safe enclosure the distance and extent of the permeation zone must be proven which depends on the gas storage capacity of the salt, i.e. porosity and mean pore pressure. Aiming on these topics and for extension of the experimental scale a large scale injection test in a vertical gas-tight sealed bore hole (i.e. with a pressurized gas volume of $50m^3$) is actually under preparation in the Merkers salt mine (D).

Literature

[1] Rothfuchs, T., Wieczorek, K., Olivella, S. & Gens, A. (2003). Lessons Learned in Salt, Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the performance of radioactive waste geological repositories. European Commission CLUSTER Conference on the Impact of EDZ on the Performance of Radioactive Waste Geological Repositories. 3-5 November 2003, Luxembourg.

[2] Marschall, P., Cuss, R., Wiezorek, K. & Popp, T. (2008). State of the Art on Gas Transport in the Tunnel Nearfield / EDZ. NF-PRO-Report. RTDC4 – WP 4.4: EDZ long term evolution. Deliverable 4.4.1. 77 pages.

[3] Popp, T., Wiedemann, M., Kansy, A. & Pusch, G. (2007). Gas transport in dry rock salt – implications from laboratory investigations and field studies. In: M. Wallner, K.H. Lux, W. Minkley & H. R. Hardy. The Mechanical Behaviour of Salt – Understanding of THMC Processes in Salt: 6th Conference (Salt-Mech6), Hannover, Germany, 22–25 May 2007. Publ.: Taylor and Francis, ISBN: 9780415443982, 17 - 26.

[4] Popp, T., Minkley, W., Wiedemann, M. & Böhnel, H. (2007). Untersuchungen zur Barrierenintegrität im Hinblick auf das Ein-Endlager-Konzept. Ergebnisbericht zum UFOPLAN Forschungsvorhaben SR 2470.

[5] Popp, T. & W. Minkley (2008): Integrity of a salt barrier during gas pressure build-up in a radioactive waste repository - Implications from laboratory investigations and field studies. REPOSAFE - International Conference on Radioactive Waste Disposal in Geological Formations – Braunschweig, November 6 – 9, 2007. Conference Proceedings, 172-185.

The gas issue in salt formations

Status from Laboratory Investigations and Field Studies

T. Popp & W. Minkley

Institut für Gebirgsmechanik GmbH, Leipzig, Germany

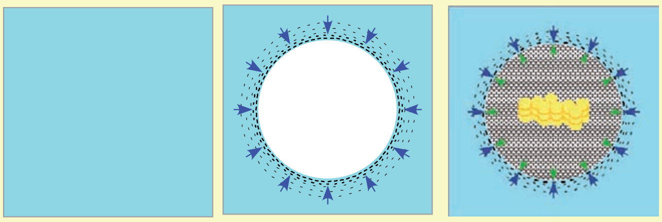
Outline

- Background
- Investigation approach
- Lab results
- Field test results
- Synthesis
- The natural analogue „rockburst Völkerhausen“
- Conclusions / Outlook

Gas transport issues in a salt repository

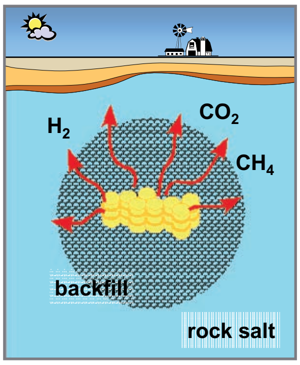
The dilatancy concept

Virgin salt	Initial - state	Transient state



Undisturbed rock salt - **nearly impermeable**	**EDZ - Excavation disturbed zone - local path ways**	**After backfill - Recovery of hydraul. integrity**

Long term

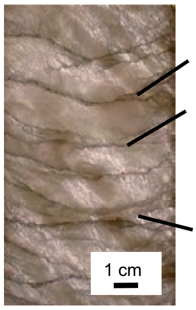


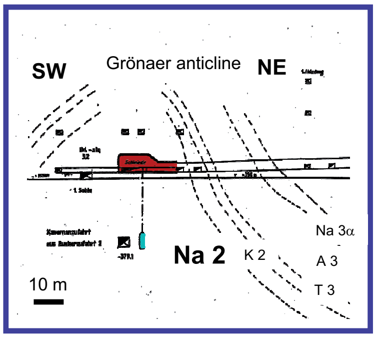
Gas production
- steel corrosion
- radiolysis
- bio-degradation

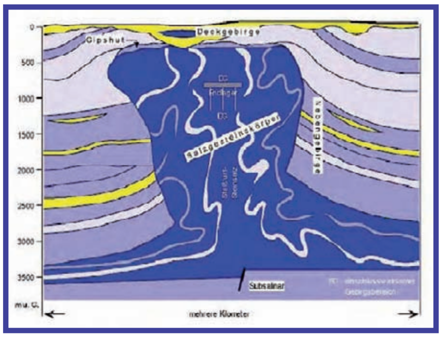
Gas pressure build-up with time
Gas-frac risk

- **Gas-frac risk probability:** How will the host rock react in the case of an increasing gas pressure ?
- **Recovery of barrier integrity:** If a leak has appeared by overpressuration can sealing- or healing processes take place ?

Investigation concept - Upscaling







Laboratory investigation – Scale (10 - 25 cm)

- ➔ **Relevant gas transport-mechanismen**
- ➔ **Representative parameters**
  - Porosity
  - Permeability
  - Capillary threshold pressure
- ➔ **Visualisation of fluid paths**
- ➔ **„Sealing/healing"**

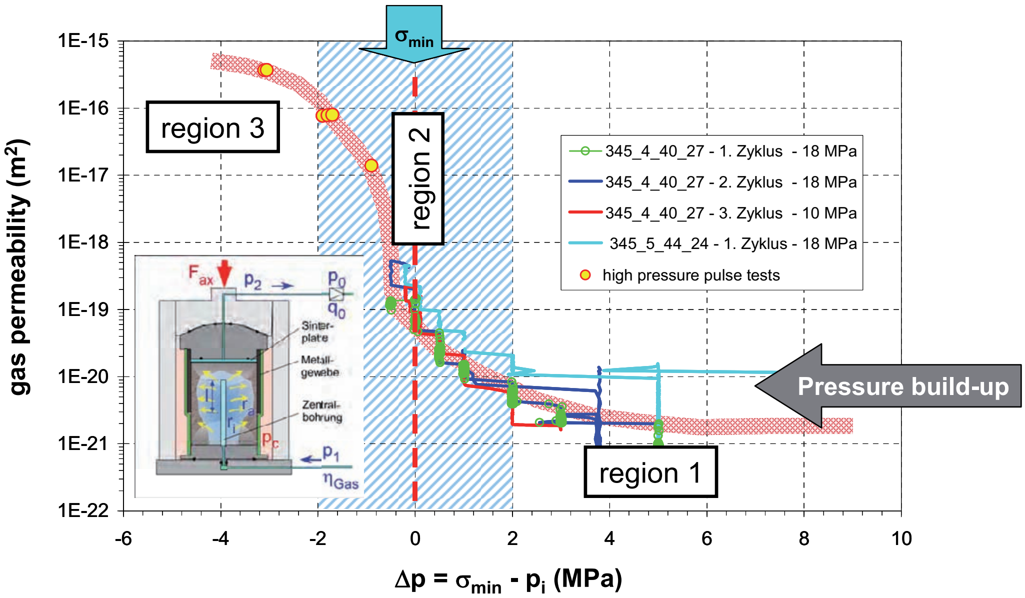
In-situ-field tests Scale (10 - 25 m)

- ➔ **Parameter determination ⇒ verification of the lab phenomena**
- ➔ **Gas injection / AE-monitoring**
  - Permeability
  - Fissure/crack detection
- ➔ **„Sealing/healing"**

Natural analogue ⇔ Modelling Upscaling (10 m - 100 - 1000 m)

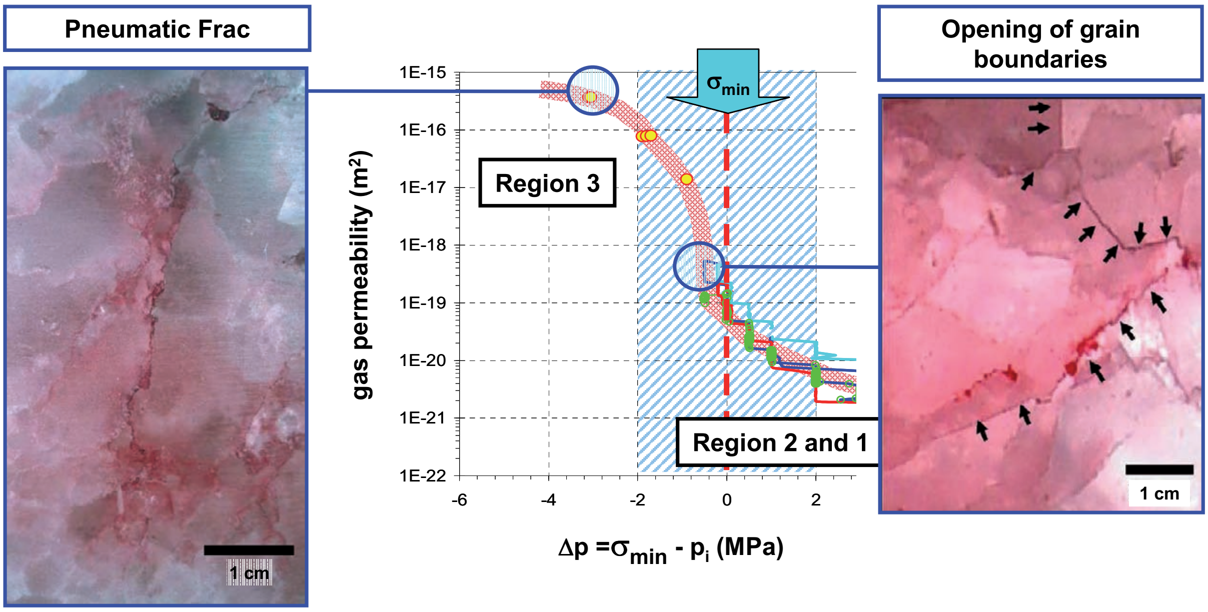
- ➔ **Parameter verification**
- ➔ **Scale relevant effects of gas transport mechanism**
- ➔ **Migration Scenario - Prognosis**

Lab test - gas injection at various σ_{min}



The permeability increase during progressive gas injection depends not on the absolute value of σ_{min} but on the difference between σ_{min} und p_{injekt} ⇒ Δp

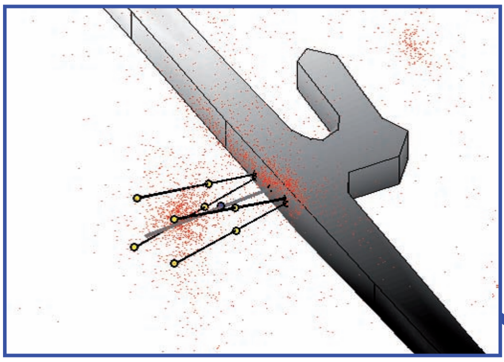
Microstructures - permeation or frac?

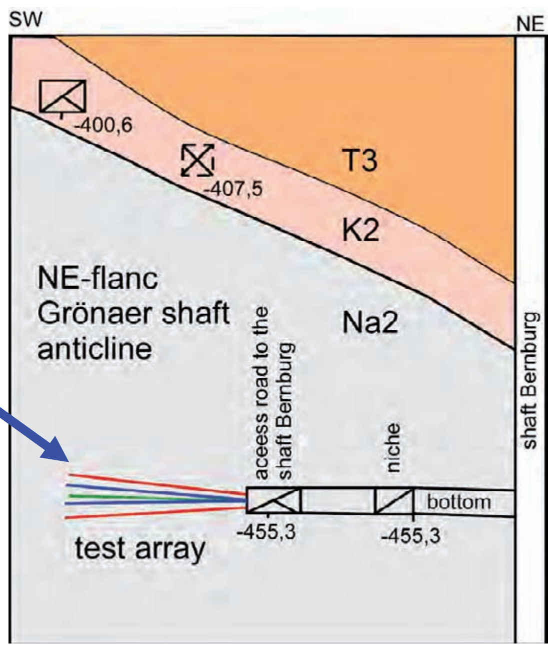


(1) and (2) Permeation ⇒ Opening of grain boundaries (reversible)

(3) Frac region ⇒ irreversible damage at $|\Delta p_i| > 2 - 4$ MPa

Layout of the in situ tests Bernburg



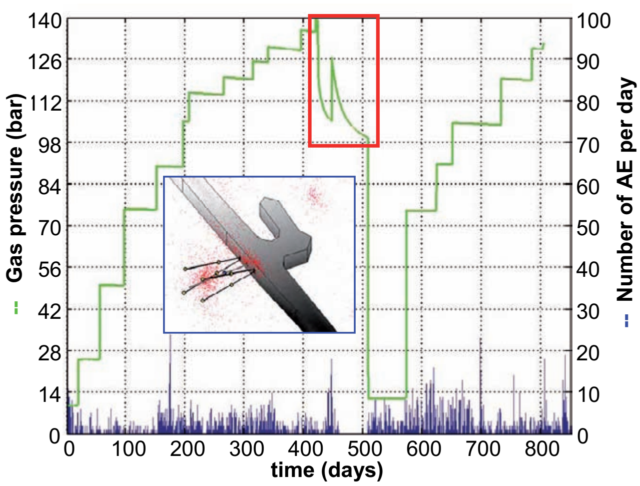


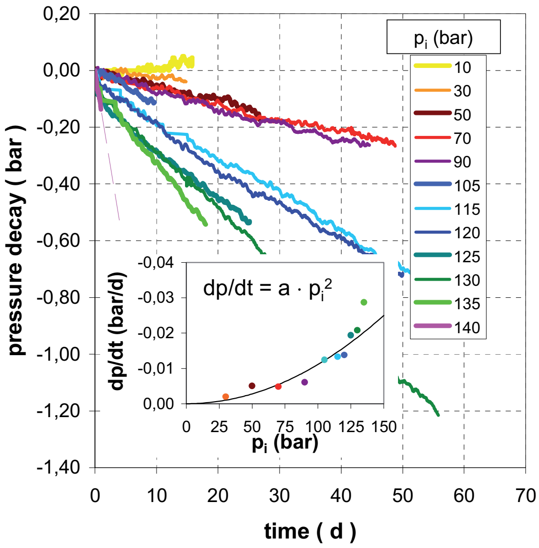
Bore hole Array (each 25 m long)

- 1x central injection bore hole (45 l gas volume, equipped with a tight packer)
- 4x observation bore holes to detect gas break through (parallel drilled with 1 m resp. 2 m distance)
- 4x bore holes as a microseismic monitoring system (funnel shaped drilled, each equipped with 2 seismic sensors)

Staßfurt rock salt (ca. 95% NaCl)
ca. 540 m depth ⇒ $\sigma_{lith} \approx 13$ MPa

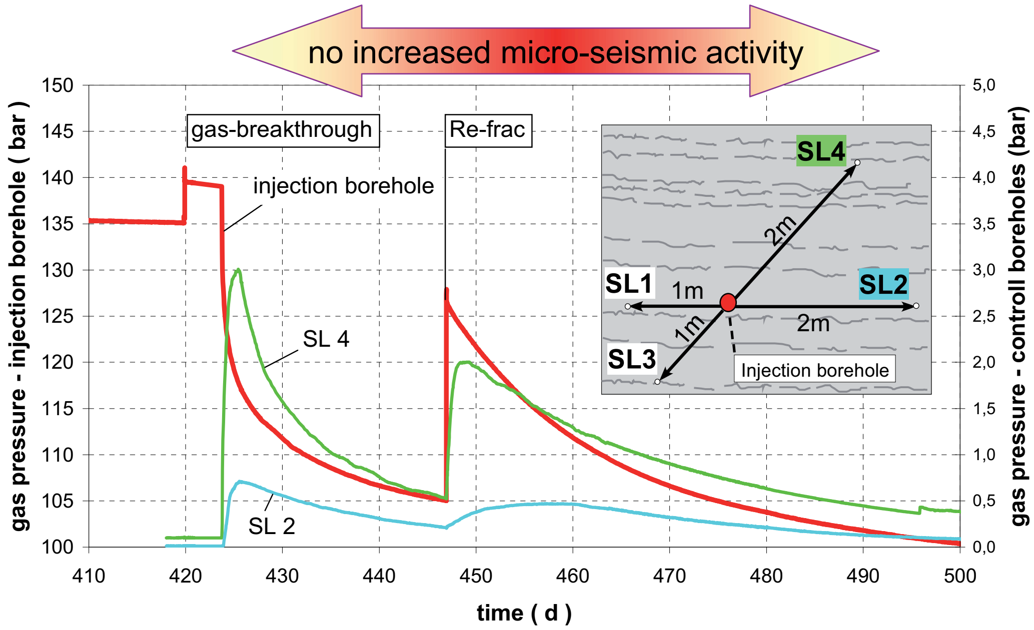
The in-situ gas injection test





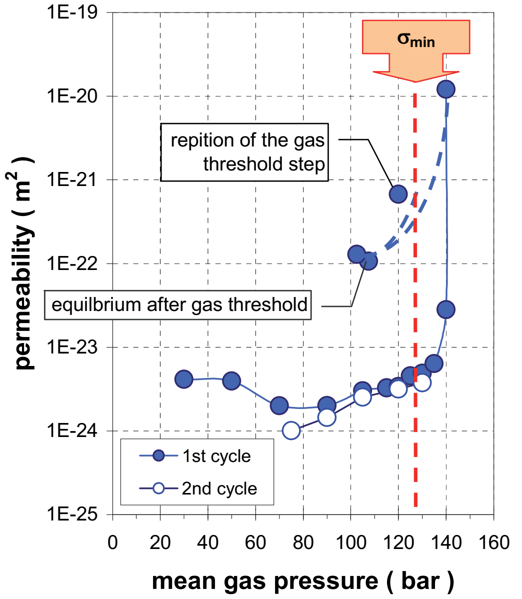
Pulse tests with stepwise pressure increase results in more or less Darcy conform single phase-gas outflow from the bore hole.

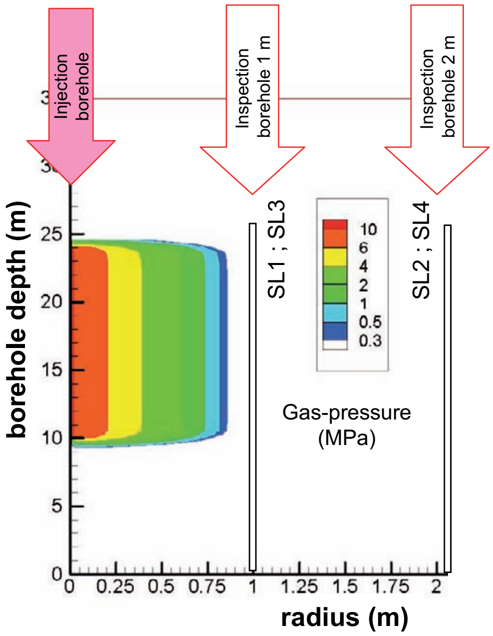
The gas break through at 140 bar



Spontaneous gas-breakthrough but self-stabilisation at a lower pressure level - Note the inhomogenous gas-flow

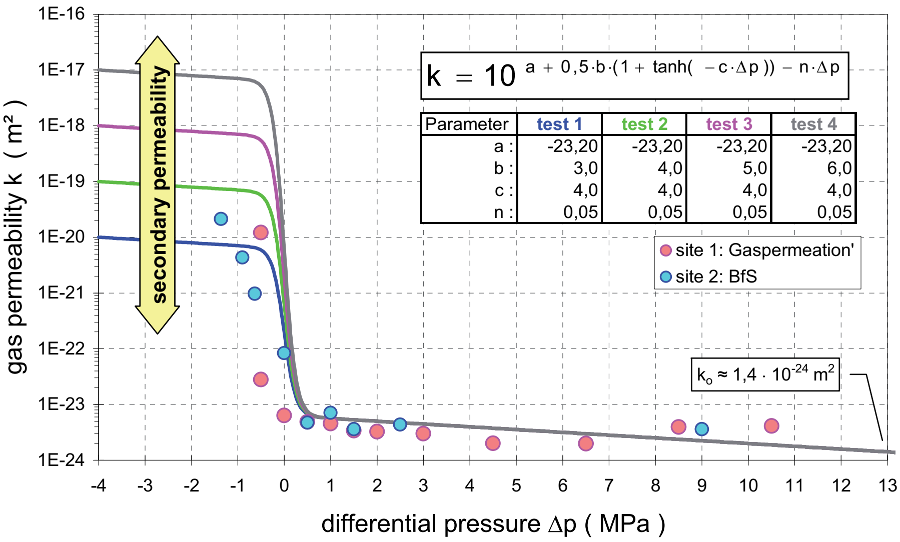
Hydraulical integrity during pressure increase





- **Permeability increases around 3 - 4 orders (almost partial reversible)**
- **Permeation zone of some meters but inhomogeneous gas spreading**

Numerical simulation of the gas injection tests

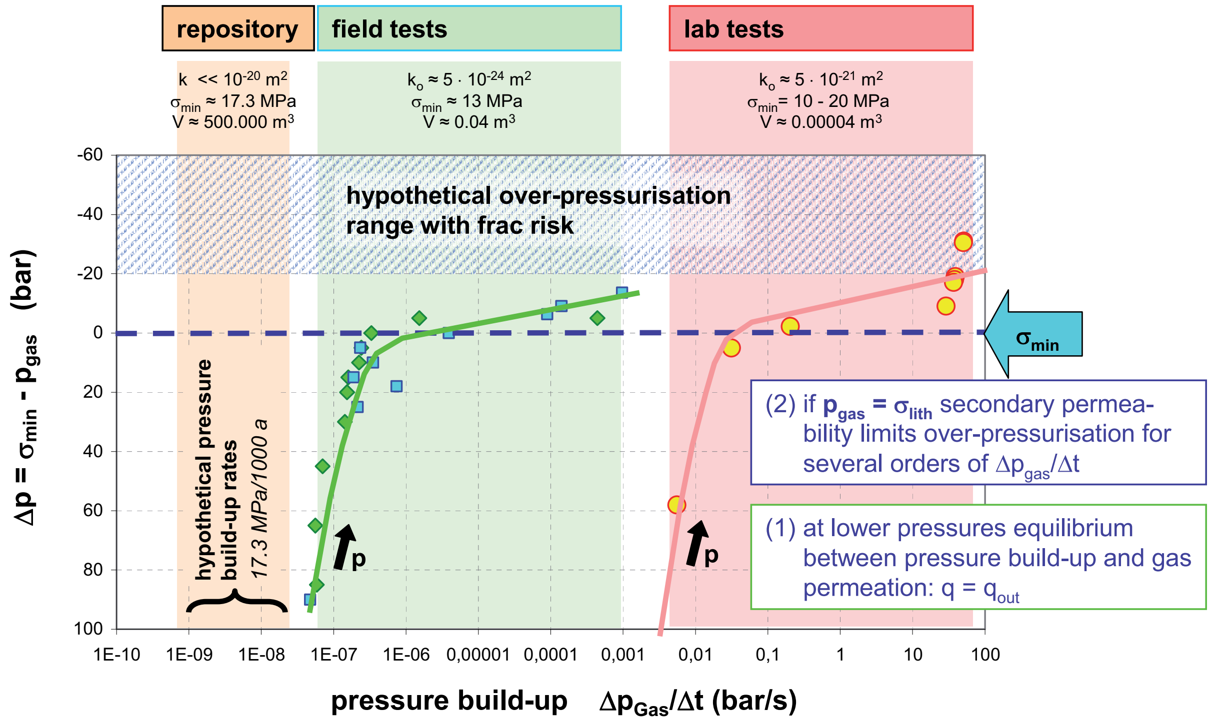


$$k = 10^{\,a + 0{,}5 \cdot b \cdot (1 + \tanh(-c \cdot \Delta p)) - n \cdot \Delta p}$$

Parameter	test 1	test 2	test 3	test 4
a :	-23,20	-23,20	-23,20	-23,20
b :	3,0	4,0	5,0	6,0
c :	4,0	4,0	4,0	4,0
n :	0,05	0,05	0,05	0,05

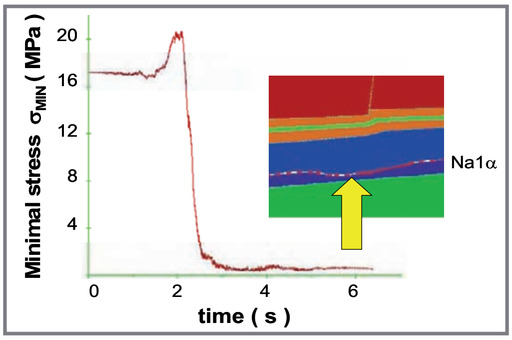
A reliable empirical relation based on a hyperbolic tangent function to describe the gas-pressure induced permeability increase related to the pressure difference is available.

Equilibrium gas pressures at various scales

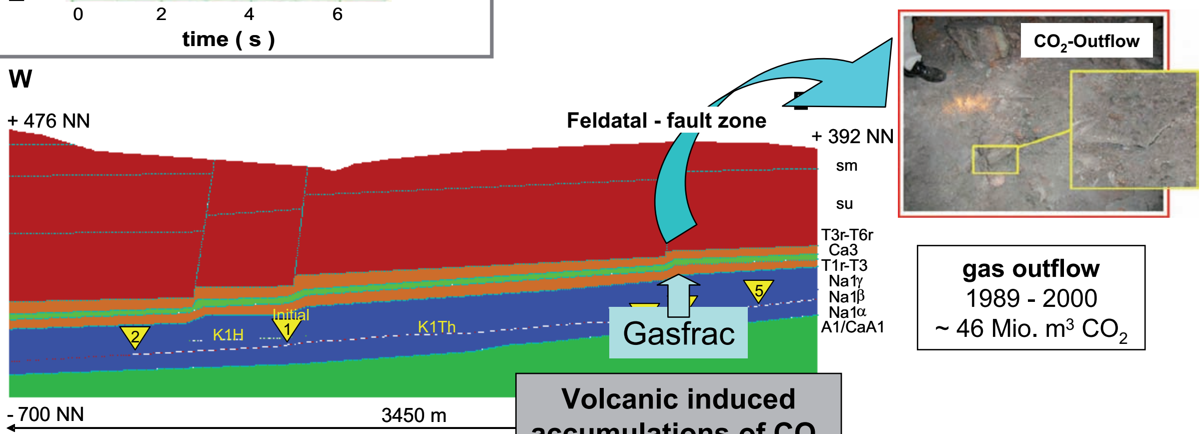


IfG **The gas issue in salt formations**
US-German Workshop on Salt Repository Research, Design, and Operation, May 26-28, 2010 - Gulfport Mississippi USA

Rock burst Völkershausen - Natural gas-frac analogon



As a consequence of the local rock burst Völkershausen 1989 an gas breakthrough of CO_2 occurred in the lower rock salt barrier in the salt mine Merkers due to the unloading of the upper mine parts.



gas outflow
1989 - 2000
~ 46 Mio. m³ CO_2

Volcanic induced accumulations of CO_2 (p_{gas} ≈ 7.5 MPa)

IfG **The gas issue in salt formations**
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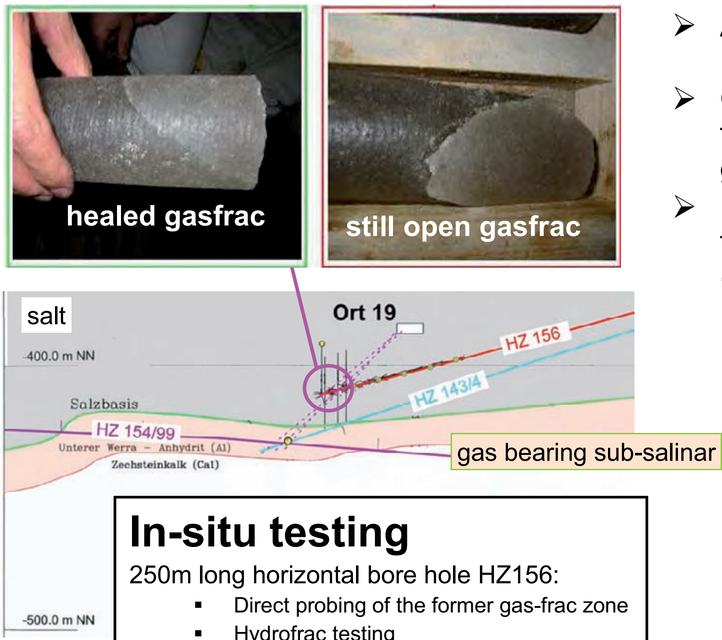
Recovery of barrier integrity after 18 years

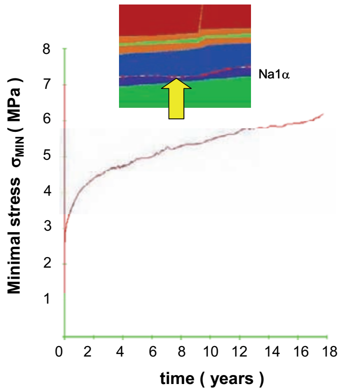


In-situ testing

250m long horizontal bore hole HZ156:

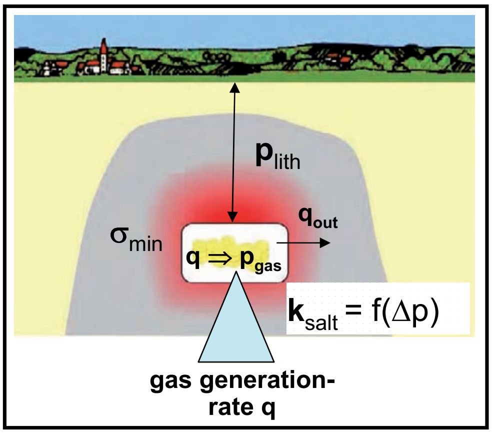
- Direct probing of the former gas-frac zone
- Hydrofrac testing
- Pressure build-up tests
- Gas-injection tests

- At least partial, but „**real**“ healing is documented
- Only local gas reservoirs were found without connection to the gas bearing sub-salinar
- Recovery of minimal stress in the former gas-frac zone was proven (higher than prognosted)



Conclusion - gas-frac scenario

- In the natural scale gas frac conditions are only possible if the over pressurisation succeeds the tensional strength of the salt rock, i.e.:
  - due to an extremely fast gas pressure increase, i.e. an explosion
  - during dynamic loading with a loss of confinement in the rock mass, e. g. during earth quakes or rock bursts.
- The natural gas-frac analogue documents the recovery of barrier integrity in the salt mass after a dynamically induced gas frac and demonstrates the capacity of rock salt for self healing.
- Gas-production rates in a radioactive waste repository in salt will not high enough to induce a macroscopic gas-frac because the fluid pressure driven grain boundary opening will act as a safety valve.

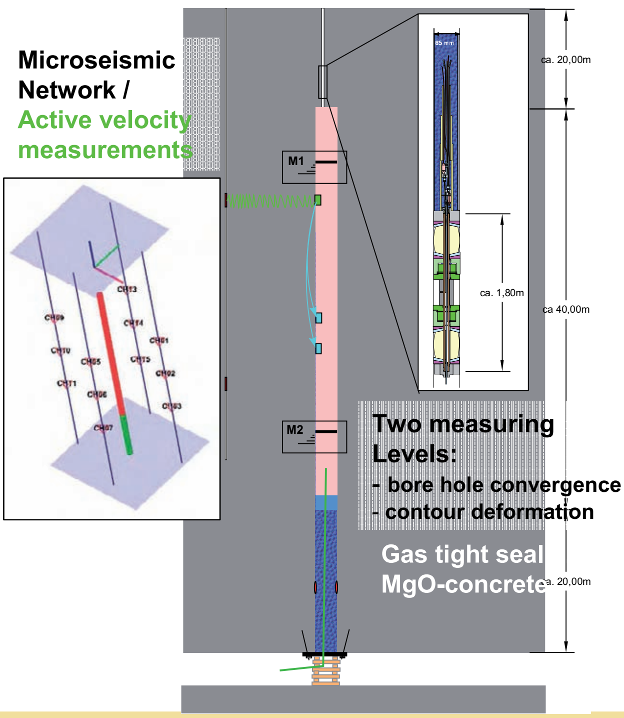


Unsolved questions:

- **Reach of gas-permeation / mechanisms**
- **Stress distribution in a salt dome:**

  $p_{lith} = \sigma_{min}$ (assumption)

Large scale gas injection test (50m³) – Merkers salt mine



Acknowledgements

Project - funding

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

BMBF-project 02C0952:
Modellentwicklung Gaspermeation
2002 - 2008

Bundesamt für Strahlenschutz

UFO-Plan project SR 2470:
Untersuchungen zur Barriereintegrität im Hinblick auf das Ein-Endlager-Konzept
2004 - 2007

UFO-Plan project (FKZ) 3609R03222:
Auswirkungen der Gasbildung im Endlager auf den einschlusswirksamen Gebirgsbereich
2009 - 2013

Project - partners

ITE Institut für Erdöl- und Erdgastechnik, TU Clausthal; GMuG

GMuG

GRS; GMuG

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

RESPEC LAB HISTORY IN SALT

Kirby Mellegard
RESPEC

RESPEC Laboratory View

U.S.-German Salt Research Consortium Workshop

Kirby Mellegard

May 25-27, 2010

RESPEC Lab History in Salt

- First Salt Tests about 1975
- Salt Repository Programs at ORNL
- Studies at Multiple Sites for ONWI
- Supported Sandia at WIPP Site

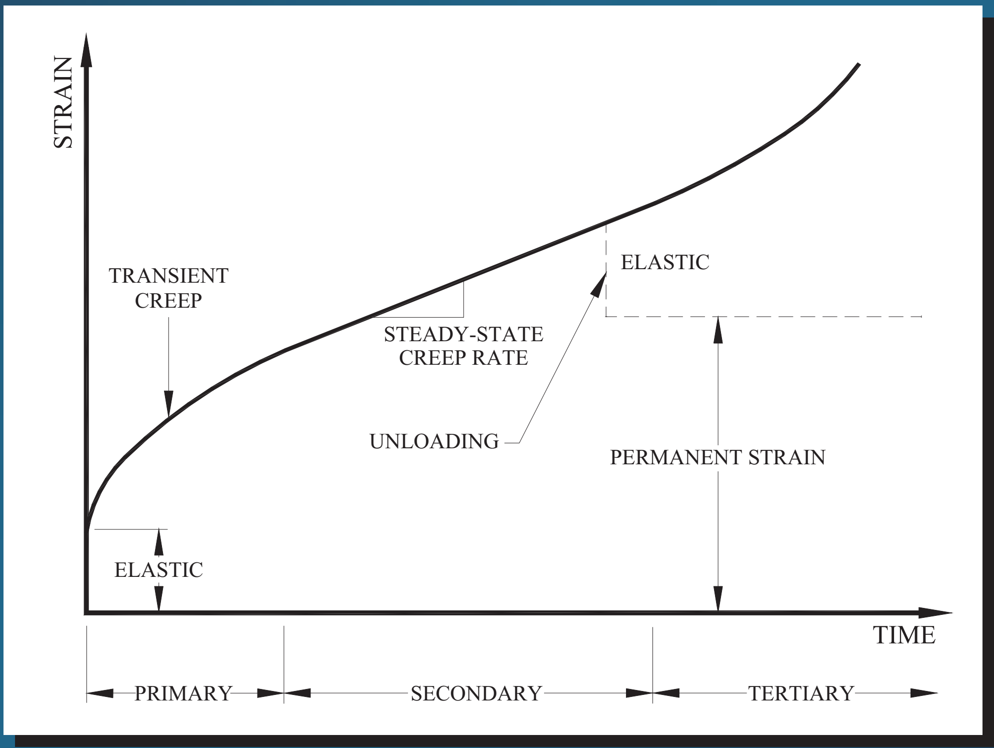
- Salt Cavern Storage Industry
- Solution Mining for Potash
- Deep Drilling Subsalt for Oil E&P

Common Tests at RESPEC

- Strength Tests (cylindrical specimens)
  - Brazilian indirect tension
  - Constant confining pressure with flexible jacket
    - Elastic constants from unload/reload
    - Dilation stress
  - Constant mean stress
    - Compression (Axial Stress > Conf. Pressure)
    - Dilation Stress
- Creep Tests (cylindrical specimens)
  - Constant stress and temperature
  - Transient and steady-state behavior
  - Multistage possible, but not preferred

Creep Test Frames

Typical Creep Test



Less Common Tests

- Extension creep tests
- Extension dilation test (Axial Stress < Conf. Press.)
- Crushed salt backfill tests
- Microfracture accumulation/healing
- Cyclic fatigue
- Fracture toughness
- True triaxial tests (thin-walled hollow cylinder)
- Hydrofrac tests (thick-walled hollow cylinder)
- Thermal & petrographic studies

"Wish List" of Lab Studies

1. Compile and maintain a database of lab results
2. Site-specific salt characterization using common tests (creep)
3. Continue development of dilation tests (extension & compression)
4. Damage accumulation in creep tests
5. Damage recovery (healing)
6. Cyclic Fatigue
7. Hardening studies (anisotropic nature?)
8. Effect of intermediate principal stress
9. Crushed salt backfill
10. Salt composites (salt/cement, brine interactions)
11. Mineralogy/petrographic studies

Short List

1. Compile Database of Existing Results (Public & Proprietary)
2. Damage/Healing Studies
   - Strength
   - Permeability
   - Creep
3. True Triaxial Mechanical Tests
   - Role of intermediate principal stress (strength, creep)
   - Compare different specimen geometries (different displacement boundaries on cylinders and cubes). Do cylinders and cubes give the same result?

Compile Database

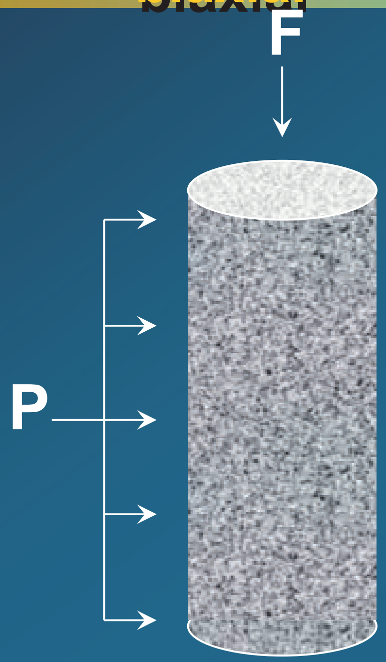
- ~1,000 creep tests (just RESPEC)
- ~1,000 dilation tests (just RESPEC)
- Miscellaneous public domain results. For example: *Laboratory Creep and Mechanical Tests on Salt Data Report (1975 – 1996),* Mellegard and Munson, SAND96-2765
- Huge database of proprietary results from the cavern storage industry. Can they be brought on board to share the data? Maybe anonymously?

Damage/Healing Studies

- Is dilatant volumetric strain the best method to measure damage? How effective are acoustic and permeability?
- How do you measure "healing"? It is more than just a reduction in volumetric strain. It seems "healing" should restore some strength.
- We need to determine the time constants on healing rates.

True Triaxial Tests

"Triaxial" tests on cylinders are really biaxial



F = Axial Force

A = Specimen X-section area

P = Confining Pressure

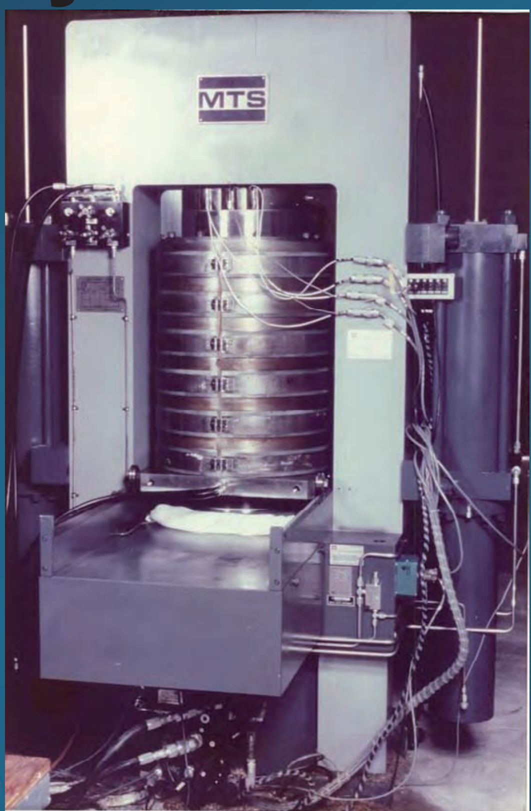
σ_m = (F/A + 2P)/3 = Mean Stress

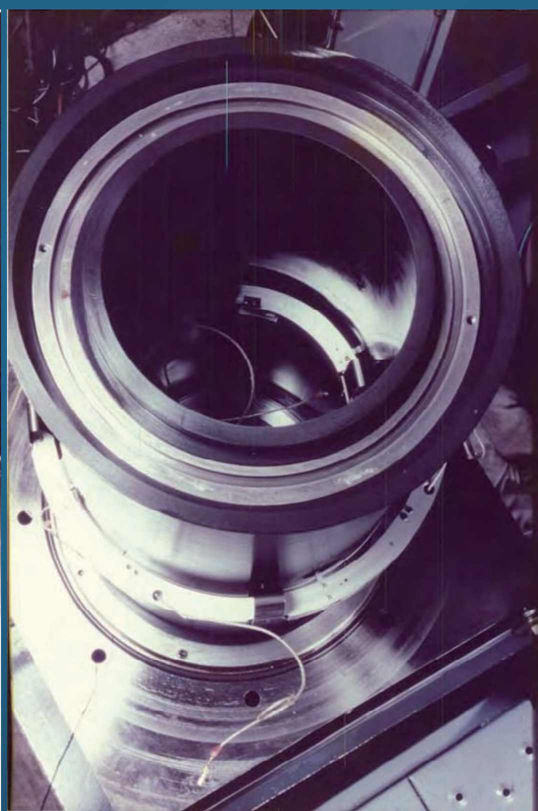
$\Delta\sigma$ = ABS(F/A – P) = Shear Stress

(F/A) > P = Compression

(F/A) < P = Extension on cylinders

Thin-walled Hollow Cylinder





Conceptual True Triaxial Machine Specs. For Cubes

Item	Estimate
Height	6 to 8 feet
Foot Print	4 to 5 feet square (16 to 25 square feet)
Hydraulic Power Supply and Instrumentation	3 to 4 feet square (9 to 16 square feet)
Power Requirements	110/220 V supply
Ambient Temperature Control	± 1°C
Servo-Hydraulic Control System	Independent variable feedback (stress, strain, temperature, pore pressure)
Elevated Temperature	Up to 200°C
Stress Level	Up to 10,000 psi
Allowable Deformation	Up to 15% strain (more if allowable)
Specimen Size	6- to 8-inch cubes
Independent Control of Three Loading Directions	Stress on each face of the cube or strain along each principal axis
Maintain Constant Stress/Temperature	Minimum of 30 days
Variable Platen System for Different Specimen Sizes	Specific sizes depend on materials
Acoustic Wave Measurements	Transducers mounted in platens

RESPEC CONSULTING & SERVICES

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Variable Platen System for Different Specimen Sizes	Specific sizes depend on materials
Acoustic Wave Measurements	Transducers mounted in platens

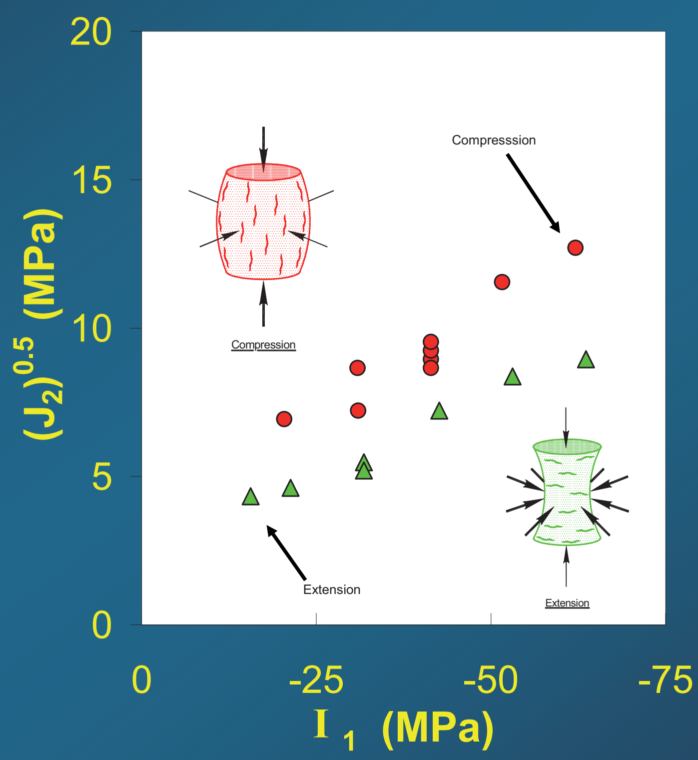
True Triaxial Project Overview

1. Two year project (3 year?)
2. NSF MRI funding source
3. SDSMT provides lead PI. Needs university approval to submit.
4. MTS is systems integrator
5. RESPEC brings commercial contacts and extensive salt background
6. Need other supporters including Mechanical Engineering department at the university. Other disciplines could also make use of a true triaxial testing machine.
7. MTS cost estimated at $1.5M
8. Labor cost estimated at $1.5M

Thank you!

QUESTIONS?

Lode Angle Effect on Dilation



831

Stress Measures

- *Constitutive Modeling*
- $\sigma_1, \sigma_2, \sigma_3$ = princ. stress
- $\sigma_1 > \sigma_2 > \sigma_3$
- $I_1 = \sigma_1 + \sigma_2 + \sigma_3$
- $J_2 = 1/6\ \{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\}$
- $\psi = \tan^{-1}\{(2\sigma_2-\sigma_1-\sigma_3) / (\mathrm{sqrt}(3)\ (\sigma_1-\sigma_3))\}$

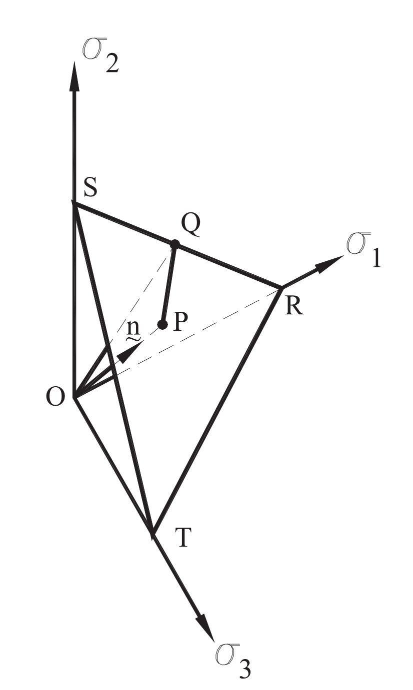
- *Laboratory Testing*
- σ_a = axial stress = F/A
- σ_c = radial stress = P
- $I_1 = \sigma_a + 2\,\sigma_c$
- $J_2 = |\,\sigma_a - \sigma_c|^2 / 3$
- $\psi = +\,30^o\ (\sigma_a > \sigma_c)$
- $\psi = -\,30^o\ (\sigma_a < \sigma_c)$

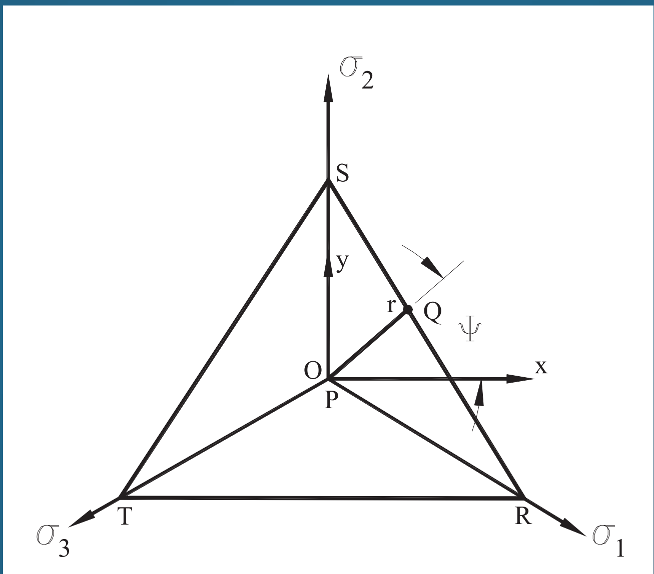
832

Tasks (SDSMT PI oversight & contribution on all tasks)

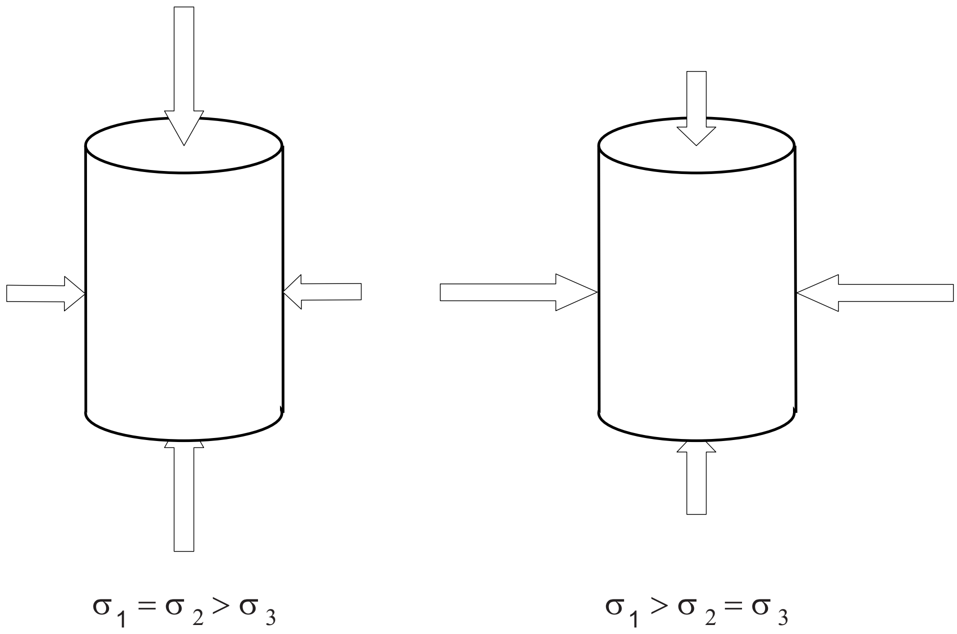
1. Design – collaborate with MTS
   1. *Non-interfering platens*
   2. *Instrumentation within the platens (?)*
2. Build – subcontract to MTS
3. Site preparation – RESPEC if needed ?
4. Installation – MTS lead
5. Shakedown Acceptance Tests

Lode Angle (Ψ) in the π-plane





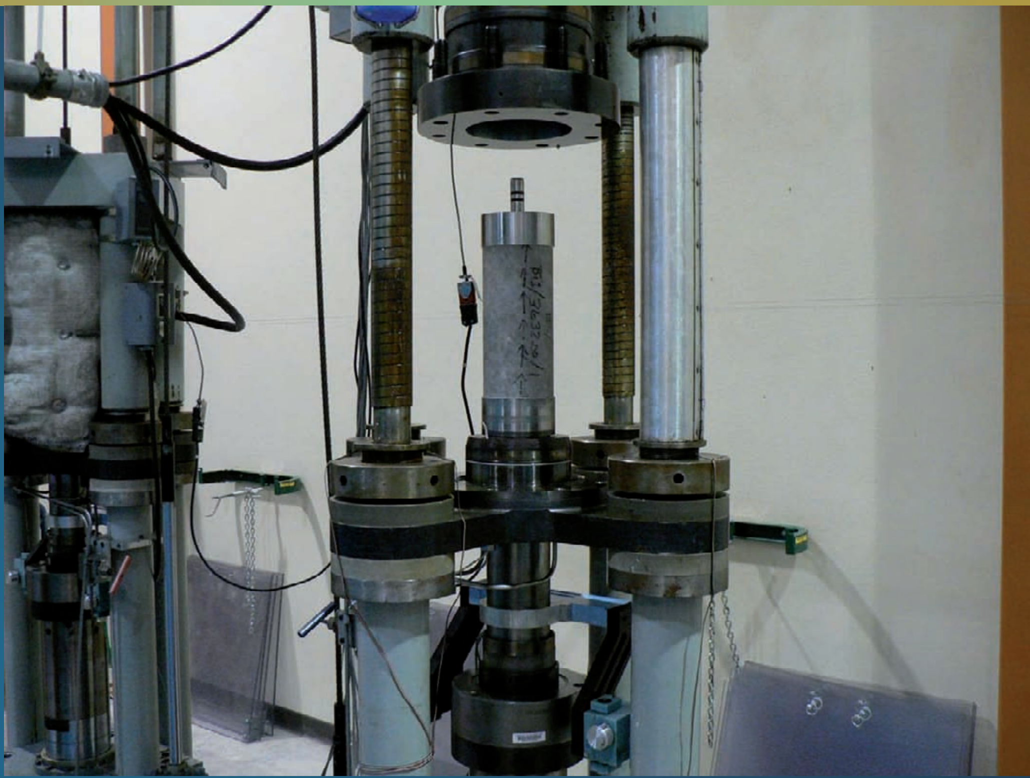
Laboratory Stress States



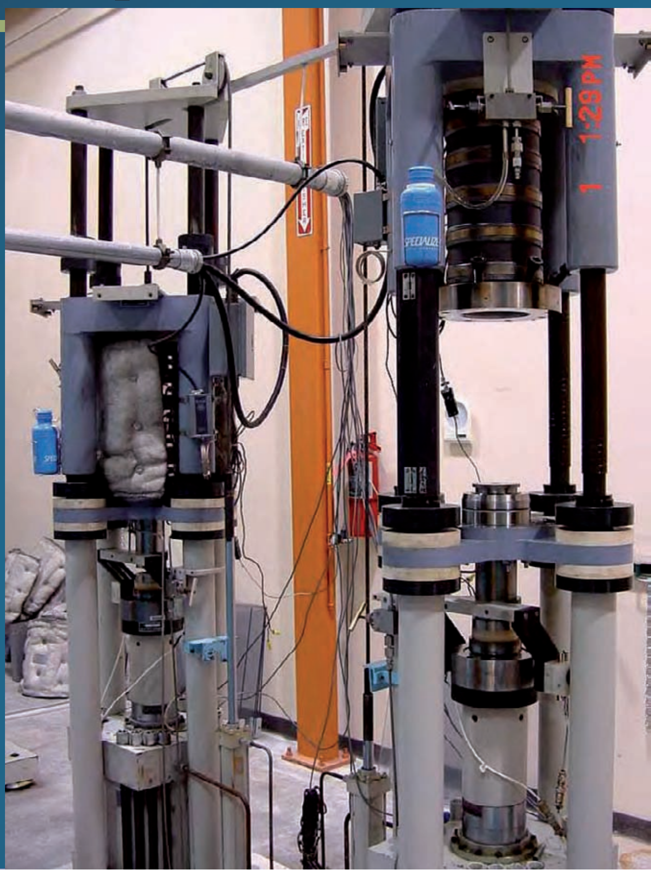
Creep in Rock Salt

- Stress field surrounding an underground opening in salt (e.g., gas storage cavern)
  - *Typical Stress Measures Considered*
    - Mean Stress (I_1)
    - Shear Stress (J_2)
  - *Relative stress magnitudes (Lode angle, ψ)*
    - Generally not considered
    - The need for true triaxial testing

Specimen Setup



Creep Test Frame



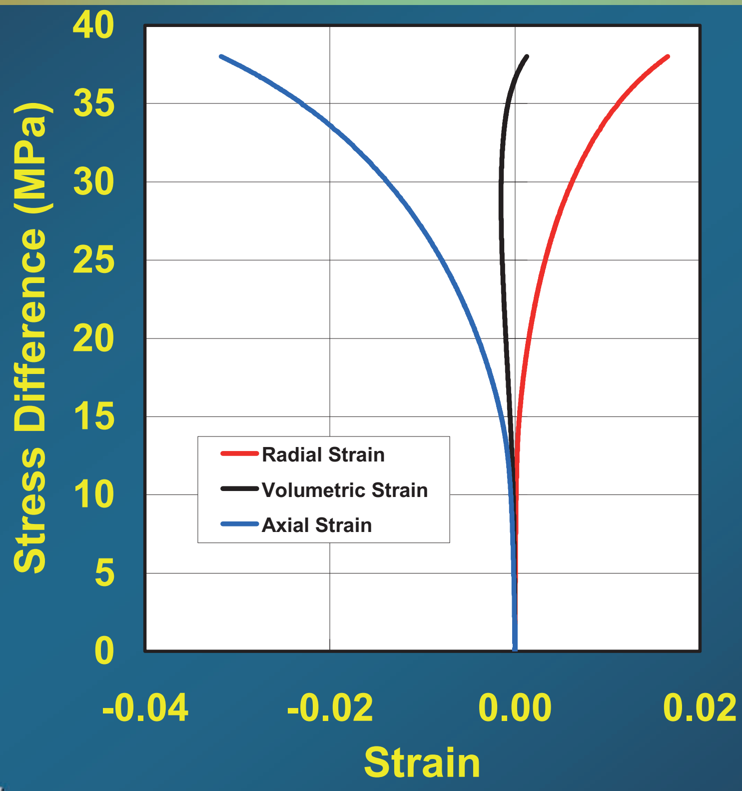
Laboratory Approach

- Solid cylindrical specimens
  - *4 inch diameter (100 mm)*
  - *8 inch length (200 mm)*
- Two types of tests using confining pressure
  - *Constant Mean Stress Tests to investigate the dilational strength*
  - *Constant Stress Creep Tests to investigate the time-dependent properties*
- Two Lode angles can be investigated
  - *Triaxial Compression (axial stress > pressure)*
  - *Triaxial Extension (axial stress < pressure)*

Conclusions

- Lode angle has no effect on the magnitude of the steady state strain rate
- Hardening is anisotropic. The evidence is the recurring transient response observed when the Lode angle is changed following a steady-state condition
- Three widely used constitutive models could not reproduce the recurring transient strain response observed in the lab tests

Constant Mean Stress Tests



Possible Project Implication

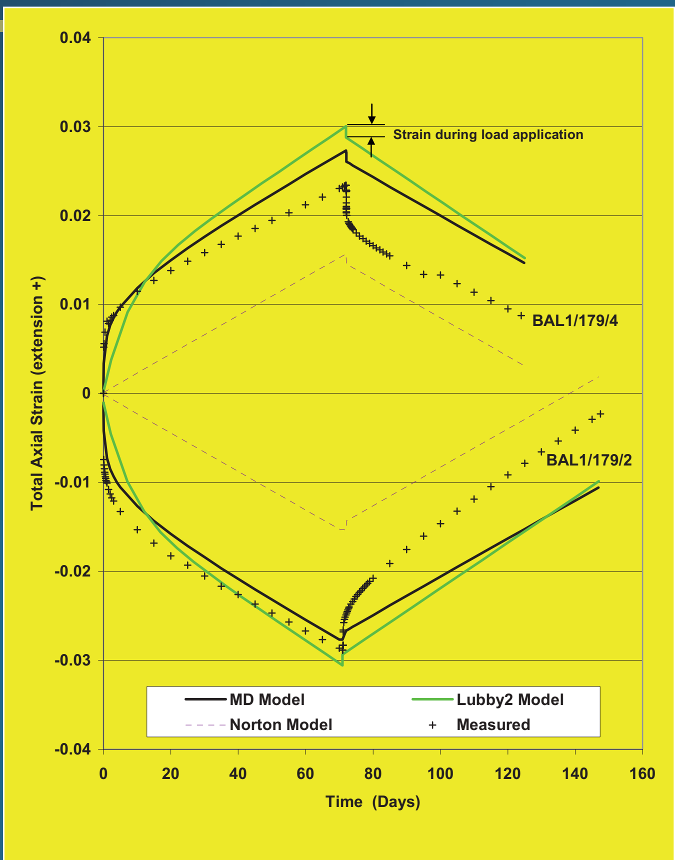
- Natural Gas Storage
  - *Pressure changes in cavern result in alternating states of stress ranging from triaxial compression to triaxial extension*
    - Transient response could increase the predicted deformation rate at localized regions surrounding the cavern
    - Increase predicted cavern closure
    - Produce shear bands by virtue of different flow rates and directions
    - Change state of stress in salt controlling minimum allowable gas pressure

Impacts ?

- Scientific interest to further the refinement of constitutive models
- Little impact on problems where the Lode angle is relatively static
- Primary interest in cases where changes in Lode angle are significant and/or cyclic

RESPEC CONSULTING & SERVICES

Model Predictions



RESPEC CONSULTING & SERVICES

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-27, 2010
Canton, Mississippi, USA

IN-SITU EXPERIMENTS – HLW-INVESTIGATIONS – RUSSIAN SALT EXPERIMENTS

Lutz Schneider
Stoller Ingenieurtechnik GmbH, Dresden

Abstract

There are a lot of opportunities for cooperative US-German-project-work:

1. Evaluation of a storage experiment concerning the final disposal of waste containers with high level radwaste in the underground measuring field of the final repository Morsleben
An ongoing experiment to demonstrate the HLW-disposal in boreholes in salt has taken place in the repository site Morsleben since 1987. This experiment should definitely be evaluated because such a long-term in-situ-experiment in a deep underground disposal in rock salt with heat generating radioactive waste will be financed in future hardly. The technical retrievability has been annually proven and reviewed in the time period of 23 years and could be a suitable example to show the technical longterm retrievability. Samples should be investigated as the dose is very high (>470 MGy) at a low temperatures, so that the disturbance of the NaCl-lattice will be extreme (low annealing under in-situ final disposal conditions).

2. Analysis and modeling of particular scenarios of brine-inflow at a heat-affected disposal zone in salt-formations

All scenarios, the "pressure-free" inflow of brine and the building of a layer of salt around the container as well as the complete filling of the cavity with brine combined with the sinking of the container will give significant predictions regarding the estimation of cases of emergency. The proposal of a joint experiment could clear up both processes as "safety relevant shielding" of the waste in the container against leaching to avoid unlimited container corrosion and to give limited hydrogen generation in the case that corrosion will occur.

3. Analysis of an underground nuclear explosion in Azgir and modeling of radionuclide migration in disturbed rock zones of salt-formations

- Investigations of the effects of nuclear explosions on the **stability/integrity of the salt stock** in comparison to the possible release of stored energy in rock salt (already done).
- Feasibility study on a Kazakh final disposal project in rock salt (already done).
- Validation of models for migration of radionuclides, as the all explosion cavities are filled with brine now and the migration started 40 years ago after all experiments were finished in Azgir.

In-situ Experiments
HLW-Investigations
Russian Salt Experiments

Lutz R. Schneider

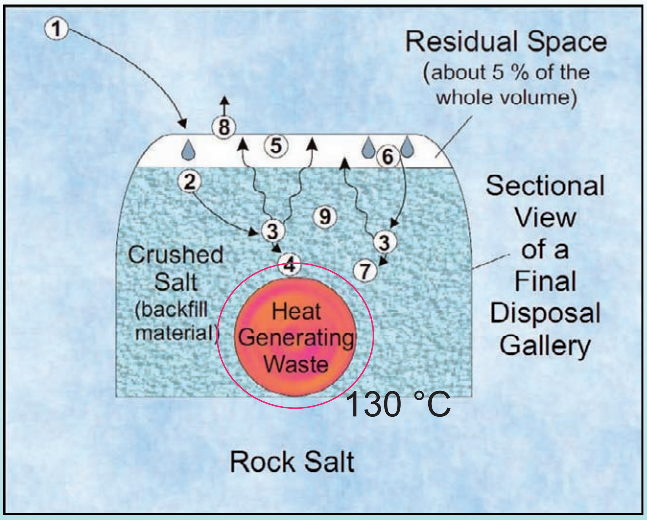
US-German Workshop, Jackson (MS)
May 26th, 2010

Content

- Modelling of physical-chemical processes after brine inflow into final disposal areas containing heat generating waste.
- Evaluation of a long time HLW storage experiment in the former final repository Morsleben (ERAM).
- Evaluation and analysis of the situation regarding the storage and disposal of radioactive waste in Russia (gas generation, model validation).

Modeling

Scheme of processes

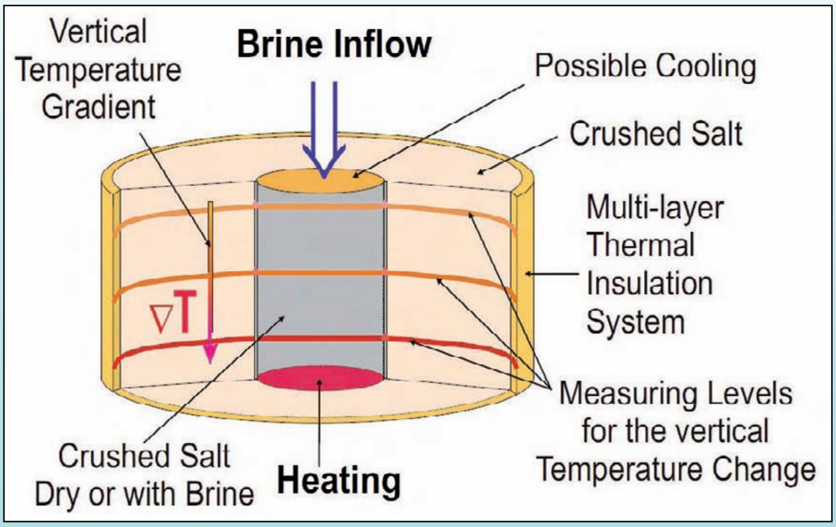


Scheme of processes caused by brine intrusion into a repository section containing heat generating waste

1. Brine inflow from shaft or through a thermally induced crack.
2. Penetration of the brine into the backfill material and beginning of cavity formation through dissolution of salt.
3. Evaporation upon reaching boiling temperature and beginning of salt precipitation.
4. Compaction of the crushed salt through crystallization of the precipitated salt.
5. Condensation of the water vapour in the “cold” section.
6. Salt separation to the point of brine saturation.
7. Deposition of salt.
8. Migration of the partially gas-filled cavity away from the heat source.
9. Migration of the liquid filled cavity towards the heat source.

Modeling

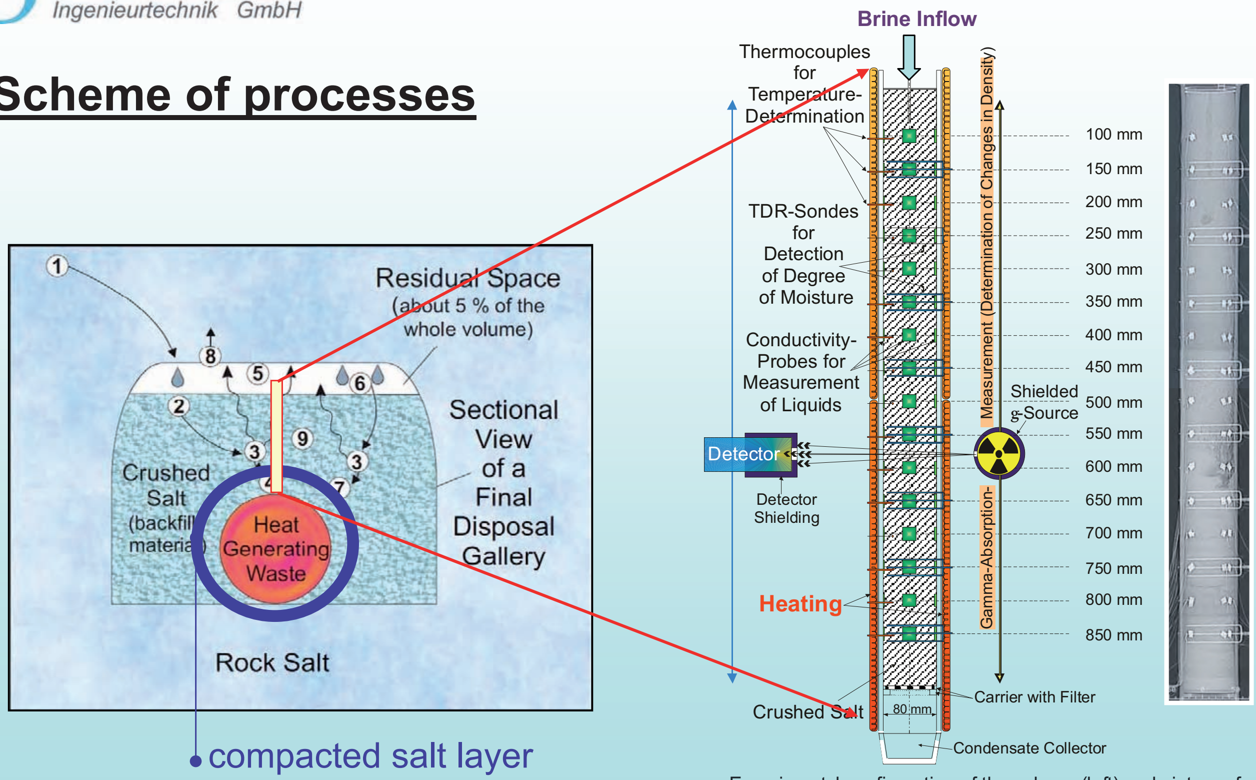
2 different experimental set-up



Investigation of different processes

- Pore space closure in brine saturated crushed salt caused by brine evaporation.
- Crust formation in crushed salt given by slow brine inflow.
- Convection and resolving processes in moist and in brine saturated crushed salt.

Scheme of processes



Experimental configuration of the column (left) and picture of the computer tomography at the end of the experiment (right)

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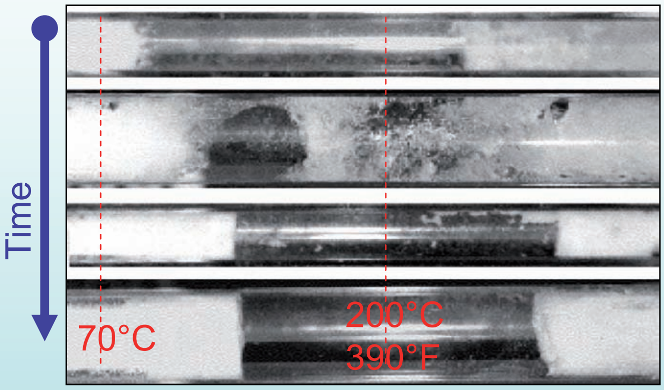
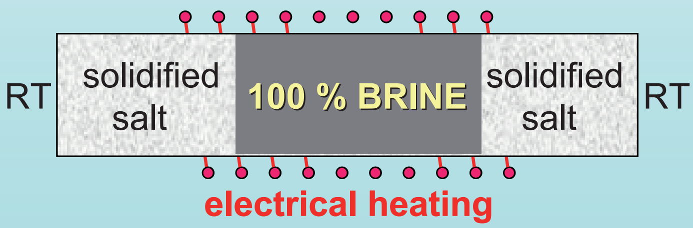
Modeling

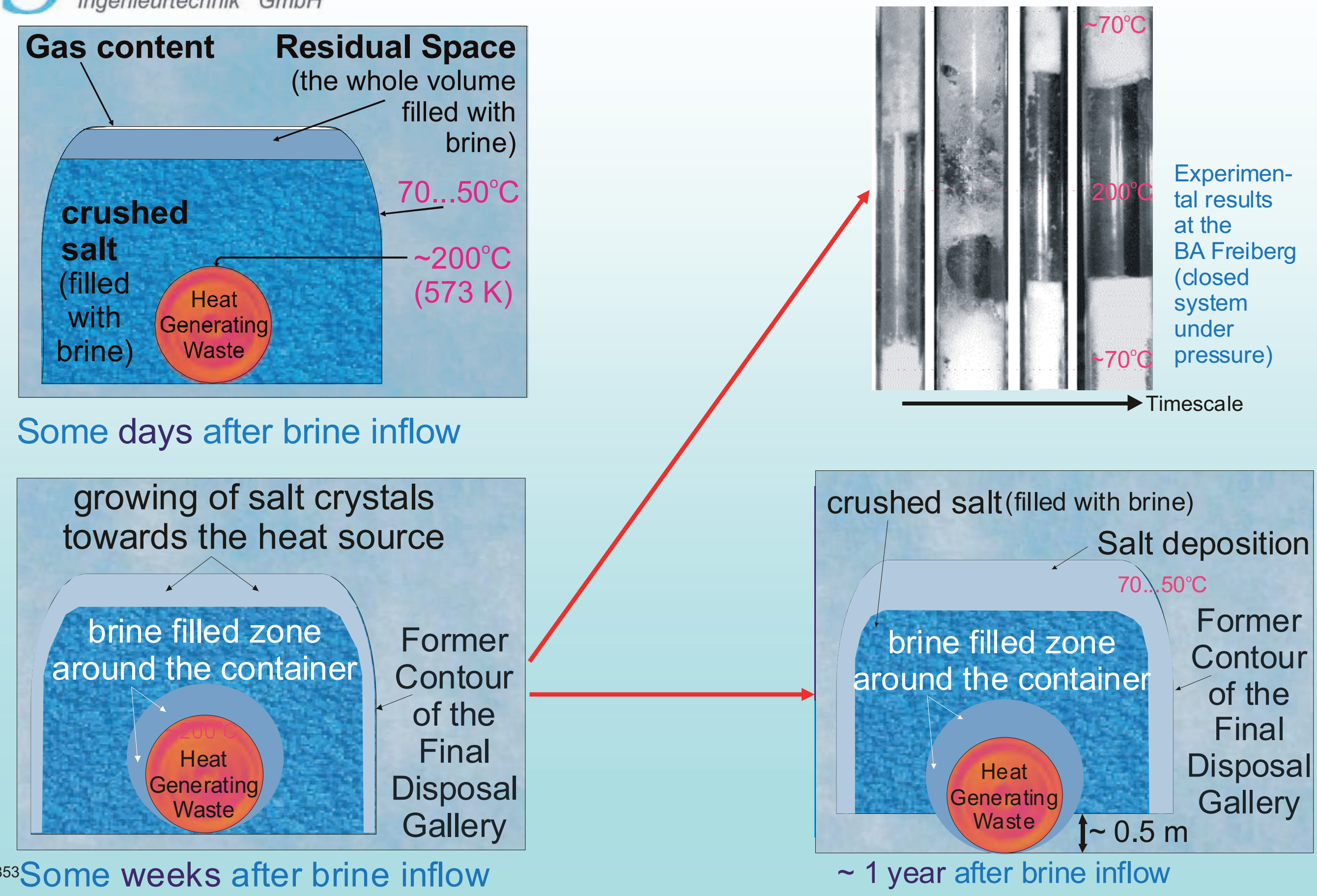
Results (+additional questions)





Four samples at the end of the tests:

- Dark areas in the middle of the four columns show brine filled zones at a zone temperature of approx. 200°C (≈ 390°F).
- Bright areas mean compacted salt at the cold ends of the columns.
- No influence of sulfatic minerals in salt fill on resolving and transport processes.



Results and Expectations

- Processes are **depending on the rate of brine inflow** as well as the content of gaseous and liquid phases in the disposal areas & pressure.
- In the case of partly filled porous space with brine and container temperature until 200°C (≈ 390°F): increase of density of **salt layers around waste container** to protect it against brine contact, corrosion and waste leaching (results of measurements in laboratory scale).
- In case of a brine filled repository section the salt will be transported towards the colder section. In addition the gravity could allow the container **to sink downwards into the rock salt formation** (postulate). This effect could result in serious (positive) safety issues under certain circumstances.
- The **compaction of salt** in the colder repository section might prevent against further brine inflow into the repository after some time and will protect at least against release of contaminated brine (postulate).

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INVESTIGATION OF PHYSICAL-CHEMICAL PROCESSES AFTER BRINE INFLOW INTO FINAL DISPOSAL AREAS WITH HEAT GENERATING WASTE

Related Projects:

- W. Bertram, L. R. Schneider, V. Simm
  Brine intrusion into shafts and galleries of saltmines
  Report in BMFT Project 02 E 8563 7; SIG-06/95, Dresden, June 1996
- L. R. Schneider et al.
  Investigations of scenario modelling in the vacinity of a heat-affected final repository in rock salt
  Final report for BMFT Project 02 E 8563 7; SIG-10/95, Dresden, June 1996
- L. R. Schneider, N.-M. Bremer, K.-J. Richter
  Experimental investigation of physical-chemical processes involving brine intrusion into final repository sections
  Final report for BMWi Project 02 E 8966; SIG-01/99, Dresden, August 1999
- D.-A. Becker, N.-M. Bremer, K.-J. Richter, L. R. Schneider, R. Storck
  Experimental and theoretical investigation of physical-chemical processes involving brine intrusion into final repository sections
  Joint final report (incl. CD) for the BMWi-projects 02C 8956 and 02 E 8966, GRS-164, SIG-02/99, ISBN 3-931995-29-1, Jan. 2000

Project Partners:
- Stoller Ingenieurtechnik GmbH (project management for experimental studies)
- GRS Braunschweig (project management for modelling)
- TU Dresden, Institut für Thermodynamik und Techn. Gebäudeausrüstung (exp. studies)
- Grundwasser-Forschungs-Institut GFI Luckner & Partner GmbH, Dresden (exp. studies)
- Boden- und Grundwasserlabor BGD GmbH, Dresden (experimental studies)
- TU Bergakademie Freiberg, Institut für anorganische Chemie (experimental studies)
- Institut Fresenius Angewandte Festkörperanalytik GmbH (experimental studies)

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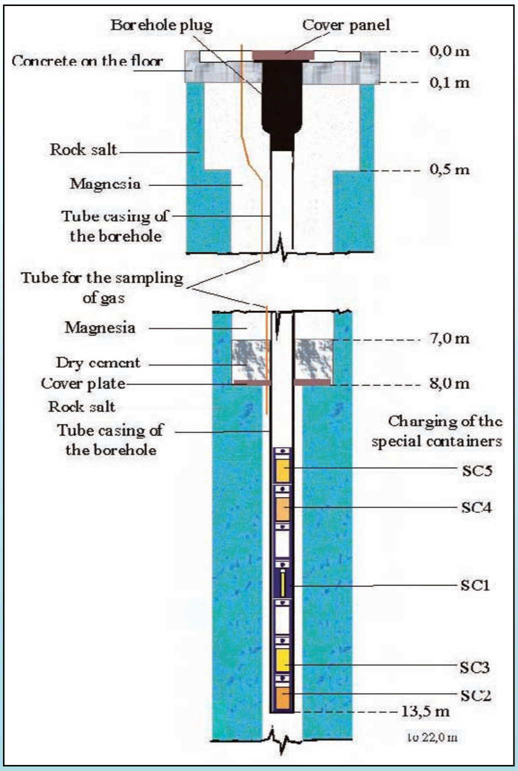
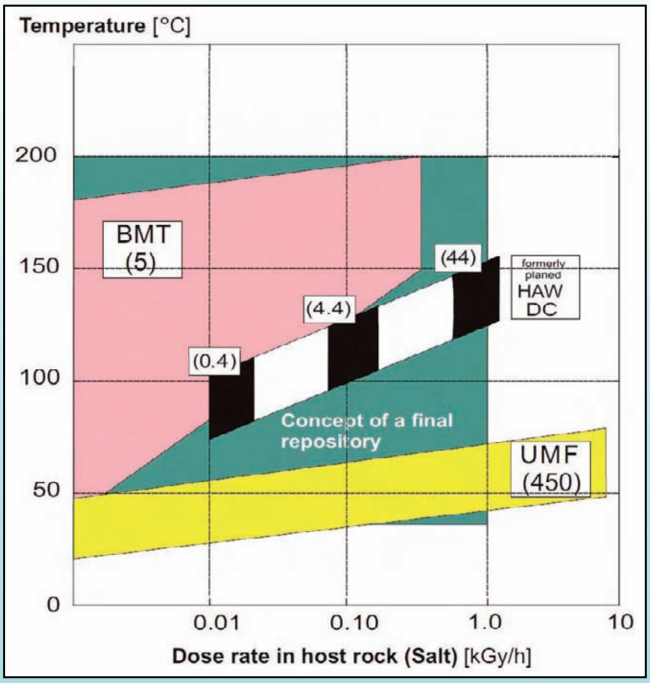
ERA Morsleben



Set-up of the A2-experiment

- HLW-experiment in the Final Repository "Endlager für radioaktive Abfälle Morsleben" started in 1986 (A1-experiment) and continued 1987 (A2-experiment) … until now
- 5 disposal special containers (SC) filled with radiation sources of high activity (Cs, Co)
- Activity level of each SC ≤ 1 PBq (between 50 and 100 times higher than all the Radwaste stored in the ERAM at this time)
- Surface temperature of the SC goes up to 150°C (≈ 300°F)
- Dose of gamma radiation in rock salt exceeds the planned level (> 400 MGy)

Classification of the A2-experiment within the German HLW-concept



Results of HLW-experiments in the experimental underground field (UMF):

Maximum Temperature (measured)			
Piping	Annular Space	Radius 0,58 m	Radius 1,25 m
98°C	87°C	37°C	35°C

Maximum Dose Rate		
Wall of the Borehole[1]	Radius[2] 0,30 m	Radius[2] 0,63 m
7,75 kGy/h	19,7 Gy/h	2,2 Gy/h

[1] calculated [2] measured

Longterm disposal: 23 years !!!
+ yearly 1 retrievability test !!!

Proposed work packages

- Radiological changes in the near field of the rock salt
- Convergence in the borehole
- Thermally changes in the structure of the near field of the rock salt with respect to the formation of fractures
- Release of materials and deposit in deeper regions of the borehole
- Mechanical analysis regarding the stability of the salt as well as microscopic changes in the granular and atomic tone
- Sampling and comparison of the piping in thermally and radiological high contaminated regions
- Gravimetric analysis of the abrasion in the piping
- Microscopic evaluation of the migration of brine in rock salt in the high contaminated area
- Estimation of the dose rate in rock salt

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ERA Morsleben

Time window for a Letter of Interest latest until September !!!

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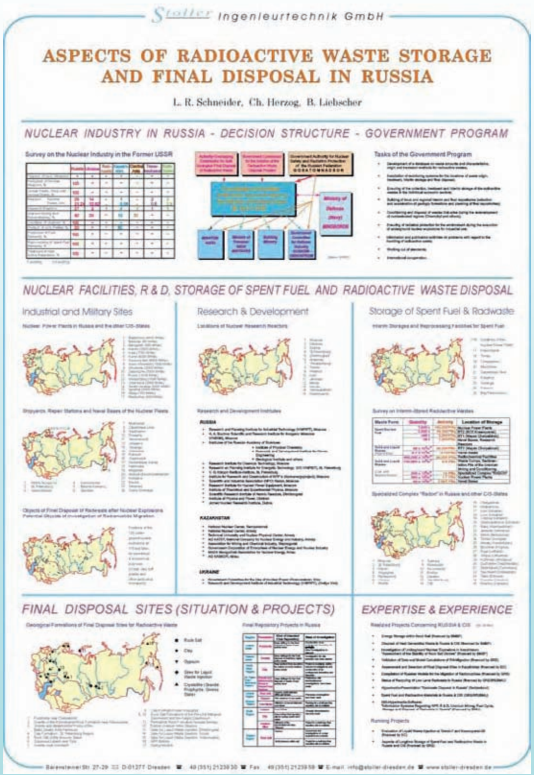
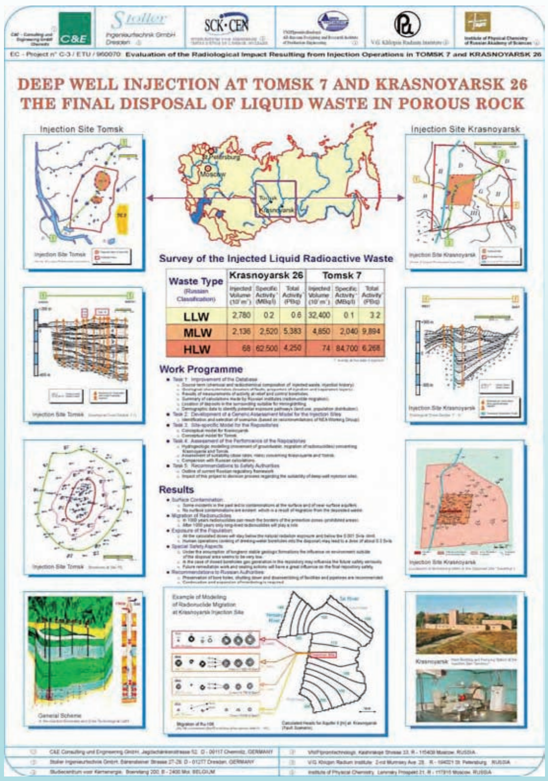
Radioactive Waste in Russia



EIA and Safety Assessment for the Russian repositories Krasnoyarsk-26 and Tomsk-7 (deep well injection of >40 Mio. m^3 liquid lowlevel radwaste and > 70,000 m^3 HLW)

Significant gas generation by biodegradation caused by HLW !!!



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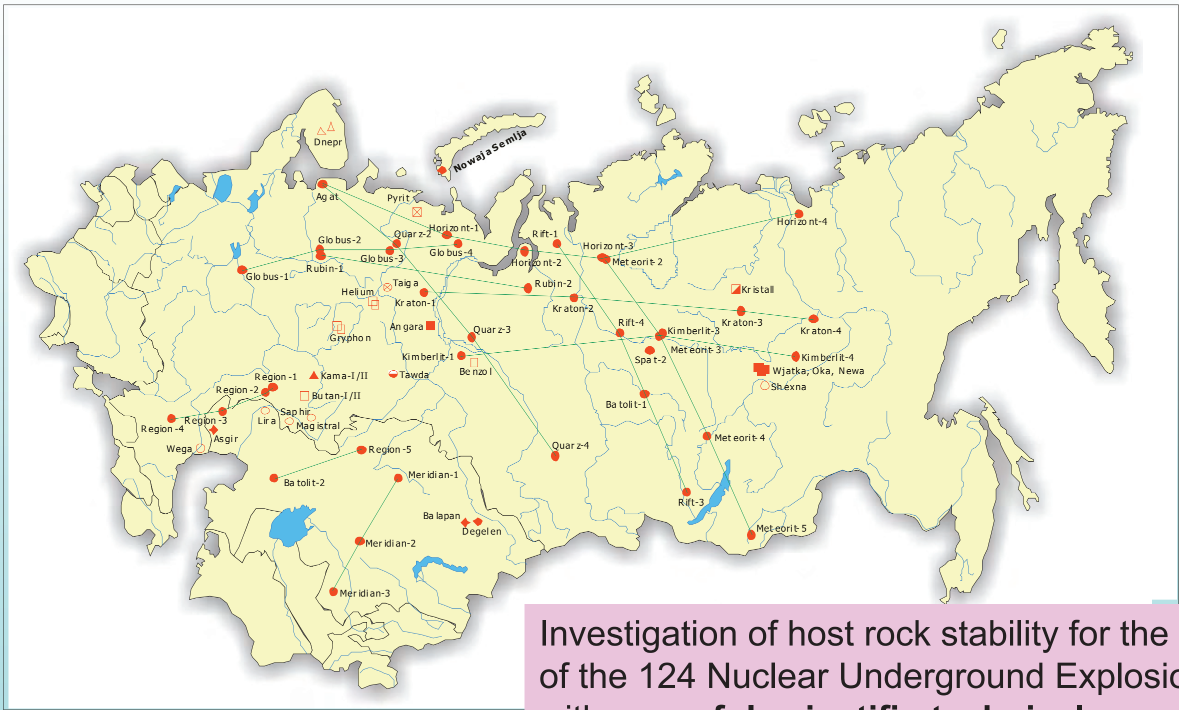
Radioactive Waste in Russia



Investigation of host rock stability for the sites of the 124 Nuclear Underground Explosions with **peaceful scientific-technical purposes.**

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Azgir

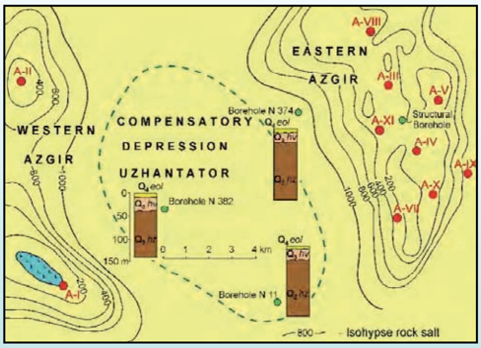
Analysis of Nuclear Underground Explosions

Goal: Investigation of the stability of host rock formations in Kazakhstan at the salt dome Azgir

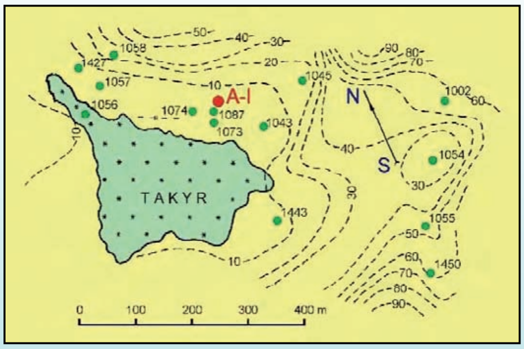
- Time period: between 1965 and 1988
- Number: 128 underground nuclear explosions at 115 sites,17 near Azgir (Kazakhstan)
- Energy range: 1.1 up to 100 kt TNT
- Depth: 160 m - 1,500 m;
- Volume: 10,000 m³ - 240,000 m³

Geographical location of the settlement of Azgir and the test area

Analysis of Nuclear Underground Explosions



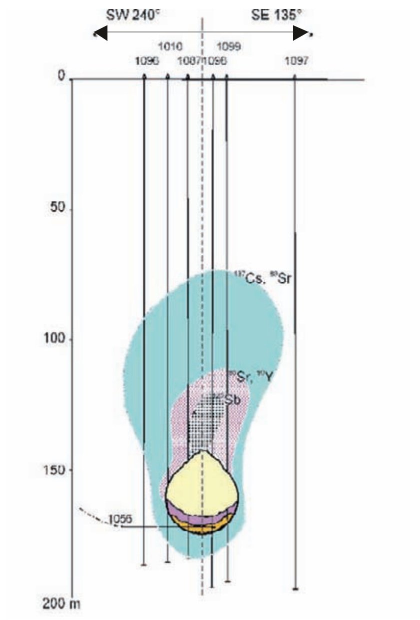
Position of the nuclear explosions A-I to A-XI in the salt-dome structure of Azgir (left) and the boreholes in the vicinity of the explosion A-I (right).



Purpose of investigation:

- Investigations of the effects of nuclear explosions on the **stability/integrity of the salt stock** in comparison to the possible release of stored energy in salt.
- Feasibility study on a Kazakh final disposal project in rock salt.
- Validation of models for migration of radionuclides in Azgir.

Data of Radionuclide Migration



Nuclear underground explosion A-I

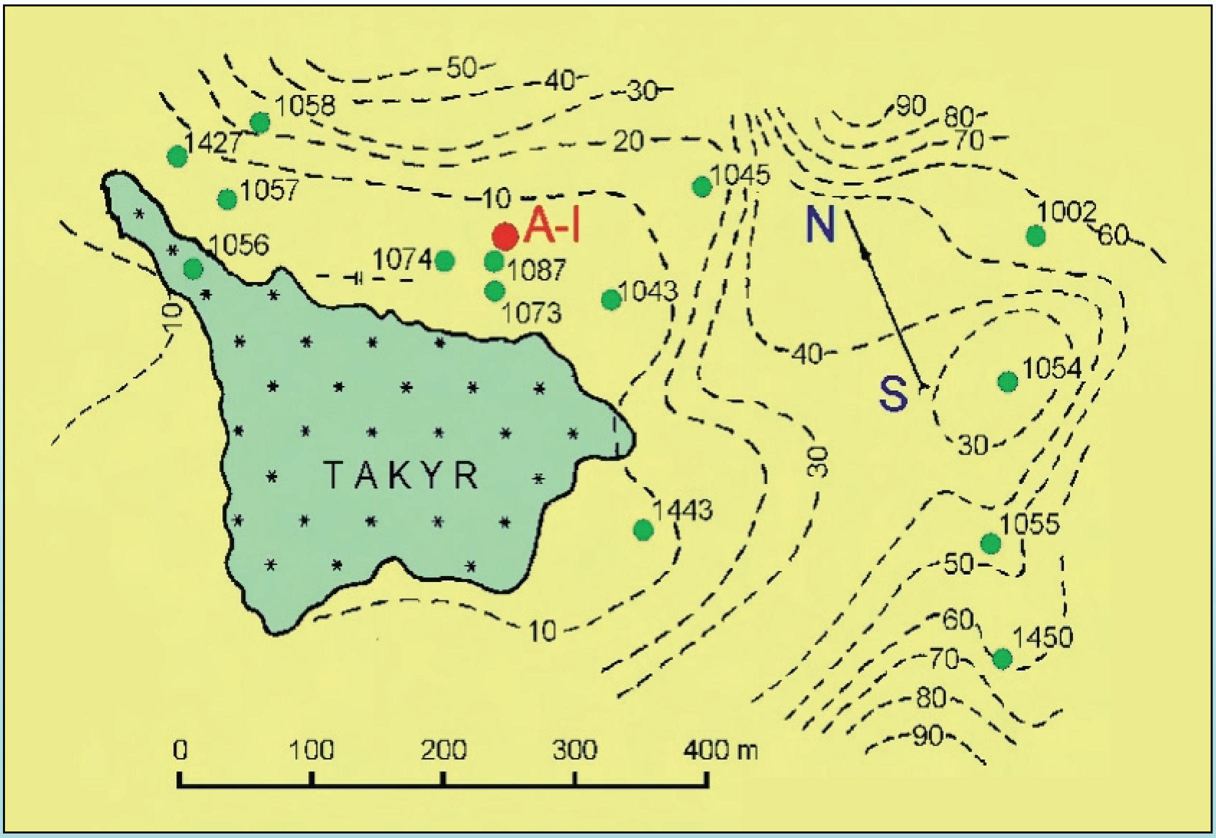
Index of borehole	Distance from technological borehole, m	Depth, m	Concentrations, Bq/l	
			^{137}Cs	^{90}Sr
A-I-1	13.5	50	161.5	14.8
A-I-2	25.0	50	141.5	—
A-I-3	49.0	50	18.6	3.0
A-II-1	30.0	225	0.04	0.05
A-II-2	70.0	225	0.03	0.02
A-III-1	200.0	250	0.66	0.37
A-IV-1	30.0	225	0.36	0.03
A-IV-2	70.0	225	0.08	0.02
A-V-1	50.0	280	6.1	0.15
A-V-2	100.0	280	17.7	3.7
Total activity of water in sources of water-supply			0.85	
Permissible concentrations in water, MPC			550	14.8

Concentration of long-lived radionuclides in ground waters derived from data on observational boreholes in 1990-1991

Index of cavern	Year of determination	Concentrations, 10^4 Bq/l		
		T	^{137}Cs	^{90}Sr
A-I	1966 -1967	not measured	31.45	1.85
A-I	1975	10.70	2.22	0.74
A-II	1968	not measured	13.32	0.30
A-II	1975	4.80	6.66	7.40
A-III	1989	9.62	34.00	4.07
A-V	1980	not measured	148.00	not measured

Concentrations of long-lived radionuclides in the brine of the caverns (the concentration of plutonium is lower than 3.70 Bq/l)

Azgir



Challanges of Cooperation

1. Evaluation of a storage experiment concerning the final disposal of waste containers with high level radwaste in the underground measuring field of the final repository Morsleben

The ongoing experiment of HLW-disposal in boreholes in salt has taken place in the repository site Morsleben since 1987. This experiment should definitely be evaluated (long-term in-situ-experiments in a deep underground labs with heat generating radioactive waste will be financed in future hardly). The technical retrievability was annually proven and reviewed in the time period of 23 years (suitable example to show the technical longterm retrieva-bility). Samples should be investigated as the dose is very high (>470 MGy) at a low temperatures under in-situ final disposal conditions).

Challanges of Cooperation

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All scenarios, the “pressure-free” inflow of brine and the building of a layer of salt around the container as well as the complete filling of the cavity with brine combined with the sinking of the container will give significant predictions regarding the estimation of cases of emergency.

The proposal of a joint experiment could clear up the processes as “safety relevant shielding” of the waste in the container against leaching to avoid unlimited container corrosion and to give limited hydrogen generation in the case that corrosion will occur.

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Challanges of Cooperation

3. Analysis of an underground nuclear explosion in Azgir and modeling of radionuclide migration in disturbed rock zones of salt-formations

- Investigations of the effects of nuclear explosions on the **stability/integrity of the salt stock** in comparison to the possible release of stored energy in rock salt (already done).
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Thank you for your attention.
Danke für Ihre Aufmerksamkeit.
Спасибо за Внимание.

There are a lot of opportunities for cooperative US-German-project-work.

Contact:
Stoller Ingenieurtechnik GmbH ● Baerensteiner Straße 27/29 ● D-01277 Dresden ● www.stoller-dresden.de
Tel...49 (3 51) 2 12 39 30 ● Fax ...49 (3 51) 2 12 39 59 ● Email: info@stoller-dresden.de

Résumé

Initiating and performing this workshop at Mississippi State University in Canton MS was successful in many a ways. After ten years of dormancy, this workshop restarted joint pursuit of activities in salt collaboration and refreshed the scientific and personal contacts in salt repository sciences. The technical exchanges permitted a contemporary assessment of the salt relevant research areas and others areas of concern where consensus might be built. This proceeding documents the conduct of the workshop, including the presentations made by the international experts and provides an opportune starting point for future actions and activities.

German and American salt research scientists gave a series of technical presentations that provided the bases for discussions of many important research areas of concern to salt repository investigations today. On the basis of excellent presentations, which are included in this proceedings document, many varied topics were addressed in open forum. Some of these areas of interest identify bases for collaborative research on salt in the near future. The participants provided the current state of knowledge on particular topics, which allowed fruitful discussion on mutual areas of concern.

In several presentations, clear research topics for collaboration were identified. Thus, following the presentations noted in the agenda and questions and answers pertaining to them, the international workshop participants explored a series of salt repository topics. Subject matter included *rock mechanics, safety case, concepts and design, site characterization, coupled process modeling (Thermal, Hydrological, Mechanical, Chemical), groundwater, transport, and engineering*. These topics could principally serve as bases for possible mutual collaborations and cross-fertilizing research agendas, for a focused science-based strategy.

In addition to the breadth of topics covered by the presentations, several points of discussions addressed contemporary salt research issues, including *brine migration, vapor transport, waste degradation, radiolysis, retrievability, solubility and transport, bouancy, heat effects, hydrofracture, dilatancy boundary, and consolidation of hot granular salt* (for more details see part A):.

To varying degrees the open discussion identified existing areas of inquiry, which warrant either comprehensive review or new investigations. In some cases, the discussions served to identify technical matters by summarizing the issue, but should not be construed as a definitive reconciliation of the questions put forward by the workshop group. In other cases, the subject represented less *research* and more a recognition that salt repository sciences and engineering aspects are saddled with some lingering open questions, which need to be reviewed and summarized before embarking upon a research agenda.

Supplemental related topics (for details see part B) included important implementation considerations and near-term collaborations. In addition to this workshop, the salt repository community can advance the research agenda at conferences, within educational institutions, and potentially through creation of a long-anticipated salt club. The American Rock Mechanics Association meeting in June hosted two sessions on salt creep, which avails further pursuit of collaboration on modeling. In the fall of 2010, the Carlsbad Field Office of the United States Department of Energy will host a closely related workshop on the topic of geochemistry. The workshop participants also discussed student support, recognizing the long-term nature of repository research and development. The intent is to recognize and formalize several avenues of collaboration, which will include instruments such as letters of intent and memoranda of understanding.

The discussions held at the German/USA workshop on salt repositories showed, that further research areas and means for cooperation will be identified as collaboration efforts continue. The workshop also reflected that despite remaining challenges, rock salt is viewed as a material with excellent, positive and advantageous characteristics requisite for a high-level waste repository.

Part A. Contemporary Research Issues

Decades ago distinguished scientists determined that salt disposal provided the best option available to dispose of high level nuclear waste. These geoscientists concluded back in 1956 that *in light of present knowledge, no insurmountable obstacles to the storage of radioactive waste in solid form in underground cavities in salt appear to exist* (NAS, 1957). This basic statement remains true today, after more than a half century since that determination. Over the decades, the vast promise of salt disposal has been scrutinized from many angles. In situ and laboratory experiments have addressed many of the first order parameters, such as thermal activation of salt deformation. Full-scale in situ tests, demonstrations, mining, and repository operations have continuously provided confirmation that salt repositories for heat-generating nuclear waste can be constructed today and house almost limitless volumes of nuclear waste.

As science marches forward, certain hypotheses emerge to challenge the notion that salt provides a robust isolation medium. The community of salt scientists and engineers involved with repository concepts has dealt with a plethora of such issues. Some issues recur because they resonate with a degree of credibility; plausible statements repeated often enough gain a social acceptance. In addition, if these statements (hypotheses) are demonstrated to be viable by the scientific method of test and discovery, they could potentially weaken the perceived robustness of salt disposal. Thus as a matter of due diligence, workshop participants discussed a wide range of claims and assertions in addition to the more credible scientifically sound subjects.

Many of the primary attributes of salt disposal are known and have been demonstrated at an operational scale over significant periods of years. However, there remain pesky issues that perhaps have either not been substantially investigated or reviewed to the point of objective reconciliation. This section examines some of the issues identified at the workshop. In some instances statements regarding these matters represent convictions or perceptions in the absence of supporting scientific evidence. However, in most cases, the questions arise from established research inquiry. To be comprehensive in the pursuit of high-level waste salt repositories it is incumbent upon the salt repository advocates to evaluate the full range of subjective and objective themes.

From the Mississippi salt workshop, some contemporary issues were identified and are shown in the following list:

1. **Brine Migration.** Brine exists in rock salt in three forms: fluid inclusions, hydrous minerals and grain boundary water. Owing to the characteristics and environments of the brine in salt, its transport or migration occurs via three primary mechanisms: motion of the brine inclusions in a temperature gradient, vapor-phase transport along connected porosity and liquid transport driven by the stress gradient.
2. **Vapor Transport.** One of the most important issues in a high-level-waste repository is the presence of and the fate of any brine that may be present. It appears that vapor transport processes account for moisture movement, and the often mentioned brine inclusion migration is less important.
3. **Gas Generation and Pressure Buildup**. Hydrogen gas generation from anaerobic corrosion of steel container materials might inhibit rock convergence and consolidation of crushed rock backfill. This topic is generally of importance and is considered in the frame of performance assessment.
4. **Buoyancy.** The movement of canisters containing heat-generating nuclear wastes buried in a salt formation has been questioned. The existence of buoyant forces due to thermally-produced density differences suggests the possibility of initiating convection cells in a plastic medium like salt.
5. **Heat Effects.** It is widely held that the heat load from high-level waste is detrimental to operations and long-term isolation in salt. This perception may be balanced by accounting for heat effects that are favorable to operations and long-term safety.
6. **Damage induced permeability.** Mechanically or hydraulically induced permeability is based on the same microphysical process of percolation flow along grain boundaries after exceeding a threshold. In both cases the induced permeability is created by removal of intergranular cohesion.
7. **Consolidation of Hot Granular Salt.** Crushed salt used as backfill may be an important element in a potential high-level-waste repository. Relatively little elevated temperature mechanical testing has been conducted for crushed salt. The accelerating effect of moisture on consolidation needs further investigation. Modeling concerned with long-term, low-porosity, two-phase flow is likely required.
8. **Solubility and Transport.** The salt repository community continues to research radionuclide solubility as if there is ample brine available within the salt to dissolve and transport the waste. There are at least two parts to this important issue: one concerns brine sources and volume and the other concerns existence of a pressure gradient capable of driving the soluble radionuclides to the biosphere.
9. **Degradation.** This research area addresses the underlying hypothesis that waste forms placed in salt will degrade sufficiently that the residue can be removed readily by a human drilling intrusion.
10. **Radiolysis.** Radiation is known to liberate hydrogen but further data are needed on the effect of combining radiation and temperature on the waste materials, waste packages, and the salt.
11. **Climate changes.** The radioactivity of nuclear waste will decay over a period of time (100,000 years or longer) in which major environmental changes have to be expected. Climatically driven changes such as glaciation, permafrost and changes in sea level will affect the subsurface environment of a salt formation and must therefore be considered in performance and safety assessments.

To be comprehensive in the pursuit of high-level waste salt repositories it is incumbent upon the salt repository advocates to objectively evaluate these issues.

This list is certainly not complete. Other related meetings (Appendix B) between German and American salt researchers will address issues of geochemistry (Carlsbad) and next generation modeling (American Rock Mechanics Association conference). However, each of the items listed above will be elaborated upon in the following sections. As the collaborations move forward, all of these issues and others will be addressed appropriately.

1 Brine Migration

Much conversation has been made about *brine migration* in salt as a serious concern for heat generating nuclear waste. The conceptual model for this phenomenon involves a fluid inclusion trapped within the crystal structure, which tends to migrate toward the heat source because of enhanced solubility on the “hot” end and relatively less solubility on the “cool” end. The fluid inclusion preferentially dissolves salt away from the hot end and deposits the dissolved salt on the cool end, thus the negative crystal migrates toward the heat. The phenomenon of brine migration has been observed in the laboratory and in field experiments.

Brine exists in bedded salt in three forms: fluid inclusions, hydrous minerals and grain boundary water. By way of example, the Salado Salt Formation at the WIPP horizon contains a variable amount (1 to 3%) of water by weight and the vast majority is associated with clay minerals. Owing to the characteristics and environments of the brine in salt, its transport or migration occurs via three primary mechanisms: motion of the brine inclusions in a temperature gradient, vapor-phase transport along connected porosity and liquid transport driven by the stress gradient (Shefelbine, 1982).

From Project Salt Vault until the demise of the civilian salt program, several studies of brine migration were conducted. The first observations of brine migration from Project Salt Vault were perhaps somewhat unfortunate, because the brine release occurred when electrical power was shut down. Loss of power to the heaters in the experiment reversed temperature gradients and reduced the tangential compressive stress at the wall of the vertical test borehole, conditions which allowed the brine accumulated and stopped by the stress gradient to be released into the test hole. In disposal operations there would be no such power shut down and concomitant reversal of the thermal gradient. Nonetheless, brine accumulation was observed after the electrical heaters were turned off, which initiated the lasting issue of moisture behavior in such a setting.

Brine migration tests were performed by RESPEC (1979 to 1982) for the Office of Nuclear Waste Isolation (ONWI) in the Avery Island salt mine in Louisiana. The migration of brine inclusions surrounding a heater borehole were studied on a macroscopic level by investigating gross influences of thermal and stress conditions in situ. Field tests were augmented in the laboratory by microscopic observations of fluid inclusion migration within an imposed thermal gradient. The maximum temperature reached in the field test was 51°C. Moisture collection amounted to grams of water per day. When the heaters were shut off, cooling caused changes in tangential stress, which led to microcracking, opening of grain boundaries, and moisture release.

A bilateral U.S.-German cooperative Brine Migration Test between 1983 and 1985 in the Asse salt mine investigated the simultaneous effects of heat and radiation on salt. This field experiment used ^{60}Co sources and the test configuration included four identical heater arrays. The maximum temperature in the bore hole was 200°C.

Concerning moisture movement there is information from experiments, e.g. DEBORA 1, that don´t show any significant problem for salt with water content that is typical for rock salt from northern Germany. However, if brine migration - and its contribution to the greater issue of vapor transport (see below) - is an issue for German/USA salt repository science exchange could be performed.

2 Vapor Transport

Introduction of heat into the salt formation will provide a thermal engine that will drive moisture movement. Schlich (1986) describes some relevant results obtained by computer simulation of water transport in German rock salt. He modeled water inflow of the heater experiments conducted at the Asse mine. The main result was that an evaporation model with Knudsen type vapor transport combined with fluid transport by thermal expansion of the adsorbed water layers in the non-evaporated zone showed the best agreement with experimental evidence. Thus, it would appear that vapor transport processes dominate moisture movement, whereas the often-mentioned brine inclusion migration is less important.

Potentially, the hydraulic gradient between the far field and the excavated room is initially very high. If the permeability is high enough to allow brine flow, nearly all the brine contained in the disturbed rock zone can flow into the waste rooms. These processes are observed in underground openings in salt. Maximal stress differences occur immediately upon creating the opening, and therefore a near maximal extent of the disturbed ground is shaped quickly, allowing the dewatering process to begin. The accessible brine is likely to migrate down the stress gradient and evaporates into the ventilation air. This issue has to be dealt with in performance assessment and could be object of advanced modeling. The topic is integrated in the FEP-catalogue and is addressed in modeling.

Points regarding brine migration and vapor transport lead to additional areas for collaboration in multiphysics modeling, as will be reviewed in the concluding comments.

3 Gas Generation and Pressure Buildup

Hydrogen gas generation from anaerobic corrosion of steel container materials might inhibit rock convergence and consolidation of crushed rock backfill. Due to the subsequent gas production a time dependent pressure build-up may occur in the long term state of the repository until a level that exceeds the pneumatic fracturing strength of the rock (generally discussed as gasfrac-scenario). For an assessment of the provable impact of increasing gas

pressures on the salt integrity comprehensive experimental investigations were performed during the last 10 years in the laboratory and field scale (e.g. Popp & Minkley, 2010).

The results from long-term gas injection tests in boreholes (at 500 m depth in the salt mine Bernburg, D) convincingly demonstrate that, if the gas pressure build-up equalizes the critical stress state in the salt, a rapid permeation process (i.e. a gas threshold) will take place. This process depends not on the amplitude of σ_{min} but on the difference between p_{Gas} and σ_{min}. The relevant incident is the order of permeability increase during the gas threshold, because it extends significantly the range of tolerable pressure build up rates. Only if the enhanced gas transport capacity of the surrounding salt is exceeded a further increase of pressure becomes likely which could result in pneumatic fracturing at overpressures in the order of several MPa.

However, if pressurized fluids can permeate into the salt, for future proof of complete containment the distance and extent of the permeation zone must be proven which depends on the gas storage capacity of the salt, i.e. porosity and mean pore pressure. In addition, scale effects have to be considered. Aiming on these topics and for extension of the experimental scale a large scale injection test in a vertical gas-tight sealed bore hole (i.e. with a pressurized gas volume of $50m^3$) is actually under preparation in the Merkers salt mine (D).

The gas topic is addressed in the FEP-catalogue and is also topic of a performance assessment. Information on the gas issue is available and has been addressed by R&D-projects and was discussed on a workshop (e.g. Rübel et al., 2007). Information exchange and discussions are of importance to evaluate the topic in detail.

4 Buoyancy

Possible movement of canisters containing heat-generating nuclear wastes buried in a salt formation has been questioned. Various arguments have been put forward, which either state the waste will melt its way downward or buoy its way upward.

The existence of buoyant forces due to thermally produced density differences suggests the possibility of initiating convection cells in a plastic medium like salt. An assessment (Dawson and Tillerson 1978) included consideration of the temperature dependence of the effective viscosity and thermal conductivity of the salt as well as decrease in the thermal output of the heat-generating wastes. A thermomechanically coupled formulation for creeping viscous flow and heat transfer has been used to predict canister motion. The large-deformation creeping behavior of the salt over long periods of time was represented as a viscous fluid with temperature dependent viscosity. Temperature dependent thermal conductivity was included in the analyses. Coupling between the flow field and temperature distribution resulted from temperature dependent material properties, temperature dependent body forces, viscous dissipation and changes in the system geometry.

The analyses performed indicated that very little canister movement will result during the heat producing life of the waste canisters (calculations to estimate the effects were performed by BGR and KT/INE). The results showed a subsidence of only a few centimeters. Nevertheless, this topic is addressed in the FEP-catalogue generated in the frame of the German ISIBEL-project and will be part of a performance assessment). The transient analyses showed that initially the canister used in their study would sink. Due to the formation of a convective cell in the salt from heating by the wastes, the canister would then rise. Eventually, as the convective cell diminished the canister began to sink again. Predicted displacements were less than a canister length during this process. The steady-state analyses provided upper bounds on the magnitudes of upward velocity possible during heating. In all cases, the velocities were sufficiently small to indicate very little movement will occur while the canister is capable of producing heat. The thermoelastic analyses predicted little surface upheaval.

These analyses are more than 30 years old. Perhaps advanced multiphysics modeling can more transparently demonstrate the phenomena associated with placing thermally hot waste in a salt formation. This may be a consideration for collaboration on multiphysics modeling.

5 Heat Effects

It is widely held that the heat load from high-level waste is detrimental to operations and long-term isolation in salt. In fact, the US NRC (10CFR Part 51 2008) states that "Salt formations are being considered as hosts only for reprocessed nuclear material because heat-generating waste, like spent nuclear fuel, exacerbates a process by which salt can rapidly deform. This process could cause problems for keeping drifts stable and open during the operating period of a repository". Workshop participants found this statement somewhat misleading because heat effects are reasonably well known and can be engineered for operational purposes. Room closure acceleration and the crystal plastic processes promote and underground evolution that might actually be favorable to operations and long-term safety.

Temperature effects on salt deformation are dramatic as shown by laboratory tests on natural salt specimens. Elevated temperature in a high-level waste repository will enhance deformation upon placement of the heat-generating waste in the rooms. High temperatures and deviatoric stress states proximal to the waste are likely to enhance dry-out of the underground opening by promoting brine liberation through the combined effects of heat and fractured rock. It is possible that such phenomena could have positive effects in terms of long-term performance because of the liberation and removal of small amounts of brine in the native salt from the disturbed rock zone.

The mechanisms by which salt deformation is enhanced by thermal activation are well known and well documented. The thermomechanical response can now be more accurately modeled using advanced geomechanics capabilities described in the summary. The thermal pulse activates the crystal plasticity of the surrounding salt, which accelerates creep closure and encapsulation. Thermally induced salt plasticity is a constant-volume process. As stress equilibrium is re-established by the accelerated salt creep, permeability is eliminated. This evolution scenario would be the focus of benchmark modeling, comparison and field test validation in collaboration with international salt research groups.

It can be reasonably postulated that heat from disposed waste will initially drive moisture out of the near-field system. It is well known that creation of the underground opening in salt induces a stress gradient, which manifests in an assortment of fractures. A disturbed rock zone forms around the opening. Brine seeps down the stress gradient into the opening, say a drift or

disposal room. A heat-generating source, such as disposed high level waste, would further liberate accessible moisture by vaporization. Thus, the disturbed rock zone and disposed waste heat combine to dry a halo around the waste. The fate of the moisture is another matter, as it may be swept away completely by ventilation, it may be hygroscopically absorbed by the salt in a downstream area where the relative humidity exceeds 75%, or it may condense as the ventilation air cools.

After hot waste is placed in the salt, heat is conducted into the salt, setting up temperature gradients deeper into the surrounding rock. It is possible that inclusions could migrate toward the heat source. However, in the early period when thermal gradients are steep, the migrating inclusion will encounter grain boundaries or microfractures. At that point, the brine inclusion moves down the stress gradient to repository ventilation and is removed from the system. Under these circumstances, a heat source placed within the salt would drive moisture away instead of attracting it. For salt repositories, the heat load can be engineered to bolster many of the positive attributes for disposal.

Furthermore: Even in the early period after emplacement of heat-generating waste, the temperature gradient will be much smaller in situ than in the laboratory experiments in which the process was investigated. Therefore, it is arguable whether fluid inclusions will migrate at all under repository conditions.

6 Damage induced permeability

Undisturbed salt rocks are impermeable. Linked flow paths inside the salt barrier may be created only due to mechanically or hydraulically induced damage (e.g. Minkley & Popp, 2010)

- under deviatoric stresses if the acting stresses exceed the dilatancy boundary (= dilatancy criterion) or
- at increased fluid pressure conditions if the acting normal stresses at the grain boundaries are lowered (= minimum stress criterion).

In both cases the induced permeability is based on the same microphysical process, i.e. removal of intergranular cohesion after exceeding a stress or pressure threshold as described by the respective rock mechanical safety criteria. However, at stress conditions below the respective threshold fortunately self-healing processes will restore the initial salt integrity.

Referring to underground repositories in salt three main processes are identified which are important for a potential loss of salt barrier integrity according to different scales:

- mechanical damage due to transgression of the dilatancy boundary. This process acts mainly in the disturbed rock zone and its extension is limited (dm up to several metres) → near field
- convergence and thermo-mechanical induced stress re-distribution. Depending on the size of the underground excavations and due to the temperature accelerated creep this process reaches to considerable extent (decametre up to several hundred meters) →far field

- fluid pressure driven creation of hydraulic pathways, preferably along discontinuities in the micro- and macro-scale in the rock salt (grain boundaries, bedding planes), at fluid pressures > minimum stress, i.e. σ_{min} → far field

The assessment of integrity for a radioactive waste repository with complete containment in salt focuses on definition of the necessary thickness of the natural geological saliferous barriers and engineered technical barrier systems (EBSAs a proposal for international collaboration on this topic the following issues were identified:

- Appropriate numerical simulation tools are needed to demonstrate the integrity of the geological barrier
- More experimental work, both on the lab and field scale, is required to close the existing gaps of understanding referring to
  - the relevance of the minimum stress criterion (not only for the overall salt barrier integrity but also for EBS) and
  - the efficiency of sealing / healing processes after damage
- Approved permeability/porosity relations under relevant stress conditions (damage/compaction field, over pressurization) are needed to simulate fluid transport inside salt.

7 Consolidation of hot granular salt

Crushed salt used as backfill would likely be an important element in a potential high-level-waste repository. The consolidation of crushed salt is an important process for some concepts of operations for high-level waste disposal. Crushed salt may experience high temperatures; therefore, appropriate information on the respective (long-term) behavior is necessary. In general, understanding crushed salt reconsolidation under these conditions is essential to establish room closure response and thermal conductivity.

Mechanical testing has been conducted at various temperatures (Kröhn et al., 2009). Concerning the measurements of the thermal conductivity of the backfill salt there are experimental results available from the BAMBUS-experiment (Bechthold et al. EUR 19124). Although there is information on various aspects of backfill behavior available, it is recommended to study some in more detail, e.g. some aspects of the influence of moisture, fundamentals of high-temperature, hot, dry reconsolidation as well as some related uniaxial tests on intact salt response would be studied in the laboratory. Moreover, although the compaction process is well described phenomenologically at porosity values above 10 % there are large gaps in the understanding of the compaction process under repository conditions at low porosity values. This concerns also the end point of the compaction process (e.g. end porosity). This should be addressed by laboratory experiments.

8 Solubility and transport

Brine is a very important factor in the overall evolution of a salt repository. As an example in the United States, the Waste Isolation Pilot Plant performance is highly dependent upon the availability of brine. In the performance assessment model brine is essential to promote

corrosion of iron and other metals and to sustain microbial activity. In the absence of brine, a salt repository is extremely robust.

There is a direct linkage between brine availability and the properties of the excavation disturbed zone, which is also called the disturbed rock zone in the USA. The science and engineering underpinning the disturbed rock zone provide the basis for evaluating ongoing operational issues and their impact on performance assessment. Contemporary treatment of the disturbed rock zone remains a key issue for German/USA collaborations.

An underlying premise of waste form solubility is that there is plentiful brine in the repository setting. If this were the case, it would negatively impact performance. In other words, if there is ample brine to dissolve the waste, it would be unlikely that salt would be suitable for repository purposes. The volume of brine depends on the mechanism bringing brine into the repository. As understood from the compliance basis for the Waste Isolation Pilot Plant, for an undisturbed repository at low temperatures, brine can only come in contact with the waste by flowing through or from the excavation damage zone. The permeability of undisturbed halite is too low to permit significant migration of brine. For a high-level waste salt repository, there will be a thermal period, and the potential exists for complete healing of the damage zone during that thermal period. A reasonable expectation of a high-level waste disposal room evolution can be predicted from existing knowledge where:

- The damaged zones around the disposal room release the accessible moisture by flow down the stress gradient and evacuation by the ventilation air
- Room closure will be accelerated by thermal activation of crystal plasticity (flow without damage)
- If the room is backfilled with crushed salt, the granular material will reconsolidate
- Stresses will drive toward equilibrium, which effectively heals damaged rock, and
- The waste is expected to be entombed in dry halite.
- Once the DRZ is healed, the permeability will be similar to that of undisturbed halite.

Nonetheless, research continues on radionuclide solubility as if there is ample brine available within the salt to dissolve and transport the waste during the thermal period. There are at least two parts to this important issue: one concerns brine sources and volume and the other is existence of a pressure gradient capable of driving the soluble radionuclides to the biosphere.

Therefore, resolution of these questions is vital to the viability of high-level-waste repositories. Collaboration on these issues would be greatly beneficial to salt repository programs.

9 Degradation

This research area addresses the underlying hypothesis that waste forms placed in salt will degrade sufficiently that the residue can be removed readily by a human drilling intrusion. In fact, for the compliance analysis for Waste Isolation Pilot Plant degraded waste strength properties, such as waste shear strength, are extremely low in comparison to the range of shear strength most likely to exist in the future states of the waste. Also included in the compliance performance calculations is a notion of particle size distribution, which is inconsistent with the probable evolution of the underground. Crushed, compacted, cemented, and possibly hydrated, solid masses of waste do not evolve to particulate form. Participants at the workshop discussed possible collaboration toward a white paper on waste degradation including analogs and a logical features, events and processes evaluation.

10 Radiolysis

The term radiolysis is used for two different radiation-induced processes that may occur in a high level waste repository. Absorption of γ-quanta in the solid NaCl crystal lattice induces a complex reaction mechanism that finally results in the formation of colloidal metallic sodium and small chlorine gas bubbles. These radiolysis products can accumulate finely dispersed throughout the salt matrix in a halo around each emplaced waste canister, so that an immediate recombination does not occur. The storage of energy is associated with this radiolysis process. The stored energy may be released suddenly by some initiating event. Since the radiolysis process is limited to a radius of about 20 to 30 cm around each high level waste canister, the barrier function of the rock salt is likely not impaired.

While the principal mechanisms are well understood some open questions remain with respect to the total amount of stored energy which is accumulated under repository conditions:

- the effect of energy storage on the γ-radiation dose rate,
- the extent to which various mechanisms may limit the energy storage, such as the reaction of the radiolysis products with water which is naturally present in rock salt,
- the kinetics of the sudden release of stored energy and its effect on the integrity of the salt barrier.

Another radiolysis process is associated with the absorption of γ-quanta and α-rays by water that is present in the vicinity of the waste. This radiolysis process results in the formation of hydrogen gas. Compared to other gas generation processes the radiolytic gas generation is generally two to three orders of magnitude lower. The radiolysis process is only relevant upon direct contact of the waste matrices with water, i.e. after failure of the canisters. This process may lead to the formation of an oxidative chemical environment which may accelerate the degradation of the waste matrices. The associated reactions are understood, in general, but the understanding of the complex reaction scheme could be improved by further in-depth investigations.

A high burn-up spent fuel pellet irradiates its near-field with a γ-dose rate of ~ 4 Gy/h, β-dose rate of ~100 Gy/h and α-dose rate of 400 Gy/h. The penetration depth of the irradiation field is in the meter range for γ- and in the µm range for α-particles in brines causing different yields of reducing or oxidizing species. Under the reducing conditions of a deep disposal in rock salt, only the oxidizing radiolysis products formed in the brine contributes to dissolution processes of spent UO2 fuel. Hydrogen interferes with the oxidative process reducing the dissolution rate, however, natural components of brines, such as bromide, counteract. For this reason, the radiolytic yields (G-values) of relevant species need further investigations.

11 Climate changes

The radioactivity of nuclear waste will decay over a period of time (100,000 years or longer) where major environmental changes may occur. For instance, during the last 100,000 years there have been major fluctuations of climate, including a glacial cycle during which ice sheets have extended from the Scandinavian mountains as far as the German Plain. Therefore climatically driven changes such as glaciation, permafrost and changes in sea level will affect the subsurface environment and must therefore be considered in performance and safety assessments also for deep repositories in salt formations.

Vertical cracks were found in some salt diapirs in northern Germany in the depth on 600 to 700 m, which are not related to internal geological structures or halokinetic processes. Bauer (1991) interpreted them as cryogenic cracks due to thermal contraction induced by cooling processes, which was supported by preliminary thermo-mechanical calculations performed in the nineties.

Referring to climate changes the following processes have to be considered:

- Mechanical/hydraulical integrity of the geological barrier during build-up resp. reduction of the glacier ↗ changing stress deviator during loading/un-loading.
- Thermo-mechanical induced processes, i.e. due to different thermal conductivities and thermal expansion coefficients of cap- and surrounding rocks compared to salt ↗ cryogenic micro-cracks or fractures in the salt barrier.
- Effect of pore-fluid pressures in the geological barrier, i.e. at the bottom of the glacier ↗ Hydro-fracs.
- Shear processes in the hanging wall of the host rock due to the movement of the glacier (in addition to fluid pressures) ↗ hydromechanical induced shear fractures in the top.
- Hydro-geological erosion processes in the cap rock (planar or linear erosion) ↗ reduction of the overburden.

Actually the investigation of relevancy of such processes is part of the preliminary safety assessment of the salt dome Gorleben (D).

Summary comments on the path forward

The issues listed and discussed above provide a beginning for possible areas of collaborations between the salt repository programs in Germany and the United States. The purposes of the workshop have been met by discussion and creation of this material. Elements of the possible path forward, as listed in Table 1, will build on some of these concepts, depending upon priorities and needs of the repository programs. Mutual laboratory testing programs may be the easiest to initiate. Workshops to develop position papers on a particular topic might also be relatively easy to arrange. However, significant advances to salt repository bases reside in melding together several of the issues articulated above into benchmark calculations and possibly into a full-scale proof-of-principle in demonstration experiments. The attendant multiphysics modeling of these phenomena is a closely related subject matter, which will be integrated into collaborative efforts.

Numerical simulations for the design and stability analysis of underground openings in rock salt were recently summarized (Hampel et al. 2010). The geomechanical and hydrological behavior of the host rock is described with constitutive models. In recent decades, various advanced models and procedures for the determination of salt-type specific parameter values and for handling numerical simulations have been developed. Between 2004 and 2010, six project partners have been funded by the German Federal Ministry of Education and Research in two joint projects in order to document, check and compare their constitutive models for rock salt. The results of specific benchmark calculations demonstrate that the models describe correctly the relevant deformation phenomena in rock salt under various influences, i.e. transient and steady-state creep, the evolution of dilatancy and damage, short-term failure and long-term creep failure, post-failure behavior and residual strength. This ensures a high reliability of simulation results that may be applied to long-term prediction of integrity of the geological barrier around an underground repository for hazardous wastes and other applications.

Hampel et al. provided several pertinent conclusions regarding the state-of-the-art in salt modeling. Their benchmark calculations and comparisons of the results in joint projects showed that the constitutive captured deformational phenomena in rock salt below and above the dilatancy boundary. These benchmark calculations modeled an isothermal case. For a high-level repository, data created in former experiments, e.g. BAMBUS, HAW, DEBORA, and, potentially a reliable in situ test result, would be extremely valuable for model validation. The choice of the constitutive model has a larger influence on the calculated strain, dilatancy and damage distributions than on the calculated stress distribution because of the high non-linearity of the stress-strain relation in rock salt. Therefore, in situ strain (convergence) measurements of considerable duration are preferred for model validation.

Collaborative research could build from the previous work and improve tools for assessment of secure storage of radioactive wastes in rock salt. Such collaboration is poised to explore the essential areas of constitutive models which are used in computer simulations for the description of the thermomechanical and hydraulic behavior of the host rock salt under various influences and for its long-term extrapolation into the future.

In the past, extended investigations of the thermomechanical behavior of rock salt were performed and used for the development of constitutive models. However, a comparison of the different models and their theoretical physical bases is still to be done. Therefore, modeling collaborations could begin with coupled thermomechanical three-dimensional benchmark simulations. These calculations would compare the evolution of stresses, strains, dilatancy (volumetric strains), damage, and permeability in rock salt under the influence of high and changing temperatures.

Based on the developments at Sandia with the SIERRA Mechanics (Stone et al. 2010) and the developments described by several German salt researchers, it would appear that different teams have collected a comprehensive experimental data base and theoretical knowledge base for the mechanical deformation of rock salt. Several advanced constitutive models have also been developed and applied. However, the strong temperature dependence on the mechanical deformation of rock salt needs to be reevaluated today if the salt disposal option is selected.

The outcome of the geochemistry workshop should attempt to integrate respective research goals with those described in this paper. The ideal future would include advancing the technical baseline regarding the processes described in the German/USA salt repository workshop, and performing appropriate code benchmark calculations, ultimately leading to a reliable in situ test for model validation.

Table 1. Areas of Interest and Possible Assessment Method

Area of Interest	Specific Data Need	Assessment Method
Response of the DRZ to combined thermal and mechanical effects	• Validation of constitutive model permeability as a function of damage • Field demonstrations • Seal system design	• International collaborations • Laboratory testing • In situ testing • Analog comparisons • Model development
Consolidation of backfill materials	• Thermal conductivity as a function of porosity • Consolidation constitutive model with temperature dependence • Low porosity behavior	• Laboratory testing • In situ testing • Microscopy
Availability and movement of brine	• 3-D coupled analysis tools • Field test measurements and validation	• Code capability development • International collaboration • Literature review • Historic field measurements • In situ testing
Vapor phase transport mechanisms	• Further development of theory • Module development for coupled codes • Field test validation	• Viability of conceptual model workshop • Code capability development • International collaboration • Laboratory testing • In situ testing
Radionuclide solubility controls	• Establish viability of scenario for radionuclide solubility studies	• International collaboration • Laboratory testing
Potential radionuclide	• Establish viability for transport mechanisms	• Theory development • International collaboration

transport mechanisms		• In situ testing
Waste degradation	• Evolution of the disposal room	• Literature research • International collaboration • Analog comparisons
Gas generation and pressure buildup	• Source term • Ensure seal system function	• Laboratory testing • In situ testing • Development of appropriate simulation tools • International collaboration • Analog comparisons
Buoyancy of waste packages	• Consensus from international peers	• Workshop with consensus report • Literature review
Radiolysis of waste materials, waste packages, and salt	• Establish the basis • Review application to HLW repository in salt	• Workshop with consensus report • A joint laboratory program regarding topics mentioned in chapter 10 on radiolysis.
Climate changes	• Local climate scenarios (identification of the relevant processes and time scales) • Coupled analysis tools for simulation of THM-long term processes (> 100,000 years) • Numerical studies of the long term evolution	• Literature research • International collaboration • Development of appropriate simulation tools • Numerical site studies • Analog comparisons

PART B LOGISTICS AND EVENTS

- Meetings and conferences
  - The American Rock Mechanics Association meeting provided an additional opportunity to explore current salt constitutive modeling and future needs for high-level waste disposal in salt. Several avenues of pursuit were identified and will be further developed.
  - Another international meeting is planned between Germany and the USA, sponsored by the Department of Energy on the topic of Salt Geochemistry. The workshop is scheduled for September 15-17, 2010 in Carlsbad New Mexico.
  - In the spirit of reenergized collaboration between salt repository research interests in Germany and the USA, workshop participants agreed to actively participate in the 7th Mechanical Behavior of Salt Conference (Salt VII). The volunteer host is Pierre Berest from Ecole des Mines (School of Mines) over the dates of April 17-19, 2012. This conference has been integrated into the Department of Energy international strategy as one of several goals established for advancing salt repository sciences.

- The concept of a Salt Club was discussed, once again. In previous times, before the German repository moratorium, the collective salt researchers in Germany and the USA outlined goals for a salt club as summarized below:
  - Perform fundamental research into areas where understanding of the deformational behavior is incomplete
  - Provide an educational basis for and knowledge transfer to next-generation researchers
  - Transfer methods and tools for salt storage facilities and mining operations to analyze operations to ensure safe, secure, long-term functionality of the underground structures
  - Make technology available to support future energy supply and infrastructure needs
  - Afford technical experts access to and interchanges with the latest international developments in salt mechanics sciences
  - Develop a central library of acquired salt data, information, and knowledge with broad access provided via the Internet.

These goals remain current, while the possibilities of formally arranging a salt club is pursued.

- The goal of creating a Student Exchange was advanced by Prof. Dr. Klaus-Jürgen Röhlig of the Institut für Endlagerforschung in the Technische Universität Clausthal (Please see the web connection provided in the references). Among the options to be explored is the possibility of German students working at the WIPP site, including the option of preparing MSc theses on a subject related to WIPP. Alternatively, research and development on topics identified in the workshop would be fertile for collaborative theses topics. As German students have varying backgrounds (BSc degrees from chemistry to geology), it should be possible to identify suitable subjects for such theses. This would result in a number of advantages for both sides. Dedicated subjects of interest for salt repository science would be investigated in an academic framework. Students would enlarge their perspective by working abroad on an interesting subject and a scientific exchange between the institutions involved could be initiated.

- Participants discussed the strategic advantage of Memoranda of Understanding between various research entities in Germany and Sandia or the Department of Energy. Another, perhaps more directly applicable vehicle for specific research goals with Sandia is the Cooperative Research and Development Agreement (CRADA). Sandia professionally defines and executes processes that enable internal customers to transact business efficiently and effectively with external customers other than the Department of Energy/National Nuclear Security Agency, while meeting compliance requirements for these engagements.

References

Bauer, G., 1991. Kryogene Klüfte in norddeutschen Salzdiapieren?, Zbl. Geol. Paläont. (Teil 1), H. 4, S. 1247-1261.

Bechthold, W., Rothfuchs, T., Poley, A., Ghoreychi, M., Heusermann, St., Gens, A., Olivella, S., Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS-Project), Final Report, Nuclear Science & Technology, EUR 19124, Brussels, 1999

Dawson, P.R., and J. R. Tillerson. 1978. *Nuclear Waste Canister Thermally Induced Motion*. SAND78-1978. Sandia National Laboratories, Albuquerque NM.

Kröhn, K.-P., Stührenberg, D., Herklotz, M., Heemann U., Lerch, Ch., Xie, M., *Permeabilität von kompaktierendem Salzgrus-Versatz REPOPERM - Phase ,*Final Report GRS – 254, Braunschweig, September 2009

Nuclear Regulatory Commission. 2008. 10 CFR Part 51.

Schlich, M. 1986. *Simulation der Bewegung von im natürlichen Steinsalz enhaltener Feuchte im Temperaturfeld*, Dissertation TH Aachen.

Shefelbine, H. C. 1982. *Brine Migration: A Summary Report*. SAND82-0152. Sandia National Laboratories, Albuquerque, NM

Hampel, A., Günther, R.M., Salzer, K., Minkley, W., Pudewills, A., Leuger, B., Zapf, D., Staudtmeister, K., Rokahr, R., Herchen, K., Wolters, R., Lux, K.-H., Schulze, O., Heemann, U., Hunsche, U. 2010. *Benchmarking of Geomechanical Constitutive Models for Rock Salt*. American Rock Mechanics Association. Salt Lake City Utah.

Minkley, W. & Popp, T., 2010. *Final Disposal in Rock Salt - Geomechanical Assessment of the Barrier Integrity.* 44th U.S. Rock Mechanics Symposium, Salt Lake City, Utah, USA, June 27-30, 2010. ARMA 10-492.

Popp, T. & Minkley, W., 2010. *Salt barrier integrity during gas pressure build-up in a radioactive waste repository – Implications from lab and field investigations* – 44th U.S. Rock Mechanics Symposium, Salt Lake City, Utah, USA, June 27-30, 2010. ARMA ID No. 10-493.

Rübel, A., Noseck, U., Müller-Lyda, I., Kröhn, K.-P., Storck R., *Konzeptioneller Umgang mit Gasen im Endlager,* GRS-205, Braunschweig , Dezember 2004

Rübel, A., Mönig, J., *Gase in Endlagern in Salz*, Workshop, Berlin, 17. -18. April 2007, GRS-242

Stone, C.M., Holland, J.F., Bean J.E. and Arguello, J.G. 2010. *Coupled Thermal-Mechanical Analyses of a Generic Salt Repository for High Level Waste*. American Rock Mechanics Association. Salt Lake City Utah.

http://www.sandia.gov/SALT/SALT_Home.html

http://www.sandia.gov/SALT/Presentations/K_Roehlig.pdf

ANNEX

The presentations by Mark Horstemeyer and Klaus-Jürgen Röhlig were put in the annex of the proceedings. They are additionally integrated although they are not directly linked to the subjects of the workshop. Seen in a greater perspective, though, it was felt that they are very important to be published and being available to a greater audience.

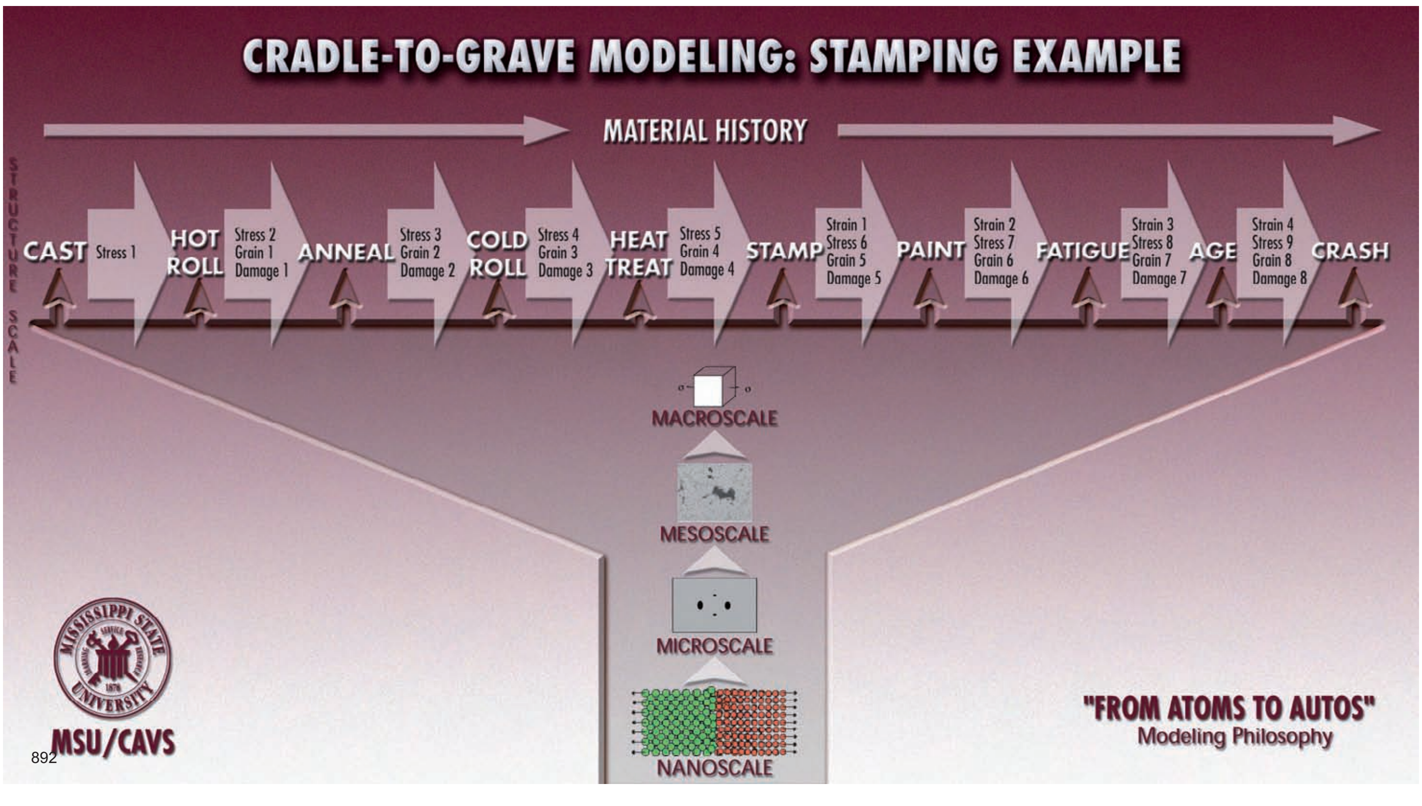
Multiscale Materials Modeling

Dr. Mark Horstemeyer
CAVS Chair Professor
ASME Fellow
Mississippi State University
mfhorst@me.msstate.edu
662.325.5449

891

Computational Manufacturing and Design

Mission: We couple multidisciplinary research of solid mechanics, materials, physics, and applied mathematics in three synergistic areas: theoretical modeling, experimentation, and large scale parallel computational simulation to optimize design and manufacturing processes.



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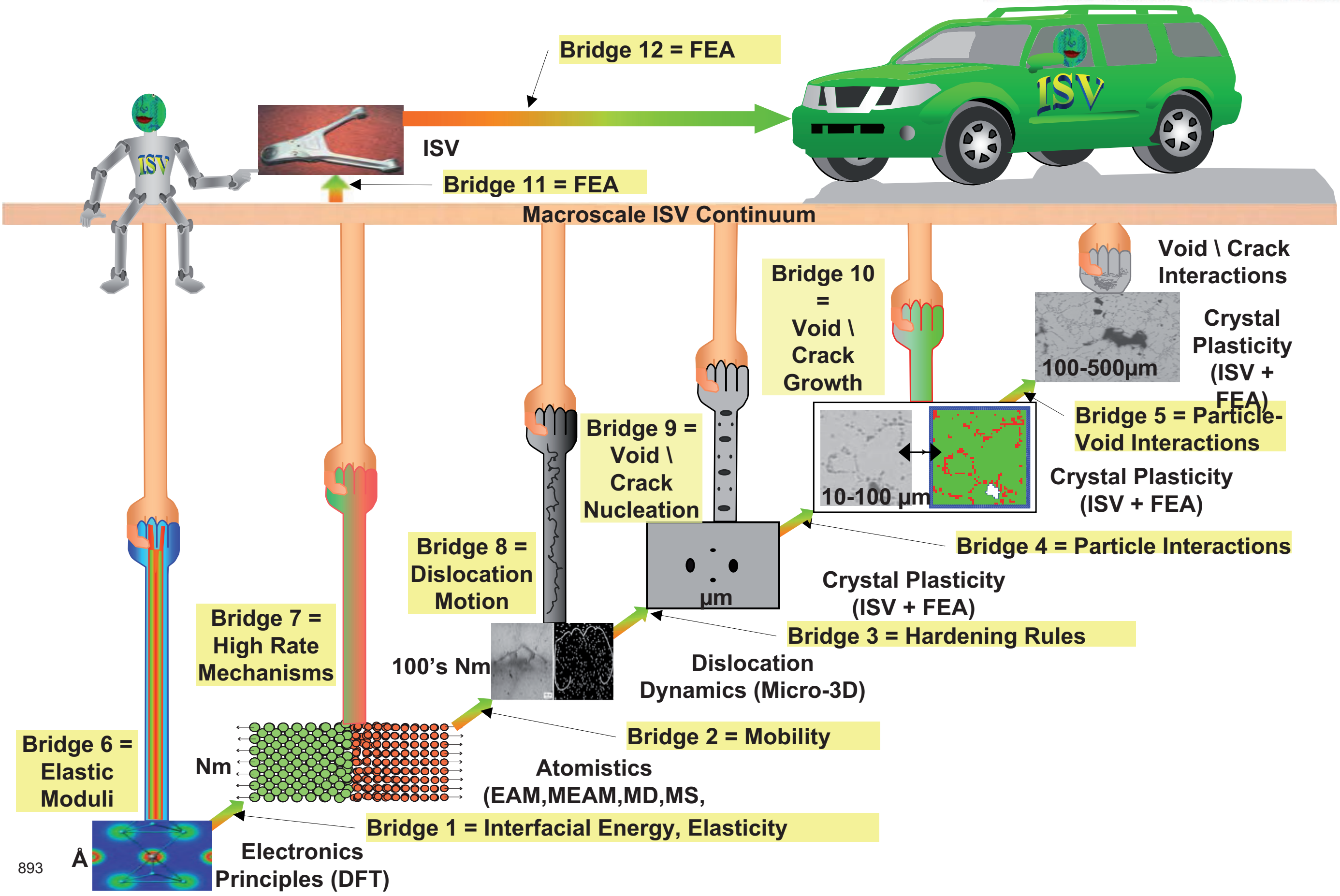
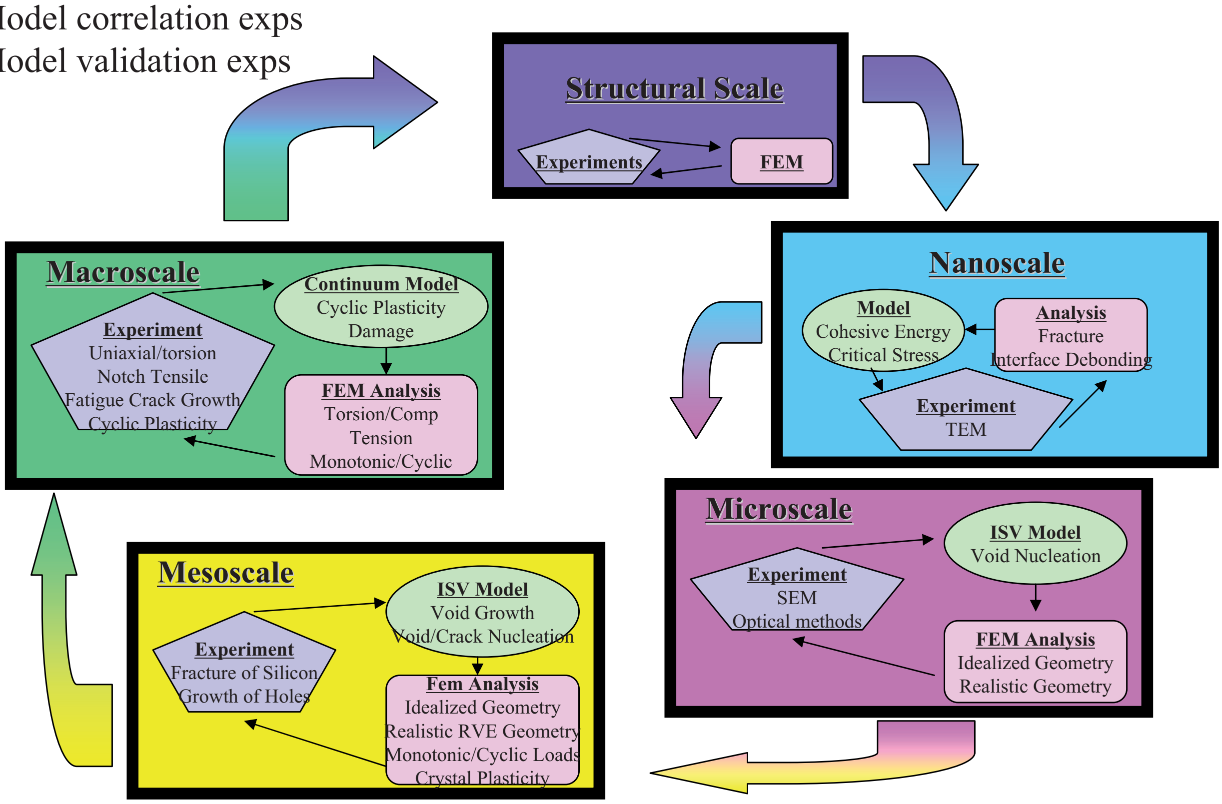
Multiscale Modeling



893

Multiscale Experiments

1. Exploratory exps
2. Model correlation exps
3. Model validation exps



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Design Optimization

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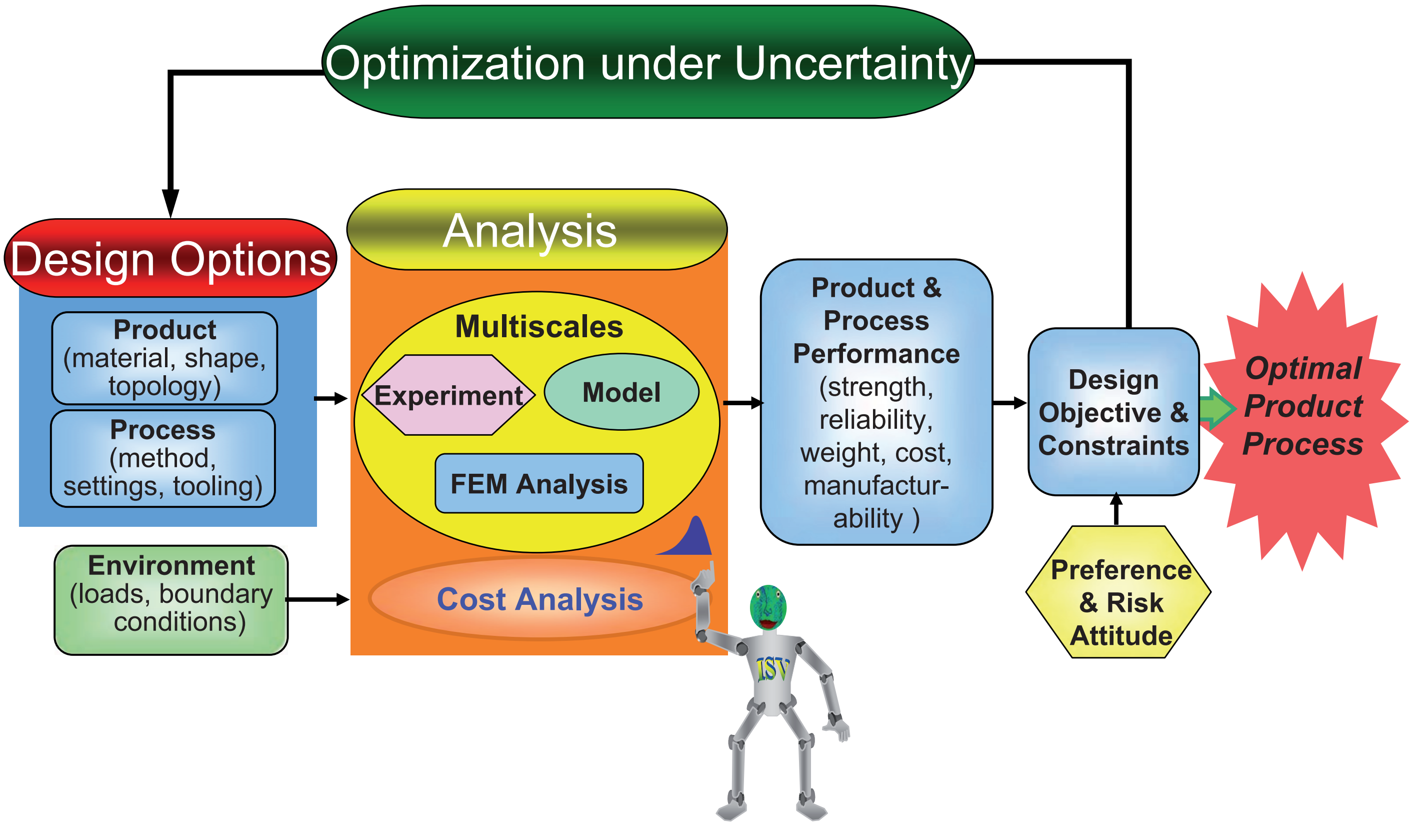

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CyberInfrastructure

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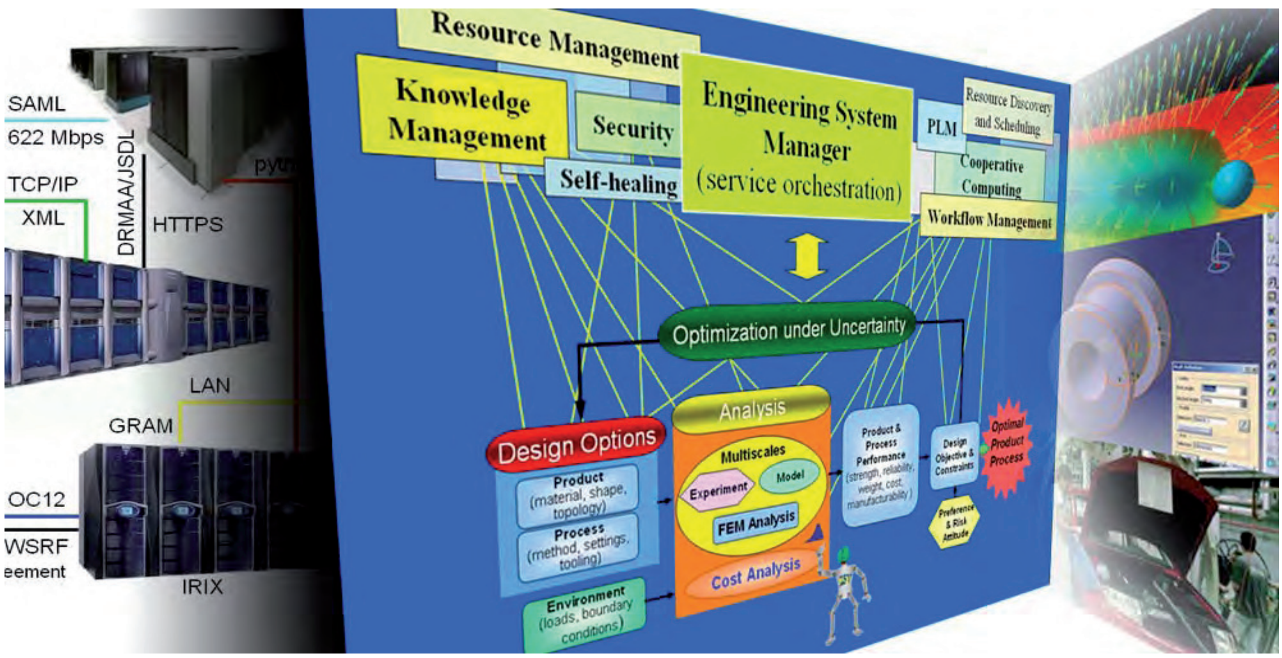
IT technologies (hidden from the engineer) | Conceptual design process (user-friendly interfaces) | Engineering tools (CAD, CAE, etc.)



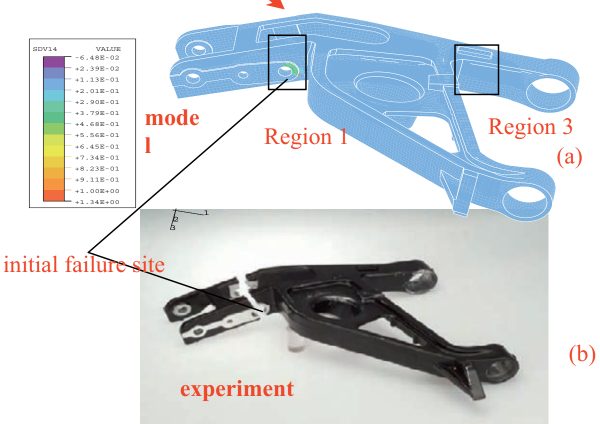
GM CADILLAC CONTROL ARM LIGHTWEIGHT DESIGN (2000)

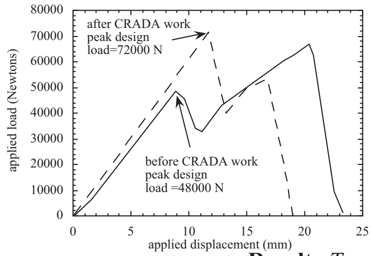
Objective: *To employ multiscale material modeling to reduce the weight of components*

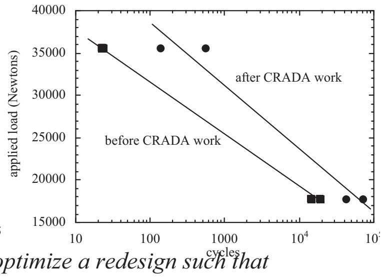
Wrong!

Truth!

Standard FEA Stress (from highest to lowest)	Inclusion (from most severe to less severe)	Damage (from most severe to less severe)
D	B	A
A	E	D
C	A	E
E	D	C
B	C	B







Result: *To optimize a redesign such that*
25% weight saved
50% increase in load-bearing capacity
100% increase in fatigue life
$2 less per part

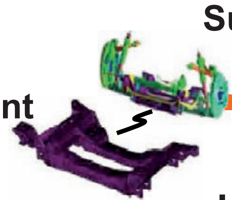
897

GM Corvette Cradle Magnesium Design (2005)

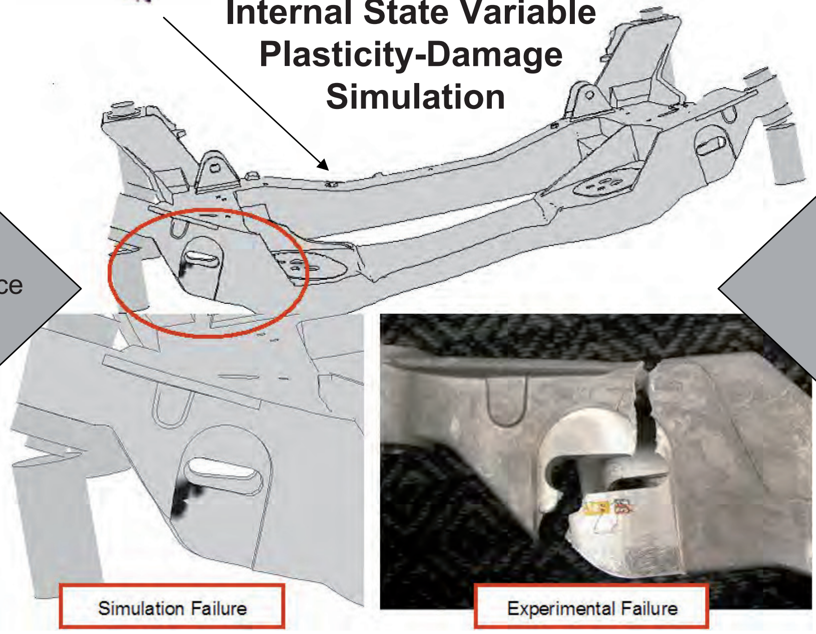
System

Subsystem

Component



Internal State Variable Plasticity-Damage Simulation



Structures
Pore size
Nearest Neighbor Distance
Dendrite Cell Size
Porosity

Boundary Conditions
Panic brake
Pothole strike
Forces
Moments

898

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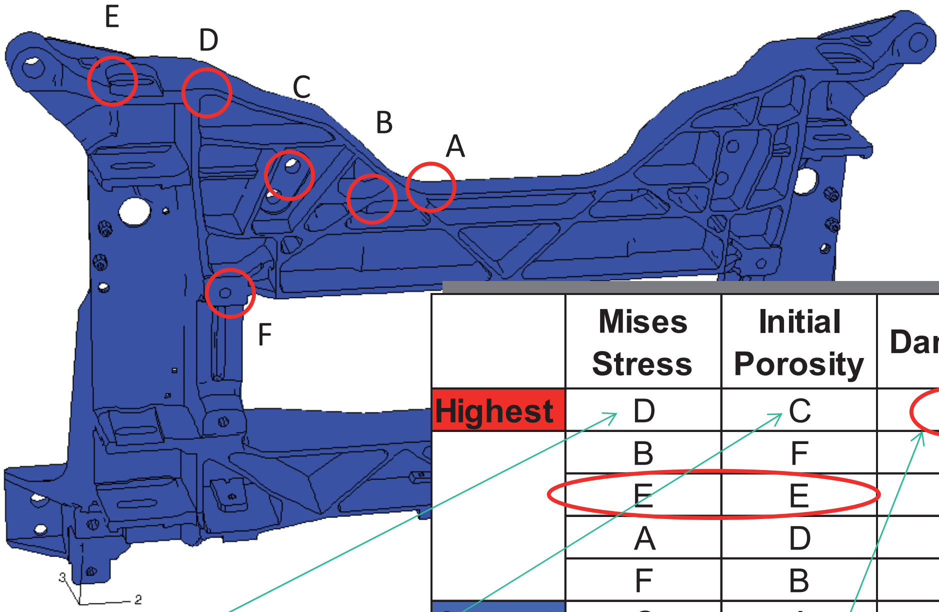
Cradle Load-to-Failure Simulation Results



	Mises Stress	Initial Porosity	Damage
Highest	D	C	E
	B	F	B
	E	E	D
	A	D	A
	F	B	F
Lowest	C	A	C

Modern FEA answer

Modern Materials Science answer

True answer

899

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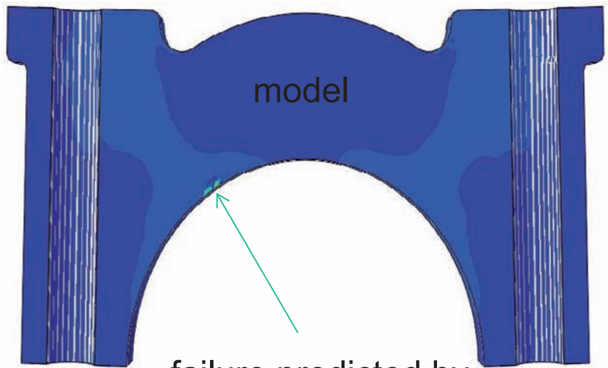
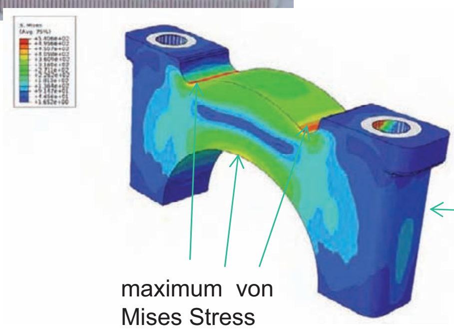
Powder Metal FC0205 Steel (2008) Compaction, Sintering, and Performance



failure predicted by damage model under performance with distribution of initial porosity



maximum von Mises Stress

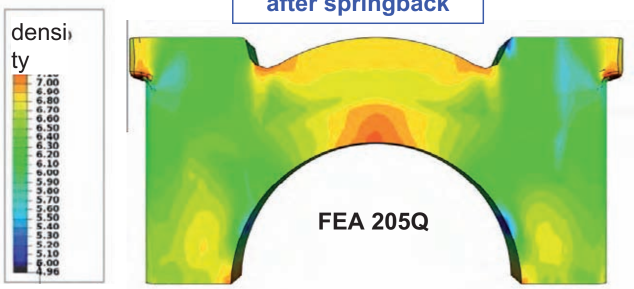
Note: standard FEA would have given the wrong location

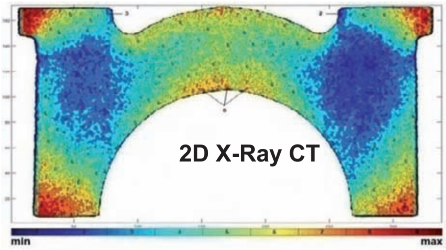
900

FEA Model
Geometry and Material Solution imported from ABAQUS/ Explicit to ABAQUS/Standard for Elastic Springback Analysis

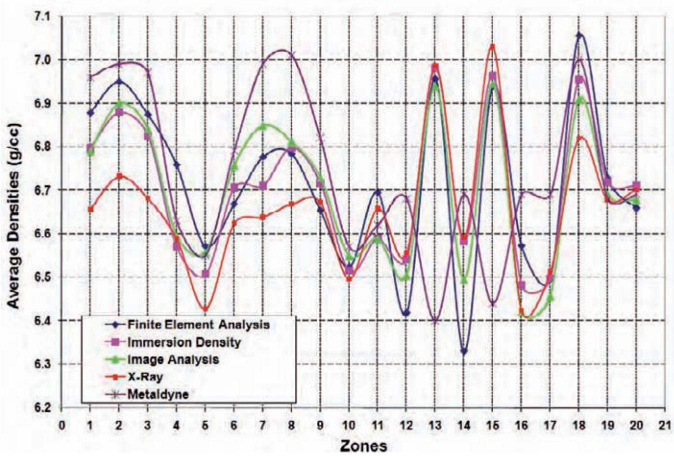
Experiment
X-ray CT

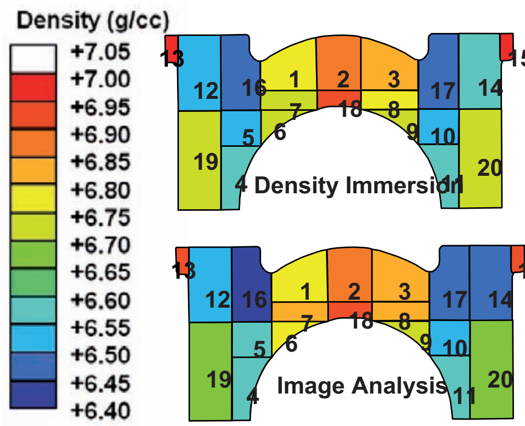
Volume grows 0.6% after springback





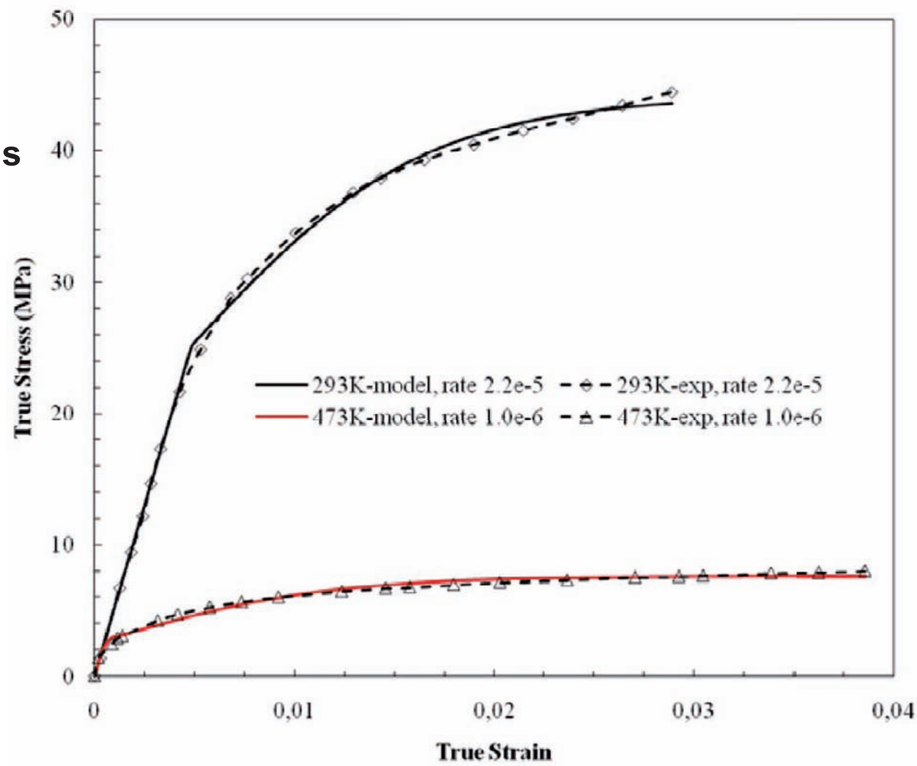
Experiment
Immersion and Image Analysis
Densities by Zone





Halide (Rock Salt) Model Correlation

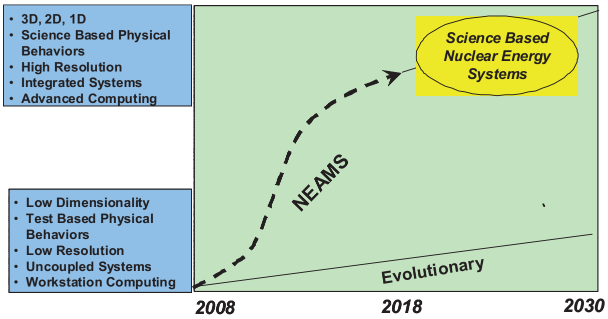
Over 70 metal alloys and other **Geomaterials** have been modeled (Marble, Olivine, & Lherzolite)



Experimental data from Aubertin et al. (1991)

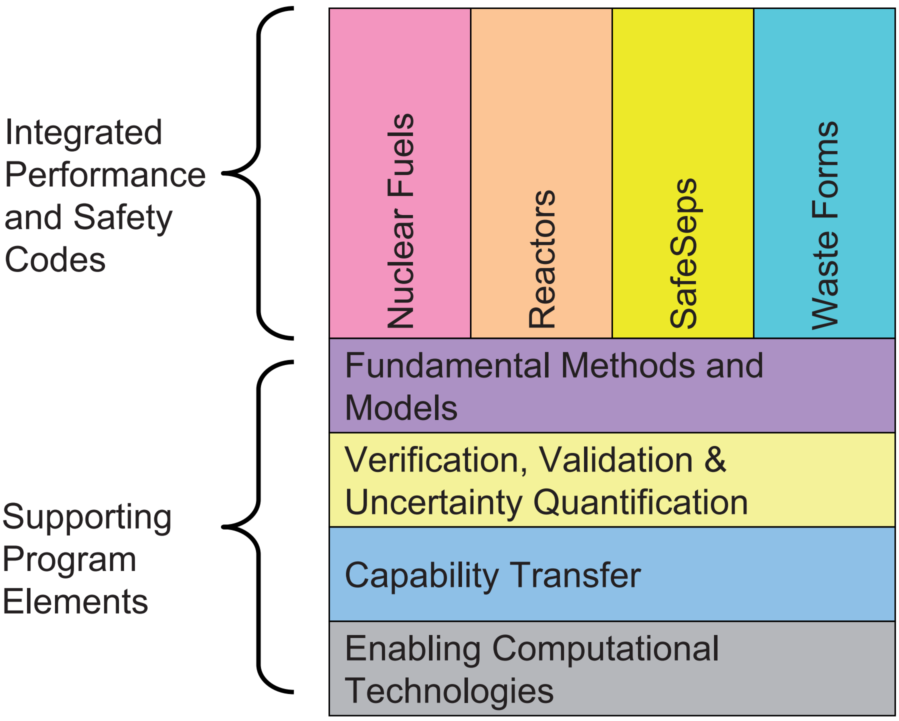
NEAMS Will Deliver . . .

- Continuously increasing capability for predictive simulation of the performance and safety of:
  - Nuclear reactors
  - Fuels
  - Safeguarded Separations
  - **Waste Forms in a Repository Environment**
- These capabilities will be flexible so they can be applied to difference types of nuclear energy technologies
- NEAMS will implement a comprehensive approach that ensures that new capabilities are fully developed and "born" with appropriate verification, validation and uncertainty quantification.



- Modeling and simulation capabilities that can be used to create scientific understanding, design, and license nuclear energy technologies for:
  - Sustainment of the current LWR fleet
  - Near term deployment of new advanced reactors
  - Innovative uses of nuclear energy
  - Proper disposal of waste
  - Closing the fuel cycle

NEAMS Organization Provides All Essential Components



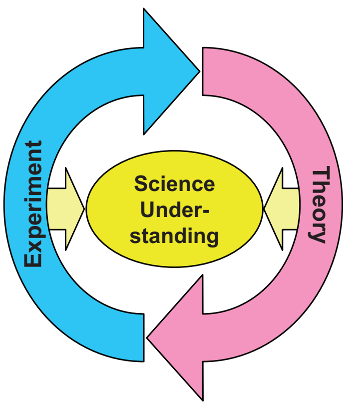
~$150M Fuel Cycle R&D
~$150M GEN IV R&D

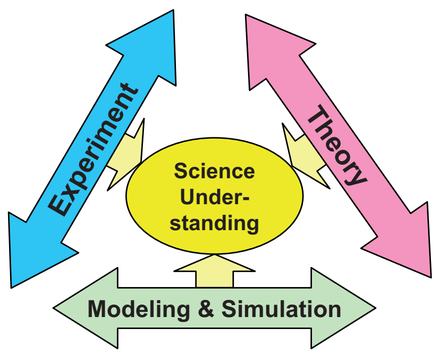
Current CAVS Nuclear Related Modeling Funding

- **PNNL**: multiscale modeling of ***cladding*** failure
- **INL**: multiscale modeling of ***ageing*** of fuels and ***corrosion*** modeling of materials
- **ORNL**: multiscale modeling for new ***materials designs***
- **NEUP**: multiscale modeling of ***inelasticity*** of ***ageing concrete***

905

Role of Modeling & Simulation in Shift to Science Based Approach





- Traditional Science Approach
  - Theory drives design of Experiments
  - Experiments provides discoveries to drive Theory
  - Empirically based modeling and simulation heavily dependent on staying close to experimental basis
- Addition of Science Based Modeling and Simulation
  - Science (1st principles) based modeling and simulation used to extrapolate and predict beyond tested states
  - Can quickly confirm or disprove Theory hypotheses
  - Improve experiments by predicting "areas of interest" and expected results

906

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MEPI
Mississippi Energy Policy Institute

Nuclear Committee

Committee Policy Recommendations

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Synthesis of Recommendations

- New Nuclear Build
  - Encourage the development of existing and future design nuclear power plants.
- Manufacturing Hub
  - Position the state as a domestic/international hub for nuclear component manufacturing.
- Used Fuel Storage
  - Develop interim and permanent storage strategies
- Used Fuel Reprocessing
  - Advocate and influence reprocessing technology
- Work Force Development
  - Develop and train the future nuclear workforce to support manufacturing and operations.
- Community Outreach
  - Execute a marketing and outreach plan to educate citizens about the perceived risks of nuclear power.

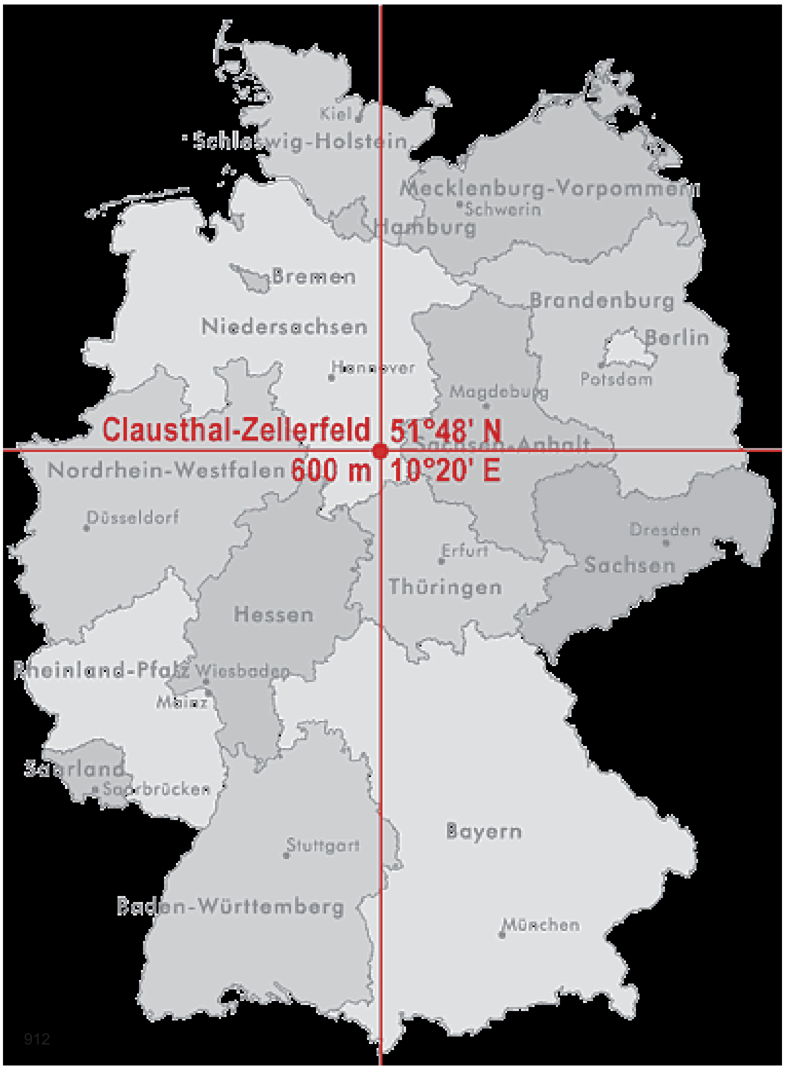
Timeline

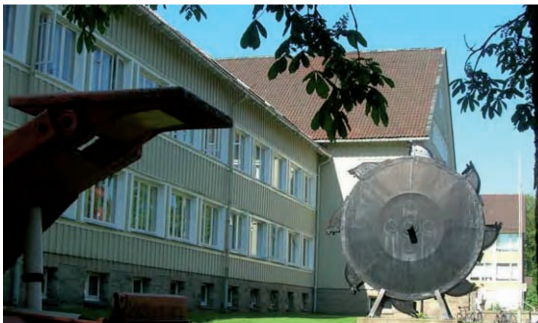
- Proposed Committee Meetings
  - October 1: Review Draft Proposals
  - October 15: Finalize Committee Proposals
- October 27
  - MEPI meeting to be held in Jackson
- December 2009
  - MEPI Public meeting to discuss path forward

TU Clausthal

Institute of Disposal Research (IELF)
Education and Training

Klaus-Jürgen Röhlig





Institute of Disposal Research (IELF)

- Founded: August 1, 2007

- Departments:
  - Geochemistry – mineralogy – salt deposits (Mengel)
  - Deposit research (Lehmann)
  - Repository systems (Röhlig)
  - Hydrogeology and hydrogeochemistry (van Berk)

  - Geomechanics (Lux, associated department)

TU Clausthal

Master of Science
„Radioactive and Hazardous Waste Management“
4 semesters, (120 ECTS)

- Consecutive for TUC BSc
  - „Geoenvironmental Engineering“
  - „Energy and Resources“

- Also accepted:
  Other BSc and diploma (Natural sciences, engineering, mathematics)
  ☾ Commission decides on acceptance and on compulsory optional modules to be attended

bologna process

TU Clausthal

Master of Science in Radioactive and Hazardous Waste Management

Competence in Engineering and Geoscience

for all Processes and Phases of
Radioactive and Hazardous Waste Management

Waste and Conditioning → Site investigation of Underground Repositories → Geotechnical and Geoscientific Analysis → Long-Time Safety Assessment and Permission → Construction, Operation and Closure

TU Clausthal

Master of Science „Radioactive and Hazardous Waste Management“ (120 ECTS)

- 11 compulsory modules
  - Site Characterization
  - Geomechanics
  - Numerical Simulation
  - Waste Inventory
  - Licenses and Regulations
  - Petrology and Geochemistry
  - Repository Concepts
  - Long-term Safety
  - Disposal Techniques
  - Main Seminar / Field Trips
  - Master Thesis
- 7 compulsory optional modules (3 or 4 out of 7 lectures / courses)
  - Hazardous Waste Treatment
  - Practical Training Geochemistry
  - Practical Training Petrology
  - Isotope Geochemistry
  - Hydrogeochemical Modelling
  - Environmental monitoring
  - Risk management & Communication
- 4 complementary modules
  - Geological Structures
  - Groundwater Flow & Composition
  - Hydrogeology & Geochemistry
  - Practical Training Hydrogeology

- 25 % of lectures and seminars are given by experts from industry and legal authorities
- Presently: Modification – replacing part of compulsory optional modules and complementary modules by modules to be chosen dependent on background of students
  - individually “tailored” curriculum

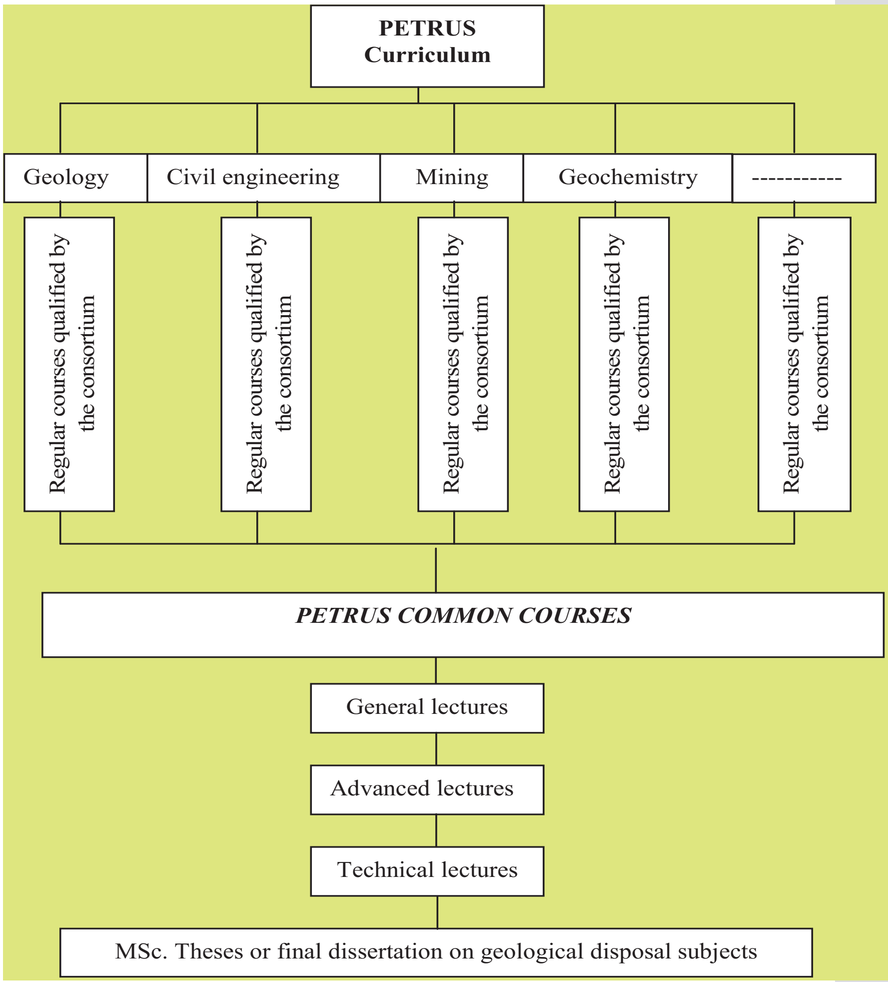
European Master
Radioactive Waste Management / Underground Storage

- Additional Certificate (no degree in itself)
- 20 – 40 ECTS, optional: master thesis
- Remote teaching
- Funded within FP6 ENEN project
- Institutions:
  - CTU Prague: Civil Engineering
  - UPM Madrid: Mining engineering / geosciences
  - INSL Nancy: Mining engineering / geomechanics
  - TU Clausthal: Complete curriculum

Program of
Education and
Training in
Underground
Storage

Each institution should select 20 – 30 ECTS among standard courses taught in different disciplines, which can be identified as having a direct link with the geological disposal.

Institutions agree to allocate 10 ECTS to the "common courses".



PETRUS II

1. Implement the Petrus curriculum according to ENEN principles

2. Create a European Training Scheme for Professional Development/ Continuing Further education

3. **Create mobility market via database offerings "Bank"**
4. **Feasibility study for recognition of Professional development and life-long learning**

5. Create a network with end-user contacts / end user council together with e.g. the TP in GD for QA and markets
6. Study on remote face-to face infrastructures
7. QA according to ENEN guidelines

Joint IAEA – TUC training

- Target group: young employees (graduate MSc or equiv. in natural or engineering sciences) of RWMOs, authorities, TSOs (mainly from developing countries? ☾ if so, „in-house knowledge" at employers different from that in more developed*) countries)

  *) „developed" = „with advanced RWM programme"
- Objective: Provide attendees with general overview of issues relevant for radioactive waste management, in particular with relevant IAEA standards framework
- Two sources of material
  - IAEA / WES syllabus
  - TUC / IELF curriculum MSc RHWM (for the latter: existing teaching experience, but courses need to be translated / transformed)
- Duration: 6 weeks including field trip(s) – weeks 36 - 41
- Venue: TU Clausthal

US-German Workshop on Salt Repository Research, Design, and Operation
May 25-28, 2010
Jackson, Mississippi USA

Today is May 19, 2010

Host:
Mississippi State University and the State of Mississippi

- Mark F. Horstemeyer, CAVS Chair Professor in Computational Solid Mechanics, ASME Fellow Mechanical Engineering mfhorst@me.msstate.edu 662.325.5455 http://www.cavs.msstate.edu/cmd/
- Rose Mary Dill. Center for Advanced Vehicular Systems, Room 2160, 200 Research Blvd., Starkville, MS 39759 Mississippi State University Mail Stop 9618 rmdill@cavs.msstate.edu (662) 325-8839

Mississippi State University (MSU) will take care of caterers, communal busing when needed, the milieu, and an appropriate technical field trip. The field trip is **optional** and details may change. We will have food brought into the conference center so we can get as much done as possible during the workshop.

Facilities:
MSU CAVSE (Center for Advanced Vehicular Systems Extension facilities located at 153 Mississippi Parkway Canton, MS 39046 has been reserved for May 25-27. The venue has been changed to Canton, MS at the behest of the host MSU. The Governor of MS may address the workshop.

Air travel arrangements:
Participants should arrange to arrive in Jackson MS by the evening of May 24, 2010. There are several carriers including American, Continental, Delta, and KLM that service Jackson-Evers International Airport.

Hotel information:
A block of 40 rooms has been reserved at The Comfort Inn, 145 Soldier Colony Road, Canton, MS (601) 859-7575. Rooms have been held under "CAVS RESEARCH" $62.99/per night (Rooms held for May 24 – May 27), continental breakfast provided by hotel.

,

Itinerary:
Technical Workshop will commence at 8 am, May 25. Travelers should arrive no later than Monday evening (May 24) at the hotel.

Vans will be available to transport participants from the hotel to the CAVSE (Center for Advanced Vehicular Systems Extension, 153 Mississippi Parkway Canton, MS 39046, (601) 407-2700) on Tuesday morning. Leave at 7:15 from the hotel lobby.

Proposed Agenda

Preamble:
Due to recent developments, both Germany and the United States are poised to renew their efforts in salt repository investigations. There is a desire on both sides 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. To this end, a workshop is proposed to map out a potential research agenda and to renew working relationships at the institutional and individual levels.

Objective:
The purpose of this workshop is to assemble invited key investigators in salt repository science and engineering and to identify a coordinated research agenda that participants can agree in principle to pursue (singularly or in concert with others), with the intent of maximizing individual resources for the mutual benefit of each program.

Presenters are asked to draft a two-page outline/abstract, which concisely reviews his/her area of expertise. Specifically describe what work has been done previously in the field and why it's important to high-level waste disposal in salt. Evaluate the current status and conclude with brief statements that identify specific research areas for advancing the state of the art. Note: Material from this workshop will be combined with constitutive model status and radionuclide chemistry information from the ARMA conference (Salt Lake City) and the Carlsbad geochemistry workshop, respectively. Defined research programs may be formalized by memoranda of agreement between the responsible funding entities (e.g., Ministry) and research institutions, as deemed appropriate.

Format:
The workshop is scheduled for two days of technical presentations and discussion followed by one day for a technical visit. Topical areas are divided into technical sessions identified in the attached agenda. Nominally, there will be an equal number of technical representatives from the US and German teams on each subject matter. Frank Hansen (Sandia/USA) and Walter Steininger (Germany) will moderate the workshop.

US/German Workshop on Salt Repository Research		
Tuesday, 5/25/10	***Workshop Day 1***	• ***Breakfast on your own*** • ***Refreshments at conference center*** • ***Catered lunch*** • ***Group dinner in the evening***

7:15 am	Bus/Van hotel to conference center	Bus/Van hotel to conference center
8:00 am	Welcome: Steininger/Biurrun/Orrell/Horstemeyer	

Introduction		
8:15 am	Opening remarks	Mark Horstemeyer, Mississippi State University
	Dr. Teresa Gammill Dr. Roger King	Assistant Vice President/ORED Director of CAVS
8:45 am	Welcoming remarks by the Governor's Office of the State of Mississippi	Michael Bograd State of Mississippi Geologist
9:00 am	Introductions of participants	Frank Hansen
9:20 am	Overview of German R&D activities	Walter Steininger
9:40 am	Overview of US R&D activities	Andrew Orrell

SESSION 1: Safety Case		
10:00 am	C. Hansen, SNL	Safety Case approaches in a world wide context – the PAMINA project: The American perspective
10:30 am	***Morning Break***	
10:45 am	J. Mönig	Towards the German Safety Case – the ISIBEL project
11:15 am	K. Röhlig	From release scenario to safe containment – evolution of the safety case for disposal in rock salt
11:45 am	T. Pfeifle, SNL	Disposal of high-level radioactive waste in bedded salt in the United States

LUNCH (CATERED) 12:15 – 1:00 PM

SESSION 2: Salt Repository Concepts and Designs		
1:00 pm	Joe Carter, Savannah River	Waste inventory, issues of above ground storage, aging and transportation, and introduction of generic salt repository studies
1:30 pm	J. VanderKratts	WIPP Operations
2:00 pm	R. Nelson DOE	How WIPP operations were applied to a conceptual repository for HLW in salt
2:30 pm	E. Biurrun	German concepts to dispose of nuclear wastes
3:00 pm	W. Bollingerfehr	Optimization of the direct disposal concept by vertical borehole emplacement of SF elements
3:30 pm	**Afternoon Break**	

SESSION 3: Modeling of Groundwater Flow and Radionuclide transport		
4:00 pm	J. Mönig	Groundwater and transport modelling using the codes d³f and r³t

4:30 pm	G. Wittum	Modeling and simulation of thermo-haline groundwater flow and transport
5:00 pm	R. Beauheim SNL	WIPP groundwater flow studies
5:30 pm	S. McKenna, SNL	Advanced concepts for groundwater flow in dynamic stress fields
6:00 pm	H. Geckeis	Research on geochemical aspects of nuclear waste disposal

Group Photograph & Adjourn

Dinner arrangements as a GROUP – 7 to 9 pm

Wednesday, 5/26/10	***Workshop Day 2***	▪ ***Breakfast on your own*** ▪ ***Refreshments at conference center*** ▪ ***Catered lunch***
7:15 am	Bus/Van hotel to conference center	

SESSION 4: Geotechnical Barriers (plugging, sealing, backfilling, buffer)

8:00 am	N. Müller-Hoeppe	An engineering approach for a safety concept for disposing of HLW
8:30 am	T. Rothfuchs	Backfill compaction and EDZ recovery
9:00 am	L. Van Sambeek, RESPEC	Science and engineering of seal design
9:30 am	F. Hansen, SNL	Monitoring and performance confirmation

SESSION 5: Site Characterization and Host Rock Characterization

10:00 am	**Morning Break**	
10:30 am	K. H. Lux	State-of-the-art in constitutive modeling
11:00 am	O. Schulze	Evolution of damage and healing in the EDZ
11:30 am	J. Hammer	Geological exploration and 3d modeling of a saliferous host rock formation – the Gorleben salt dome
12:00pm	D. Holcomb, SNL	Laboratory and field R&D investigations of salt

LUNCH (CATERED) 12:30 – 1:30 PM

1:30 pm	P. Kamlot	Geomechanical layout and barrier integrity of a rock salt repository
2:00 pm	T. Popp	The gas issue in salt formations - Status of laboratory studies
2:30 pm	K. Mellegard, RESPEC	Laboratory testing of salt
3:00 pm	L. Schneider	In-situ experiments, Investigations, HAW investigations, Russian Salt Experiments

3:30 pm	**Afternoon Break & transition to wrap-up session**

SESSION 6: Wrap up, final discussion, future

4:00 pm	W. Steininger, A. Orrell, E. Biurrun, F. Hansen	Panel: Wrap up and final discussion Optional Topics
Optional Topics	F. Hansen, T. Rothfuchs E. Biurrun	Urban legends, salt club Vapor transport

Thursday, 05/27/10	***Workshop Day 3 Technical Visit***
7:00 AM	(Optional field trip) Depart Canton for U.S. Army Research and Development Center, Vicksburg (On your own) LUNCH Civil War Memorial & return to Canton

Additional Attendees			
King	Roger	Director	CAVS
Dill	Rose Mary	Administrative Assistant	CAVS, MSU
Brewington	Debi	Administrative Assistant	CAVS, MSU
Waggoner	Charlie	Deputy Director & Assoc. Research Professor	Institute for Clean Energy Technology, MSU
Francis	David	Grad Student	Mechanical Engineering, MSU
Prabhu	Raj	Grad Student	Mechanical Engineering. MSU
Grewal	Harpreet	Grad Student	Mechanical Engineering, MSU
Tschopp	Mark	Assistant Research Prof.	CAVS, MSU
Moody	Jack	Geologist	Mississippi Development Authority
Bograd	Michael	State Geologist and Director	State of Mississippi
Dean	Jason	Staff	Fidelis Policy Group
Coleman	Rick	Engineering Manager	Southern Ionics, Inc.
Sundbeck	Milton	President	Southern Ionics, Inc.
Weimer	Randy	V. P. of Sales and Commerical Development	Southern Ionics, Inc.
Steelhammer	J.		Southern Ionics, Inc.
Knox	Eric	Operations Manager, Energy & Construction	URS
Gammill	Teresa	Assistant Vice President	Research and Economic Development for MSU

LAST NAME	**FIRST NAME**	**TITLE**	**COMPANY**
German Participants			
Biurrun	Enrique	Head of Int. Coop. Dept.	DBE TEC
Bollingerfehr	Wilhelm	Head of R&D Projects Dept.	DBE TEC
Düsterloh	Uwe	Senior Scientist	TU Clausthal
Geckeis	Horst	Prof., Head of Institute	KIT, INE
Hammer	Jörg	Head of Department	BGR
Kamlot	Peter	Senior Scientist	IfG
Lux	Karl-Heinz	Prof. Head of Institute	TU Clausthal
Mönig	Jörg	Head of Department	GRS
Müller-Hoeppe	Nina	Senior Scientist,	DBE TEC
Popp	Till	Senior Scientist	
Röhlig	Klaus-Jürgen	Prof. Head of Institute	TU Clausthal
Rothfuchs	Tilmann	Head Endlagersicherheitsforschung	GRS
Schneider	Lutz	CEO	Stoller Ingenieurechnik
Schulze	Otto	Senior Scientist, Eng. Geology Department Head	BGR
Steininger	Walter	Program Manager International Cooperation	KIT, PTKA-WTE
Wittum	Gabriel	Prof. Head of Institute	Uni Frankfurt
US Participants			
Beauheim	Rick	Technical Staff	Sandia National Laboratories
Carter	Joe	Senior Scientist	Savannah River
Freeze	Geoff	Technical Staff	Sandia National Laboratories
Hansen	Frank	Technical Staff	Sandia National Laboratories
Hansen	Cliff	Technical Staff	Sandia National Laboratories
Holcomb	David	Technical Staff	Sandia National Laboratories
Horstemeyer	Mark	CAVS Chair Professor	Mechanical Engineering, MSU
McKenna	Sean	Technical Staff	Sandia National Laboratories
Mellegard	Kirby	Laboratory Manager	RESPEC
Nelson	Roger	Chief Scientist	DOE
Orrell	Andrew	Director	Sandia National Laboratories
Pfeifle	Tom	Manager, Geomechanics	Sandia National Laboratories
Van Sambeek	Leo	Field Test Manager	RESPEC
VandeKraats	John	Manager	URS/WIPP
Rempe	Norbert		WIPP

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Waggoner	Charlie	Deputy Director & Assoc. Research Professor	Institute for Clean Energy Technology, MSU
Francis	David	Grad Student	Mechanical Engineering, MSU
Prabhu	Raj	Grad Student	Mechanical Engineering. MSU
Grewal	Harpreet	Grad Student	Mechanical Engineering, MSU
Tschopp	Mark	Assistant Research Prof.	CAVS, MSU
Moody	Jack	Geologist	Mississippi Development Authority
Bograd	Michael	State Geologist and Director	State of Mississippi
Dean	Jason	Staff	Fidelis Policy Group
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Sundbeck	Milton	President	Southern Ionics, Inc.
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Gammill	Teresa	Assistant Vice President	Research and Economic Development for MSU

Source: http://www.sandia.gov/SALT/SALT_Home.html

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