ARMA 15-303

SAND2015-1234C

Geomechanics Issues Regarding Heat-Generating Waste Disposal in Salt

Hansen, F. D.
Sandia National Laboratories, Albuquerque, New Mexico, USA
Popp, T.
Institut für Gebirgsmechanik (IfG), Leipzig, Germany

This paper was prepared for presentation at the 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco CA USA.

ABSTRACT: With an abundance of scientific information in hand, what are the remaining geomechanics issues for a salt repository for heat-generating nuclear waste disposal? The context of this question pertains to the development of a license application, rather than an exploration of the entire breadth of salt research. The technical foundation supporting a licensed salt repository has been developed in the United States and Germany since the 1960s. Although the level of effort has been inconsistent and discontinuous over the years, site characterization activities, laboratory testing, field-scale experiments, and advanced computational capability provide information and tools required for a license application, should any nation make that policy decision. Ample scientific bases exist to develop a safety case in the event a site is identified and governing regulations promulgated. Some of the key remaining geomechanics issues pertain to application of advanced computational tools to the repository class of problems, refinement of constitutive models and their validation, reduction of uncertainty in a few areas, operational elements, and less tractable requirements that may arise from regulators and stakeholders. This realm of issues as they pertain to salt repositories is being addressed in various research, development and demonstration activities in the United States and Germany, including extensive collaborations. Many research areas such as constitutive models and performance of geotechnical barriers have industry applications beyond repositories. And, while esoteric salt-specific phenomenology and micromechanical processes remain of interest, they will not be reviewed here. The importance of addressing geomechanics issues and their associated prioritization are a matter of discussion, though the discriminating criterion for considerations in this paper is a demonstrable tie to the salt repository safety case.

1. INTRODUCTION

Geomechanical response of the geologic formation to perturbations caused by excavation, structural evolution over time, subsequent disposal of heat-generating waste, and emplacement of sealing systems are first-order concerns for heat-generating nuclear waste disposal in salt. Use of salt formations for toxic waste and transuranic waste disposal is supported by broad technical understanding and experience gained from operating facilities in the United States (U.S.) and Germany. The Waste Isolation Pilot Plant (WIPP) in New Mexico represents a successful process of site characterization and licensing of a salt repository in the U.S., while Germany has compiled the Preliminary Safety Analysis for Gorleben (Vorläufige Sicherheitsanalyse Gorleben or VSG) [1]. Sufficient scientific bases exist to develop a viable safety case for heat-generating waste if a national program should decide to move in that direction.

Ongoing collaborations between U.S. and German salt researchers continue to add to the imposing scientific basis for permanent disposal in salt. In this document, it is possible to present only a few highlights of salt-repository scientific inquiry. Additional detail of the most recent several years of accomplishment can be found on our website [2]. Collaborations facilitate evaluation of many elements of salt research, design and operation, which include testing on all scales, advanced thermal-mechanical modeling and benchmarking, and seal system performance, to name a few. Laboratory and field testing applied to nuclear waste disposal, particularly dealing with temperature effects, has been conducted since the 1960s. Decades of research and development have rendered a mature understanding of salt formation behavior as well as interactions between the salt and engineered and geotechnical barriers. The maturity of the technical basis for salt disposal also facilitates identification of areas where uncertainty can be reduced, areas where advanced computational capabilities can be brought to the problem and areas where operational and long-term improvements can be gained.

The U.S. Department of Energy's goal is to have a repository sited by 2026; the site characterized, and the repository designed and licensed by 2042; and the repository constructed and its operations started by 2048 [3]. Given this time line, one daunting challenge will be preservation of accumulated knowledge over the next 20 years or so. Ongoing international salt research collaboration is one well recognized development that contributes to knowledge preservation, which is systematically achieved by mentoring the next generation of scientists.

The geomechanical reaction to excavation establishes the starting point for all repository activities that ensue. Section 2 provides a brief description of the mechanical response and evolution of the salt underground initiated by excavation. These inescapable developments establish boundary conditions for the concept of operations, long-term repository evolution, and any field-scale testing that might be undertaken. Section 2 also provides an overview of ongoing geomechanics matters pertaining to room closure. Section 3 reviews code benchmarking of salt constitutive modeling and implementation using large, modern computational capacity. Section 4 summarizes progress made through international collaborations, particularly with German research groups. As documented in Section 5, the experience of preparing the preliminary safety assessment for Gorleben represents not only a high level of knowledge and advanced long-term safety analyses, but helped also to identify specific areas for additional research. U.S./German workshops on salt repository research, design and operation have progressively identified and addressed common issues, many of which pertain to geomechanics. Section 6 summarizes some of the geomechanics issues that can be constructively addressed in the near future.

2. EVOLUTION

The technical basis for salt disposal of nuclear waste resides in salt's favorable physical, mechanical and hydrological characteristics. Undisturbed salt formations are essentially impermeable and exist in essentially isostatic equilibrium. When openings are created the state of stress is altered and salt deformation ensues. Understanding the features of salt deformation constitutes the bulk of geomechanics addressed in this paper. Salt deformation can occur while preserving constant volume (isochoric) or can include damage, which increases permeability. Salt damage can be reversed under certain stress conditions and fracture healing is a vital feature of operational and long-term salt repository performance. Room closure is a combined result of isochoric creep at some distance from the opening, damaging salt deformation proximal to the free surfaces, and discontinuity contributions from inner beds, such as anhydrite and clay. Depending on design and operational choices, room closure eventually brings salt formation into contact with material placed within the openings, whether it is waste packages, geotechnical barriers, or run-of-mine salt used for backfill. Reconsolidation of granular salt constitutes another fundamental process that must be understood to ensure operational and long-term sealing performance. Geomechanics is concerned with all these phenomena, including possible thermal effects.

Accurate prediction of salt repository response is enhanced by a thorough understanding of the mechanistic processes and application of valid models. In the instance of a salt formation providing the host medium, the scientific community has made great strides toward formulating and using models that capture observed physical phenomena in computational mechanics applications. Incorporation of micromechanics helps explain history effects, normal transient response, inverse transients, and dependence of creep rate on stress difference and temperature, which are a direct consequence of existing and evolving substructures. If one understands the physical processes, operational and long-term predictions can be made with a measure of confidence.

Extension of this principle to micromechanics of deformation at very low stress difference is especially challenging. Minute strain measurements require extreme load and temperature control, although some outstanding experiments have been conducted [4]. Changes to the microstructure would likely be below detection and documentation using normal microscopic techniques. Nonetheless, creep behavior of salt at low stress differences appears to be substantially faster than predicted from extension of power law models based on dislocation creep mechanisms parameterized from tests under repository conditions as shown in Figure 1. Conventional laboratory experiments, usually performed at differential stresses > 5 MPa, reflect steady state dislocation creep rate as a function of stress difference raised to a power greater than one, of which 4.9 is typical [5]. When this relationship is extrapolated to low stress levels, the creep rate is much less than measured. Recently, an extensive series of creep lab tests on clean WIPP rocksalt was performed using a new sophisticated

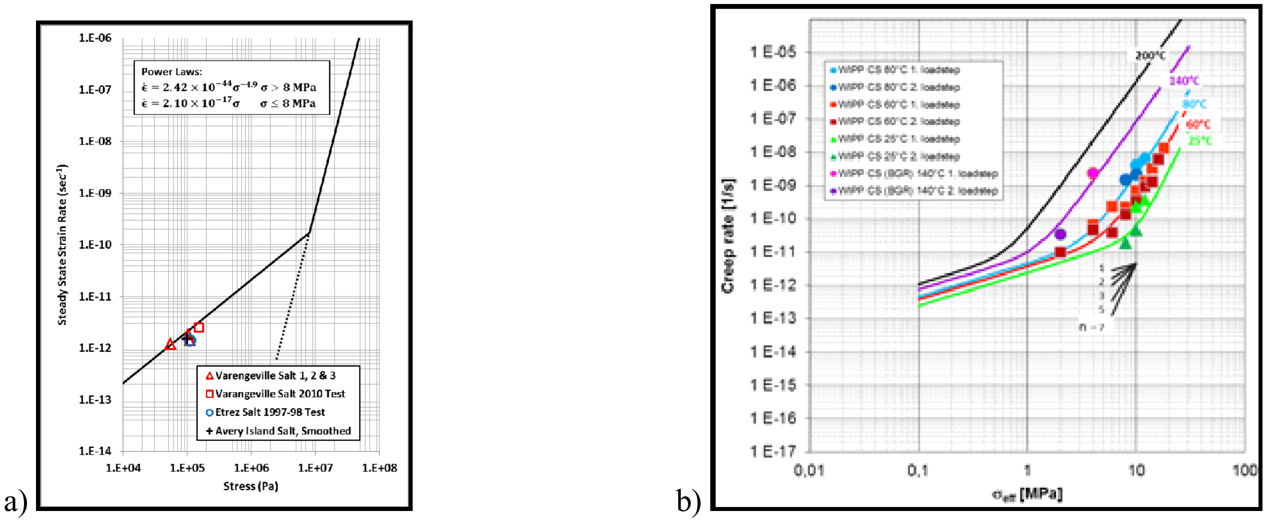


Fig. 1. Creep of rock salt. a) Extension of a power law creep model to low stresses compared to measurements at low creep stresses [5]. b) Creep tests results of WIPP clean-salt samples at different temperatures approximated with the Günther-Salzer law [6].

creep test approach consisting of a series of single tests with load and unloading steps at overlapping stresses [6]. The test results confirm qualitatively the suggested dependence of creep behavior according to different stress regimes and show, in addition, the overlapping effect of temperature. A reasonable approximation of creep behavior is obtained using the advanced Günther/Salzer material law, but the remaining uncertainties at low stresses are obvious. Therefore, further work is needed to evaluate creep at low stress and high temperature levels and to resolve the deformation mechanisms.

Upon mining, a salt formation experiences damage in the near-field rock proximal to the mined opening and salt permeability increases dramatically. The volume of rock that has been altered by such damage is called an excavation damage zone or disturbed rock zone (DRZ). Creation of the DRZ can enable formation brine to flow into the mined opening via increased permeability. The mechanical response to excavation initiates several important changes to the favorable characteristics that exist in salt formations before excavation takes place. Investigations that utilize the underground for experimental activities would benefit greatly from the knowledge of initial, undisturbed conditions, the evolutionary changes imparted by excavation, and the boundary conditions extant when field activities are undertaken [7]. Regulatory compliance of a geologic repository in salt is demonstrated in part by credible representation of DRZ development and healing around panel and shaft seals to prevent this zone from becoming a pathway for radionuclide movement. Understanding DRZ development is essential to design and analysis of waste containment systems during disposal operations as well as to the design and analysis of repository sealing systems to fulfill permanent closure functions. Looking forward, ongoing research in these areas provide the basis for modular repository design, including closure systems in drifts, sectional closure, performance assessment, and input to sequential licensing.

Concepts for disposal operations and seal systems often include elements of crushed salt. Disaggregated salt can reconsolidate to a state approaching the native, undisturbed salt. Mechanical, thermal, and hydrological properties change as a function of porosity. Of these, the permeability/porosity function is the most important in terms of repository performance. Considerable research has gone into illuminating nuances of the permeability/porosity function, as illustrated in Figure 2 [8, 9]. The preponderance of consolidation experimental work, as well as analogue examples, suggest that reconsolidating granular salt will achieve a state of extremely low permeability. Development of the arguments is still advancing, which include new experiments that consolidate salt/bentonite mixtures (shown as symbols in Figure 2). How quickly granular salt reconsolidates to performance specifications remains a key question. Construction techniques can utilize research results to place crushed salt seal elements to maximal density using optimal additives.

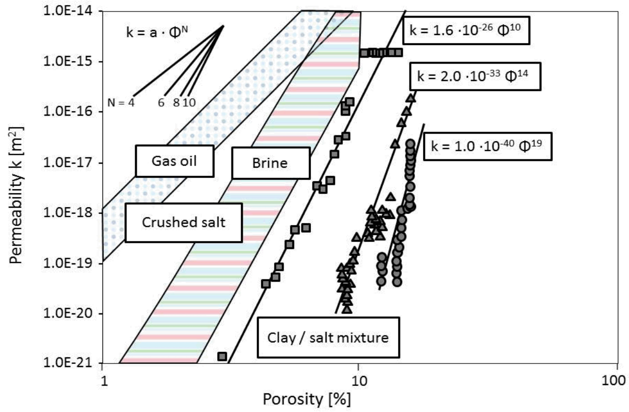
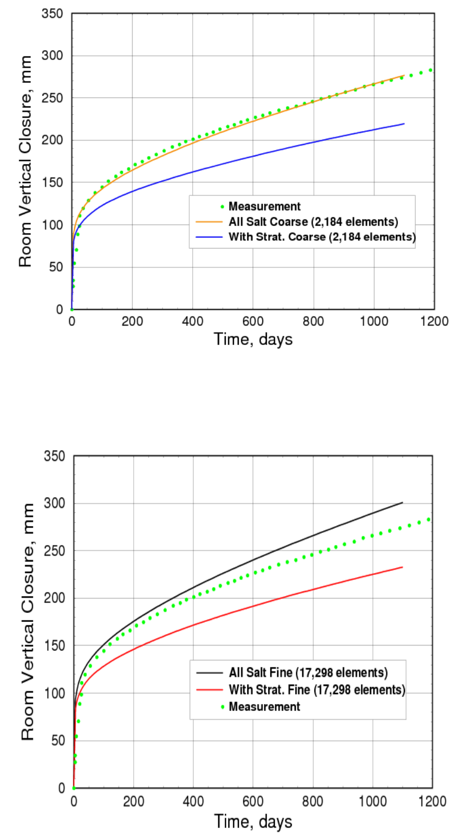


Fig. 2. Permeability-porosity data sets for crushed salt and mixtures [8, 9].

3. MODELING

Computer-based geomechanical modeling of salt repositories has been one of the most important activities in salt repository science and remains so today. Remarkable progress is possible because computational hardware has advanced significantly over the last 20 years. Modeling capability includes representation of thermal-mechanical behavior over long time periods, appreciable variations of temperature, nonlinear large deformation (finite strain) and other phenomena associated with salt deformation in the repository setting. Integral to modeling studies are conventional issues of discretization, stability, and accuracy. A current research challenge is to identify the best-in-class constitutive model, platform, simulation architecture, and solution algorithms appropriate for analyzing the performance of underground salt repositories. To this end, a consortium called the Joint Project between Sandia and German partners is comparing constitutive models and simulation procedures. Modeling will simulate WIPP Rooms B and D, of identical geometry but different thermal loads. Calculations are isothermal, thermal-mechanical uncoupled, and thermal-mechanical coupled. Sandia uses a state-of-the-art Sandia Integrated Environment for Robust Research Algorithms (SIERRA) solid and thermal mechanics computer codes [10], while the German partners use their respective codes and models as described by Hampel et al. [11]. All calculations use highly advanced constitutive laws that mathematically describe deformational processes inherent to those found in nuclear waste repository environment. The first goal of the project is to check the ability of numerical modeling tools to correctly describe relevant deformation phenomena in rock salt under various influences.



a)

b)

Fig. 3. Benchmarking Room D deformation [10].

Twenty years ago or longer, models of WIPP large-scale experiments often matched the field data well [12, 13]. Despite limited discretization, modeling symmetry assumptions, two-dimensional plane strain grids, field test results could be remarkably well reproduced by finite element models. Validation modeling in the Joint Project will include existing ambient and elevated temperature room response data to compare current constitutive models and simulation procedures for calculations of the thermal-mechanical behavior and healing of rock salt. A preliminary example of these benchmarking legacy calculations of WIPP Room D is shown in Figure 3a) and 3b). In Figure 3a) an all-salt idealization with relatively coarse mesh matched the vertical closure precisely, while a model with more detailed stratigraphy resulted in calculated closures below the measured values. By comparison, using a mesh about 8 times finer, Argüello [10] obtains the results shown in Figure 3b). As Argüello [10] points out, an under-refined mesh is typically stiffer, but it would appear that parameters and features, such as the coefficient of friction of clay seams, were adjusted to match test results in legacy calculations. In lieu of testing, assumptions were made about the clay seam behavior in closure measurements associated with

Rooms B and D. These are just examples of challenges being addressed by the Joint Project partners.

International collaboration on model benchmarking is complemented immensely by additional testing of WIPP salt by German research laboratories. In concert with benchmarking of WIPP in situ experiments, German research groups are parameterizing their respective model variables through a series of special laboratory tests on WIPP salt. Thus their codes and models, which have been thoroughly calibrated against in situ experiments conducted in domal salt formations, will be appropriately parameterized for generic salt repository analysis with the inclusion of parameters representative of bedded salt. The benchmark problem extent, geometry, initial and boundary conditions and history will be established from well-documented technical information from existing WIPP literature. Thus far, preliminary benchmark validation efforts suggest that additional characterization of non-salt elements such as anhydrite and clay seam would improve model fidelity. Results from independent calculations will be compared and critically reviewed to assess how well the respective modeling and simulations capture full-scale field response. Continued work on the leading-edge constitutive models will provide the next generation of modeling capability that would then be applied to salt repository design, operations, seal systems, in situ test prediction, and performance assessment.

4. US/GERMAN COLLABORATION

In addition to the specific benchmarking discussed above, German and U.S. salt researchers are addressing numerous salt repository issues, both technical and societal. The U.S. Department of Energy offices of Environmental Management and Nuclear Engineering (DOE/EM and DOE/NE) have collaborated on international salt repository research under the auspices of a 2011 Memorandum of Understanding with the German Ministry. Consistent with this agreement, collaboration in laboratory and field testing and geomechanical modeling has advanced significantly [2]. This work has ensured validated and verified computational capabilities for both bedded and domal salt are being developed and parameterized. In addition to a technical mission, the scope of international collaborations explores public outreach initiatives implemented successfully in other countries to help frame a societal strategy. International collaboration on salt repository research, especially with Germany, builds and reinvigorates previous partnerships.

Recent developments in Germany and the U.S. have renewed efforts in salt repository investigations. On a yearly rotational schedule, workshops including representatives of institutions in both countries have reinitiated collaborations and cooperation on overall salt repository science. Workshops showcase accomplishment witnessed in several areas, such as repository analogue studies, treatment of uncertainty, granular salt reconsolidation, seal systems, constitutive modeling, thermal effects on mechanical deformation, knowledge archive, a salt underground research laboratory, an international catalogue for features, events and processes for a salt repository, and readiness for the safety case [2]. Progress made on these topics also contributes to the Organization for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) *Salt Club* [14].

International salt collaborations address geomechanics as well as other issues:

- Operational safety
- Site selection and characterization
- Laboratory and field tests under projected repository conditions
- Development of credible conceptual and numerical models
- Time dependent creep closure
- Excavation-induced damage to the host rock
- Engineered barriers
- Waste form, backfill, and rock interactions
- Contaminant flow, transport, and retardation tests and models
- Sealing of shafts and disposal areas
- Compliance with regulatory requirements
- Stakeholder involvement, education, and participation
- Peer review
- Transportation, handling and storage
- Repository development design, construction, and maintenance
- Performance confirmation monitoring

Close technical ties with the international nuclear waste disposal community allow the U.S. salt repository program to capitalize on research being supported by other countries and to develop and have at its disposal the best salt repository capabilities in the world. The scope of these initiatives advances our nation's international repository position by leveraging collaborative salt science at favorable return on investment.

5. LESSONS LEARNED FROM THE VSG

In Germany, salt domes have been discussed as possible sites for a repository for heat-generating radioactive waste since the 1960s. As a candidate site, the Gorleben salt dome located in Northern Germany has been investigated since 1979, at first from the surface and since 1986 from underground when shaft sinking started (Bornemann et al. [15]). Investigations came to a halt between 2000 and 2010 based on an agreement between the German government and the electric utilities. In 2010 site investigations were resumed and the preliminary safety assessment for the Gorleben site (VSG) was started.

The VSG is not a safety demonstration for a licensing process, which is still required by the Atomic Energy Act. Rather, the objective was to prepare a comprehensive safety analysis for a salt dome with focus on long-term performance. An important part of work was identification of needs for future research and development and additional Gorleben site investigations. With elaboration of an overall synthesis the project was brought to a close in 2013. A short overview was given by Bracke and Fischer-Appelt [16]; the complete reports (written in German) are available at Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) [1].

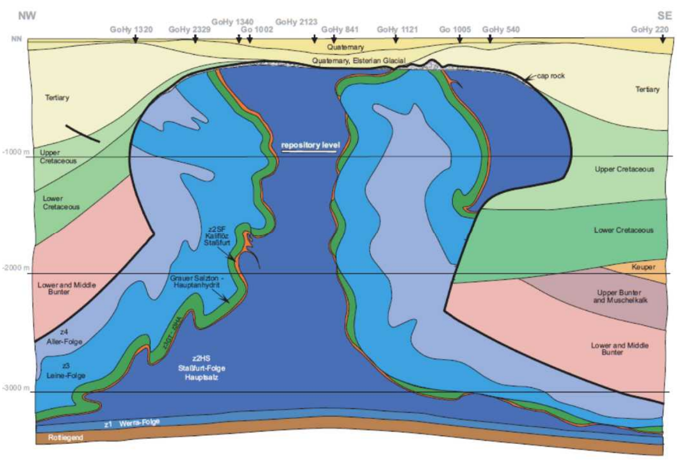


Fig. 4. Simplified NW-SE geological cross-section of the Gorleben salt dome.

As shown in Fig. 4, the Gorleben dome is 4 km wide and nearly 15 km long. It is composed of different salt rock types of the Zechstein (Upper Permian) series and extends to the Zechstein basis in a depth of more than 3 km. In the course of the dome formation, the salt was moved and uplifted several kilometers resulting in an extensively folded and complex internal structure [15]. During the uplift, anhydrite as a competent layer was broken to isolated blocks. In the core of the salt dome the Hauptsalz forms a homogeneous halite body with a volume of several cubic kilometers. Contemporary with the diapiric movement of the salt, the effective stresses repeatedly fractured the rock salt and then healed it again, due to its high creeping capacity. This caused the Hauptsalz to become homogenized into a mixture in which blocks of primary rock salt crystals, and shredded and crumpled fragments of anhydrite float in a matrix of recrystallized rock salt. Thus, in the central part of the Hauptsalz no lithological or stratigraphic discontinuities such as bedding exist.

The Hauptsalz contains small amounts of gaseous and liquid hydrocarbons in separated zones of decimeter to meter dimensions. Brine reservoirs with fluid volumes in the range of liters to hundreds of cubic meters exist in certain regions of this part of the salt dome. The average water content of the Hauptsalz is below 0.02 %. Interconnected pores do not exist in the salt rock outside of fluid bearing or fractured areas, i.e. the salt rock is impermeable.

Following the German safety requirements, released in 2010 by the Bundesministerium für Umwelt (BMU) [17], a safety concept and a process for demonstrating long-term safety were developed, which became the basis for the design of the repository and the safety assessments performed in the Project VSG. Based on the safety concept, specific requirements were derived concerning the site, the repository concept, the design of the mine openings and the assessments to be performed within the Project VSG. The requirements concerning the site have to be fulfilled by the characteristic properties of the host rock and the overall geological situation. The main objective of the disposal is to contain the radioactive waste inside a defined rock zone, which is called containment-providing rock zone. The radionuclides shall remain essentially at the emplacement site, and at the most, a small defined quantity of material shall be able to leave this rock zone. This shall be accomplished by the geological barrier and a technical barrier system, which is required to seal the inevitable penetration of the geological barrier by the construction of the mine.

The repository is planned at a depth of 870 m and will have a maximum length of approximately 4 km and a width varying between 300 m and 700 m, according to the geology and depending on the emplacement concept. An overview describing the technical design of the repository and the detailed design of the geotechnical barriers is given by Bollingerfehr et al. [18]. Special engineered barriers comprising dams made of MgO-concrete are implemented in the drifts at selected locations. The main technical long-term barrier, crushed salt, reconsolidates and compacts due to convergence of the surrounding rock and thereby seals the backfilled drifts. The estimate for the minimum porosity that the backfill can achieve is 1 % ± 1 %. Since moisture accelerates compaction of crushed sat, slightly moistened backfill will be placed in the main drifts (0.6 wt.-% moisture).

According to the objective of safe waste containment, a crucial part of the Project VSG was to analyze the integrity of the geological barrier to determine whether stresses, which occur over time as a result of the forecast behavior of the geologic repository system, could violate the integrity of the barrier over the specified verification period. In other words, it was necessary to investigate whether the properties of the geological barrier forming the effective isolation system are maintained. The geomechanical integrity analysis was jointly performed by the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, and the Institute for Geomechanics (IfG), Leipzig, [19], considering two concepts: (1) the emplacement of Pollux casks in drifts and (2) the emplacement of BSK3 fuel element canisters in boreholes [18]. Both institutions used different material models, whose parameters were derived from site-specific investigations, according to the different rock units (Fig. 5).

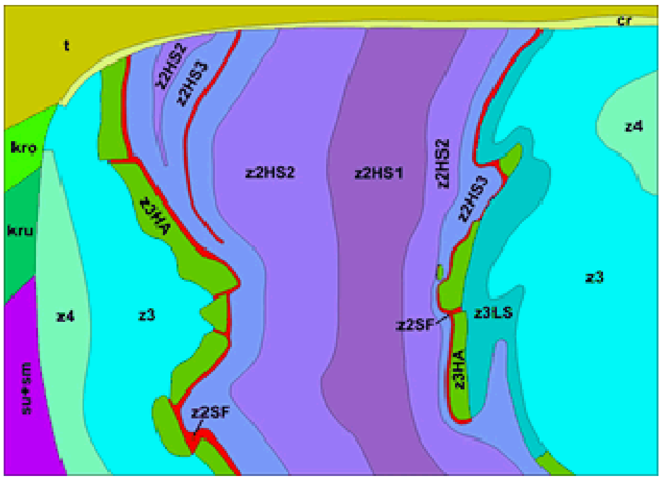


Fig. 5. Detail section of the simplified geological model with the main saliferous homogenous zones: Hauptanhydrit (z3HA) and/or the Liniensalz (z3LS): Aller Series rock salt (z4), Leine Series rock salt (z3), Staßfurt Series rock salt (z2).

To assess the barrier properties of rock salt layers under the influence of thermo-mechanical effects associated with the release of heat in the emplacement zone, computer simulations were carried out on the geomechanical processes which give rise to the creation of micro-fractures due to mechanical damage or fluid-pressure-driven opening of grain boundaries. Understanding this process is important because the migration paths created in this way could ultimately allow liquids to penetrate the emplacement zone. This conceptual procedure means that the assessment of the hydraulic barrier properties is undertaken on the basis of mechanical parameters. This involves the use of the dilatancy criterion and the minimal stress criterion as proof of the BMU-safety requirements [17], according to the two well-known mechanisms of hydro-mechanical integrity loss:

- deviatoric stress inducing growth and connection of intercrystalline and transcrystalline cracks—assessed by the dilatancy criterion
- fluid pressure driven crack and grain boundary opening and their interconnection—assessed by the minimum (or fluid) stress criterion.

2D models (IfG) and 3D models (BGR) were used for the thermo-mechanical calculations, illustrating all relevant loading conditions at different scales, i.e. in the proximal emplacement zone (near field) including the drifts and emplacement containers, as well as the thermal effects on the salt dome as a whole (far field).

The emplacement of heat-generating highly radioactive waste gives rise to temperature changes in the rock mass which itself causes stress and deformation changes, and can diminish the integrity of the geological barrier locally as shown in Fig. 6. The thermo-mechanical simulations delivered the following results:

- Although the emplacement of heat-generating waste can cause the salt dome to heat up over a large area, the thermally-induced stresses do not give rise to any continuous migration paths.
- The highest thermo-mechanical stresses affecting the salt barrier occur within the first hundred years after sealing the geologic repository, so loss of barrier integrity becomes increasingly unlikely in the periods that follow.
- Mechanical damage caused by exceeding the dilatancy limit affects mainly the area adjacent to the underground cavities, but otherwise is localized in the top salt zone and is of secondary importance with respect to the integrity of the salt barrier.
- The possibilities of fluids from the cap rock penetrating the salt structure is a crucial aspect. The calculations confirmed that temporary local violations of integrity (due to the thermally induced uplift) initiated at the top of the salt could penetrate down approximately 130 m into the salt dome. However, they terminate several hundred meters above the emplacement horizons and therefore still leave in place a thick intact barrier. If in the hypothetical extreme case, the steeply dipping stratigraphic boundary horizons reaching the top of the salt are assumed to be potential zones of weakness with reduced shear strength, the temporary violation of integrity could extend as far as a few hundred meters into the salt dome. However the extreme scenario would still leave an adequately thick intact barrier in place.
- The thermo-mechanical stresses calculated for the borehole emplacement concept are higher than those calculated for the drift emplacement concept because the heat is released in a more concentrated area.

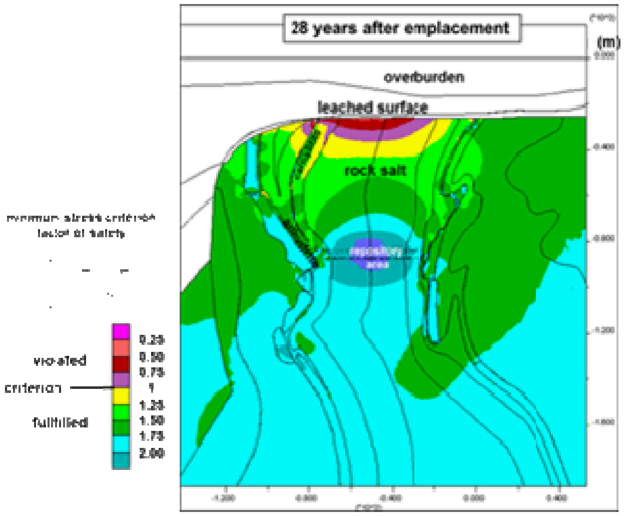


Fig. 6. Evaluation of the minimum stress criterion 28 years after the start of emplacement. Note the criterion violation ($\eta_F < 1$) in the purple to red zone at the salt dome top.

The integrity analysis clearly documents the high level of safety analysis based on geomechanical modeling, which demonstrates compliance with a one-million year geological barrier for the site Gorleben. Additional studies on liquid and gaseous transport of radionuclides as presented by Kock et al. [20] confirm that the compaction behavior of crushed salt backfill is one of the most relevant factors for the hydrodynamic evolution of the repository and the transport of contaminants.

Focusing on the geomechanical integrity, future safety analyses should involve more detailed investigations on the pressure-driven infiltration of fluids, e.g. along stratigraphic boundary horizons (bedding planes) within salt rock masses or zones where the integrity criteria are not fulfilled. Coupled thermal-mechanical-hydrological calculations on fluid infiltration into the barriers (both geological and technical) require further development of appropriate numerical tools supplemented by a comprehensive experimental data base that explores mechanical and hydrological properties of the discontinuities.

6. GEOMECHANICS GOING FORWARD

U.S. scientists continue to cooperate with international peers to establish the integrity of salt repositories. Although a strong basis for salt disposal exists, analysis tools can be improved and updated, special studies to reduce uncertainty can be championed, and process improvements are always possible. This paper stresses geomechanics issues, while recognizing importance of societal, stakeholder, operational, and regulatory input to the licensing processes. Confidence toward licensing a salt repository is couched in many instances by our deep understanding of the geomechanical behavior and our ability to engineer safe systems.

The Joint Project III [11] provides a prime example of updating analysis capabilities, which can applied to a salt repository for heat-generating nuclear waste. The best available constitutive models and computational methods provide the tools for next generation of design, analysis, operations, sealing, and performance assessment. New testing of WIPP salt coupled with existing data from bedded and domal salt allow for timely assessment of generic differences and similarities as regards repository geomechanics. A compendium that compares and contrasts bedded and domal salt as applicable to repositories would be beneficial for U.S. and international salt repository programs.

The Project VSG represents a milestone of the long-lasting German research activities aiming toward establishing an underground repository for heat-generating radioactive waste in salt formations. The outcome provides convincing results demonstrating not only the highly developed level of safety analyses, but also supporting the general assumption of suitability of salt formations. A homogeneous halite body with a volume of several cubic kilometers was identified as possible host rock unit. The occurrence of fluid inclusions (brine or locally hydrocarbons) of Permian age documents tightness has been preserved over geological time scales. As major part of the safety analysis geomechanical modeling demonstrates the integrity of the salt barrier under consideration of likely and unlikely load conditions, especially with respect to heat-generated effects. The overall synthesis indicates presently the compatibility of a repository in Gorleben with the German safety requirements, i.e. the investigation of the Gorleben salt dome has revealed no findings which contradict the suitability of the location for the construction of a geologic repository for safe disposal of high-level waste. Nevertheless, the integrity criteria were found not to be fulfilled in all parts of the salt dome, e.g. at the salt dome top due to heat-induced uplift effects. This suggests the need for development and improvement of advanced numerical tools for coupled hydro-mechanical calculations of pressure driven fluid transport in the salt mass (and the technical barriers).

Granular salt is likely to be used in the mine design for repository applications to provide structural support and other operational functions, thus reconsolidation processes and properties as a function of porosity continue to be key areas of ongoing research. Analogue evidence of reconsolidation to conditions that mimic native salt is substantial and supports the proposition that granular salt becomes effectively impermeable under many conditions. Owing in part to difficulty in measurement, uncertainty remains concerning flow behavior at low porosities. Because characteristics that approach undisturbed salt are desired for many repository safety functions, demonstration is potentially more influential in the licensing arena than is model prediction of performance. Repository functions of granular salt can be advanced via analogue studies, evaluation of low porosity characteristics, and enhanced engineering performance attained by additives to the crushed salt. Until recently, most backfill research and design used run-of-mine crushed salt without additives such as bentonite. Evidence suggests that performance characteristics could be improved with admixtures that enable placement at greater density with lower initial properties. This engineering achievement reduces uncertainty and perceived reliance on modeling. Repository designs, analyses and performance assessment for heat-generating waste will hinge on our state of knowledge concerning reconsolidation of granular salt.

A salt repository for heat-generating waste should take advantage of experience gained at WIPP, VSG and elsewhere. Rooms can be designed structurally stable to minimize geotechnical ground support. Forward looking engineering and performance assessment is likely to require intrinsic modular closure, which will no doubt include drift seal elements comprising reconsolidated granular salt. A recurring debate is the prerequisite that seals need to be demonstrated at full-scale. For reconsolidation of granular salt this can neither be attained in any reasonable time nor can the functionality be monitored. On the positive side, multiple construction demonstrations of various seal elements have been completed. In addition to crushed salt, the other most important engineering materials are concrete and bentonite. Looking forward, salt repository collaborators should consider compiling seal-system information into a document nominally called *A Synthesis of Salt Repository Seal Systems.* Such a jointly authored state-of-the-art report could include reconsolidation analogues, experience with bentonite and performance of special concretes. In the meantime, tests with admixtures are further enhancing the database.

A generic description of the evolution of the underground setting expounding upon geomechanics highlights as identified in this paper would be of utility for analysts new to the field. Perhaps it would be useful for U.S. and German collaborators to write another position paper that describes the evolution, properties and mitigation of the salt DRZ. Creation of a disturbed rock zone in salt is well recognized and for many engineering purposes sufficiently understood to provide confidence in its forward evolutionary characteristics and its mitigation through healing processes. However, quantification of anisotropic permeability associated with damage levels is elusive. Time-wise healing has little full-scale documentation aside from dammjoch measurements being modeled in the Joint Project [11]. It will be mandatory to close a repository; therefore, it is essential to establish that it can be sealed by appropriate and integrity-proven seal systems, including both shaft and drift settings. Fruitful collaboration is ongoing in the U.S./German workshops.

Salt remains a well characterized material for waste isolation. However, the future path is anticipated to be long. The U.S. repository program has identified a goal of 2048, while the German future repository policy is embarking on a review of the site selection process. Considering the long times planned before a salt repository site is established through a new consent-based negotiated-consultancy siting process, it may be worthwhile for the established salt scientists to write a geomechanics salt repository primer that documents fundamental concepts. Such a book would be useful today as a means of knowledge preservation and for education purposes for the next generation of salt repository scientists and engineers.

REFERENCES

1. GRS (Gesellschaft für Anlagen- und Reaktorsicherheit). 2012. *Vorläufige Sicherheits-analyse für den Standort Gorleben*, Köln, Germany. http://www.grs.de/vorlaeufige-sicherheitsanalysegorleben-vsg.
2. http://energy.sandia.gov/?page_id=17258.
3. DOE (U.S. Department of Energy). 2013. *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.* Washington, DC: U.S. Department of Energy.
4. Bérest, P., P.A. Blum, J.P. Charpentier, H. Gharbi and F. Valès. 2005. Very slow creep tests on rock samples. *Int. J. Rock Mech. & Mining Sci*. V.42.
5. Hardin, E., K. Kuhlman, and F. D. Hansen. 2014. Technical Feasibility of Measuring Low-Stress, Low Strain-Rate Deformation Relevant to a Salt Repository. Prepared for U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. FCRD-UFD-2014-000614 Rev. 0. *SAND2014-17435R*. Sandia National Laboratories, Albuquerque, NM.
6. Günther, R.-M., K. Salzer, T. Popp, and C. Lüdeling. 2014. Steady state-creep of rock salt - Improved Approaches for Lab Determination and Modeling to describe transient, stationary and accelerated creep, dilatancy and healing*. 48th U.S. Rock Mechanics Symposium Proceedings.* Minneapolis MN USA. ARMA 14-7051.
7. Hansen, F.D., C. Howard, K. Kuhlman and J. Holland. 2015. A Test Plan to Capture Early Evolution of Salt Openings. *49th U.S. Rock Mechanics Symposium Proceedings*. San Francisco CA USA. ARMA 15-300.
8. IfG (Institute for Geomechanics). 2012. *Laboruntersuchungen am Gemisch Schnittsalz - Friedländer Ton*. Institut für Gebirgsmechanik GmbH, Leipzig.
9. Kröhn, K.-P., D. Stührenberg, M. Herklotz, U. Heemann, C. Lerch, and M. Xie. 2009. *Restporosität und –permeabilität von kompaktierendem Salzgrus-Versatz, REPOPERM – Phase 1*. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-254.
10. Argüello, J. G. 2014. Results from the US-German Benchmark Initiative for FY14. *SAND2014-18272 R.* Sandia National Laboratories, Albuquerque NM USA.
11. Hampel, A., K. Salzer, R.-M. Günther, W. Minkley, A. Pudewills, B. Leuger, D. Zapf, K. Staudtmeister, R. Rokahr, K. Herchen, R. Wolters, and K.-H. Lux. 2012. Joint Projects on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt - II. Overview of the models and results of 3-D benchmark calculations. In P. Bérest, M. Ghoreychi, F. Hadj-Hassen and M. Tijani (eds.), *Mechanical Behavior of Salt VII, Proc. 7th Conference*. Paris. London: Taylor & Francis Group (Balkema)
12. Munson, D., R. Jones, D. Hoag, and J. Ball. 1988. Mining Development Test (Room D): In-Situ Data Report (March 1984 – May 1988) Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. *SAND88-1460*. Sandia National Laboratories, Albuquerque NM USA.
13. Munson, D., R. Jones, J. Ball, R. Clancy, D. Hoag, and S. Petney. 1990. Overtest for Simulated Defense High-Level Waste (Room B): In-Situ Data Report (May 1984 - February 1988) Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. *SAND89-2671*. Sandia National Laboratories, Albuquerque NM USA.
14. http://www.oecd-nea.org/rwm/saltclub/.
15. Bornemann, O., J. Behlau, R. Fischbeck, J. Hammer, W. Jaritz, S. Keller, G. Mingerzahn, and M. Schramm. 2011. *Description of the Gorleben Site. Part 3: Results of the geological surface and underground exploration of the salt formation*. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), ISBN 978-3-9813373-6-5, Hannover, Germany.
16. Bracke, G. and K. Fischer-Appelt. 2013. Overview on the Preliminary Safety Analysis of the Gorleben Site. *WM2013 Proceedings*. Phoenix AZ USA. WM-13298.
17. BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit). 2010. *Sicherheitsanforderun-gen an die Endlagerung wärmeentwickelnder radioaktiver Abfälle.*
18. Bollingerfehr, W., W. Filbert, C. Lerch, P. Herold, N. Müller-Hoeppe, F. Charlier, and R. Kilger. 2013. Technical Design and Optimization of a HLW-Repository in the Gorleben Salt Dome including Detailed Design of the Sealing System. *WM2013 Proceedings.* Phoenix AZ USA. WM-13305.
19. Eickemeier, R., S. Heusermann, M. Knauth, W. Minkley, H.-K. Nipp and T. Popp. 2013. Preliminary Safety Analysis of the Gorleben Site: Thermo-mechanical Analysis of the Integrity of the Geological Barrier in the Gorleben Salt Formation. *WM2013 Proceedings.* Phoenix AZ USA. WM-13307.
20. Kock, I., J. Larue, H. Fischer, G. Frieling, M. Navarro and H. Seher. 2013. Results from One- and Two- Phase Fluid Flow Calculations within the Preliminary Safety Analysis of the Gorleben Site. *WM2013 Proceedings.* Phoenix AZ USA. WM-13310.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy. SAND2014-.