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Salt Repository Geomechanics Research Agenda

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Abstract: The proposed research and development program to advance disposal concepts for heat-generating waste in salt comprises four general initiatives: Laboratory Testing, Modeling and Simulations, Workshops and International Collaborations, and Field Testing. In a chronologic sense, some laboratory geomechanics studies can be started in the immediate future and would begin by adding to the data bases accumulated previously, when the U.S. supported salt repository research for heat-generating waste. The science-based testing would provide long-term benefit and could be scoped at an appropriate level of effort commensurate with national policy. Sophisticated multi-physics analysis techniques are now available to model features, events, and processes that determine salt repository performance. Thermomechanical modeling and simulation would naturally progress, beginning with a benchmark comparison of existing capabilities with similarly motivated international colleagues. These benchmark analyses would show case constitutive models as well as needed development. The third initiative promotes an internationally sanctioned workshop environment for discussion, definition, and reconciliation of technical issues. Ultimately, based on advancements from laboratory testing, enhancement of model capability, and workshop deliberations, a proof-of-principle field test could be deployed. This roadmap provides the science basis for salt repository design and performance assessment.

1. INTRODUCTION

Disposal of heat-generating nuclear waste in a suitable salt formation is attractive because the material is essentially impermeable, self-sealing, and thermally conductive (Table 1). Conditions are chemically beneficial, and a significant experience base exists in understanding this environment. Within the period of institutional control, overburden pressure will seal fractures and provide a repository setting that limits radionuclide movement. A salt repository could potentially achieve total containment, with no releases to the environment in undisturbed scenarios for as long as the region is geologically stable. Much of the experience gained from United States repository development, such as seal system design, coupled process simulation, and application of performance assessment (PA) methodology, helps define a clear strategy for a heat-generating nuclear waste repository in salt. This paper contributes to the national discussion regarding geologic disposal by synthesizing technical information regarding salt disposal of high-level-waste (HLW). It agrees with a well-known study by the National Academy of Sciences National Research Council in the 1950s [1] that states,

> *The most promising method of disposal of high level waste at the present time seems to be in salt deposits. The great advantage here is that no water can pass through the salt. Fractures are self-sealing…*

Over time, a considerable body of research has been conducted to advance the state of knowledge with respect to waste isolation in salt. Much scientific and technical knowledge about disposal in salt has accumulated since the initial conclusions made by the National Academy of Sciences. Hansen and Leigh [2] update the technical basis for disposal in salt and discuss the performance issues that should be addressed when considering disposal of HLW in salt.

Table 1. Advantages of salt for HLW disposal [2]

1	Salt can be mined easily
2	Salt has a relatively high thermal conductivity
3	Wide geographic distribution (many potential sites)
4	Salt is essentially impermeable
5	Fractures in salt are self-sealing
6	Salt has been geologically stable for millions of years

In situ field tests to study the effects of HLW in bedded salt were initiated at an underground salt mine in Lyons, Kansas in 1965. By 1968, elevated-temperature HLW field experiments had begun at the Asse salt mine in Germany. In situ tests for brine migration resulting from heating were conducted at the Avery Island salt mine in Louisiana beginning in 1979. Soon after, an extensive suite of field thermal tests were initiated at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits.

In concert with these field tests, the need for laboratory testing and development of a creep law for salt became clear. The field testing was soon augmented with lab experiments, which led to parameters for mathematically representing the creep behavior of salt. The U.S. salt programs experienced two policy decisions that impacted the progress in salt geomechanics: 1) WIPP would not accept heat-generating waste and 2) second, the civilian salt program was canceled in favor of a single site at Yucca Mountain.

A substantial base of information was accumulated before thermomechanical salt investigations came to a halt. If one imagines a pyramid as illustrated in Figure 1, the technical foundation for salt disposal represents the vast majority of the requisite information and programmatic experience supporting salt disposal. In addition, the salt disposal information already developed and vetted provides objective bases for defining the research and development (R&D) roadmap for HLW salt disposal. The intent of Figure 1 is to convey that much of the bases for HLW disposal in salt exist today, and the increment of work to move to a salt repository is far less than any other geologic option for the U.S. This paper summarizes the geomechanics aspects of salt repository investigations including what has been done, where we are today, and where we need to continue R&D if the U.S. selects a salt disposal option.

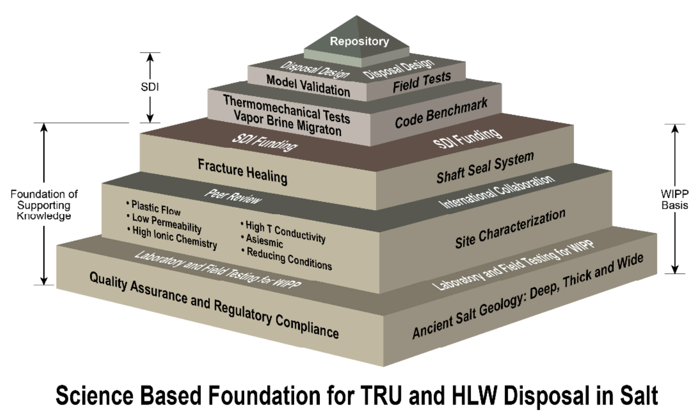

Figure 1. Science based foundation.

2.0 STATE OF THE ART

A recent conceptual salt repository study [3] called the "generic" salt repository for HLW advanced a new disposal concept based on lessons learned from the WIPP, Asse, and Morsleben. The generic study involved a conceptual mining layout that was developed for a high-thermal-load salt repository based on experience and mining observations. First a rough layout was proposed based on waste handling, convenience, expectation of standup time, and other criteria. Contributors to the generic salt repository study developed a possible repository layout and also generated some basic operational and structural conclusions, including 1) use rubber-tire disposal vehicles, 2) avoid use of predrilled holes, 3) do not use shielded containers for disposal, and 4) use narrow room widths to improve mining efficiency and structural stability.

The design of the seal system for a HLW salt repository would benefit from design and performance calculations on seal systems developed for the WIPP, which were subject to extensive technical peer review and comprise published portions of the *Compliance Certification Application* to the EPA [4]. The fundamental design principle for seal systems in a nuclear waste repository is to limit water flow from disposal cells to access shafts to zero or specified acceptable levels. Extensive design, analysis, and testing for shaft seals were performed for the WIPP repository, which provides the basis for performance expectations.

A recent international conference held in Luxembourg [5] addressed the features, events and processes (FEPs) associated with thermally driven processes in a salt repository. The conference focused on the appraisal of the current capabilities of coupled models used by numerical simulators for the assessment of the long-term evolution of geological repositories for high-level radioactive waste. One of the most important topics concerned the interplay between the disturbed rock zone (DRZ--also called the excavation damaged zone or EDZ) and the engineered barrier systems. Creation and development of the DRZ is well characterized as described in the proceedings of the Luxembourg workshop. However, the reversal and healing of the DRZ and the attendant reduction of permeability is less well understood. These relationships are important to long-term PAs, particularly because of a new approach to the concept of disposal performance: design a salt repository with no releases.

Much information has been collected in the past fifty years that supports development of a HLW repository in salt. The next step in establishing the case for HLW disposal in salt is to exploit the available information and develop a solid basis for modeling thermally driven coupled processes. This section evaluates what is presently known versus what information is still needed: a preliminary gap analysis as stylized in Figure 2. More detailed analyses of the "gaps" might be undertaken if there is a U.S. decision to investigate HLW disposal in salt. Nonetheless, the bases exist to begin constructive R&D on this topic immediately.

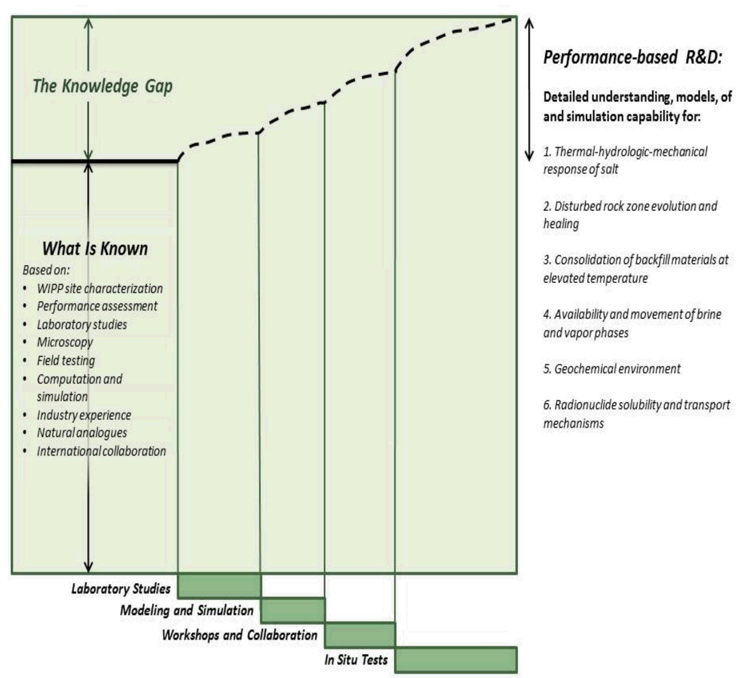

Figure 2. Gap analysis for a HLW repository in salt [2].

The current paper addresses geomechanics issues central to design, analysis and PA. With this type of analysis, proposed research and characterization activities can be prioritized into a performance-based directed science program. The following sections discuss geomechanics related issues, though pertinent geochemistry issues were also summarized by Hansen and Leigh [2], see Table 2. This discussion establishes the framework for performance-based directed research and development should the U.S. decide to investigate HLW disposal in salt. In addition, the summary below incorporates the geomechanics findings of the U.S./German salt repository workshop held in May 2010 [6]. Thus, R&D activities recommended in the following sections are consistent with many of the primary goals of salt repository programs internationally.

Table 2. Key findings of Hansen and Leigh [2]

1	Thermal, hydrologic, and geochemical considerations suggest that radionuclides in a salt repository for HLW would not migrate from the disposal horizon
2	Current knowledge of thermal effects supports a viable concept of repository operations.
3	Three-dimensional multiphysics capabilities offer advanced capabilities for PA modeling and field test development.
4	The suitability of salt as a medium for HLW disposal has been recognized by national and international repository programs

2.1 Thermal-Hydrologic-Mechanical Response of Salt

The thermal-hydrologic-mechanical response of salt is likely to prevent any release for an undisturbed HLW repository, and it may attenuate releases from a disturbed repository. The empirical evidence available suggests that an appropriately sited and designed salt repository would allow no significant transport of radionuclides from the emplaced waste to the accessible environment.

The mechanisms by which salt deforms with thermal activation are known and documented. Modeling capabilities available today provide advanced tools for thermal-hydrologic-mechanical and other coupled process evaluations. These advanced modeling capabilities can be improved with key science-based testing, including site-specific testing, if a salt option is selected for investigation. Benchmarking of the best available codes has the potential to identify a preferred constitutive model for thermal-mechanical salt deformation. Laboratory testing and benchmark calculations using advanced hardware and software are essential to support salt repository investigations.

2.2 DRZ Evolution and Healing

The DRZ is fundamentally important for any mined repository in any lithology, such as granite, shale, volcanic rock or salt. However, salt and shale have the desirable characteristic that damage caused by excavation can be reversed, because fractures heal as the pre-mining stress state approaches equilibrium owing to the backstress created by compression of the waste or crushed salt within the room. Healing arises when the magnitude of the deviatoric stress decreases relative to the applied mean stress. The healing mechanisms for shale have not been elucidated as those for salt have been. Salt healing processes include microfracture closure and bonding of fracture surfaces. Microfracture closure is a mechanical response to increased compressive stress applied normal to the fractures, while bonding of fracture surfaces occurs either through crystal plasticity, a relatively slow process, or pressure solution and redeposition, a relatively rapid process. Confirmation of healing has been obtained in laboratory experiments, small-scale tests and observations of natural analogues.

The DRZ is usually explicitly implemented in PA process models used to predict future repository conditions and evaluate the possibility of brine flow to the accessible environment. The properties of the DRZ control a significant portion of the brine that is postulated to flow into waste rooms. The most important DRZ properties are extent (or thickness), porosity, and permeability as they are the three fundamental parameters used for analysis. Evidence suggests that the DRZ is much smaller in extent and has a lower permeability than currently modeled in the WIPP PA and therefore the amount of brine that could flow into the disposal rooms should be more realistic (much less) in future PAs.

The damage volumetric strain gives rise to high permeability. The evolution and healing processes are fundamental to seal system design considerations. Building on information available, several approaches would be used to study the DRZ, including laboratory testing, in situ testing, and analogues. These approaches are compatible with international research goals and objectives.

2.3 Consolidation of Backfill Materials at Elevated Temperature

Crushed salt used as backfill would likely be a key performance element in a potential HLW repository. Relatively little elevated temperature mechanical testing has been conducted for crushed salt consolidation. In some disposal concepts, the salt could experience peak temperatures ranging from 200°C to 300°C. Collaborative laboratory programs are recommended to measure thermal conductivity of the backfill salt at temperatures up to 300°C for a range of fractional density. A thermal conductivity–porosity relationship could then be obtained as a function of porosity and temperature and used in simulations.

Whereas the reconsolidation of crushed salt with a small amount of moisture at ambient temperature is well understood mechanistically, the large-scale reconsolidation of hot and dry salt has been less well described. Understanding crushed salt reconsolidation under these conditions is essential to establish room closure response and thermal conductivity. The fundamentals of high-temperature, hot, dry reconsolidation are important to establish the long-term complete encapsulation concept.

2.4 Availability and Movement of Brine and Vapor Phases

The availability and movement of brine and water vapor in a thermally driven salt repository remain uncertain despite some scientific investigation of these phenomena. If it can be shown that the environment in the vicinity of the waste and/or waste packages is dry through the regulatory period, then issues of chemical degradation of the waste package and/or waste forms could be screened out in the FEPs analysis. Description of the evolution and movement of brine and water vapor in a hot salt repository requires multiphysics modeling for all three of the brine movement mechanisms described below.

One conceptual model for brine migration 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 crystal void migrates toward the heat. The phenomenon of brine migration has been observed in the laboratory and in field experiments.

Another evaluation by Schlich [7] concludes 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. Based on his studies it appears that vapor transport processes dominate moisture movement.

A third mechanism is advective flow, a commonly observed phenomenon of brine movement that is controlled by the hydraulic gradient between the far field host salt formation and the excavated room. If the permeability is high enough to allow brine flow, nearly all the brine contained in the DRZ can flow into the waste emplacement openings. Stress differences occur immediately upon excavation and initiate microfracture growth and enhanced permeability, so the dewatering process begins quickly. Brine then migrates down the hydraulic gradient and evaporates into the ventilation air. Understanding the rate and extent of moisture removal by these processes is important for advanced modeling and PA.

3.0 GEOMECHANICS R&D AGENDA

Table 3 presents a general proposal for addressing geomechanics data or information gaps. The table lists the broad areas of interest, specific data needed, and potential assessment methods that can be used to advance the technical baseline.

Table 3. Geomechanics areas of interest and possible assessment methods [2]

Area of Interest	Specific Data Needed	Assessment Methods
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 • Analogue comparisons • Model development
Consolidation of backfill crushed salt	• Thermal conductivity as a function of porosity • Consolidation constitutive model with temperature dependence	• 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 mechanism	• 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

The proposed research and development framework comprises four general elements:

- Laboratory Testing—could begin immediately, as the state-of-the-art is known and incremental R&D identified.
- Modeling and Simulations—international collaboration in this effort can position salt repository sciences in a very favorable position for field testing, design and analysis.
- Workshops and International Collaborations—a workshop environment with subject matter experts can reconcile many of the issues.
- Field Testing—a proof-of-principle test could advance salt sciences sufficiently to lead to efficient and safe disposal.

In a chronologic sense, some laboratory studies can be started in the immediate future and would begin by adding to the data bases accumulated previously. Modeling and simulation would include benchmark comparison of existing capabilities and international collaboration is already in progress. The third initiative for international collaborations in geomechanics areas was restarted in 2010 at the U.S./German workshop in Mississippi [6]. Ultimately, based on advancements from laboratory testing, enhancement of model capability, and workshop deliberations, a proof-of-principle field test could be deployed.

3.1 Laboratory Thermal and Mechanical Studies

Several information needs have been identified in the realm of thermal-mechanical salt response, which can be addressed in laboratory studies. Collaborative work with international researchers could lay the foundation for laboratory experiments on both intact and granular salt, which provide information for modeling. Any proof-of-principle field testing should use the latest models to facilitate design, analysis, instrumentation, and data quality objectives. Laboratory testing could readily inform remaining uncertainties in material phenomenology and process description, particularly mathematical description of granular salt reconsolidation under isostatic loading at elevated temperature. In related but separate investigations, thermal conductivity of crushed salt can and should be determined as a function of porosity and temperature. For thermal conductivity studies, an oedometer press could be manufactured to perform heated consolidation simultaneously with line-source radial conductivity testing. Preliminary hot, intact salt phenomenology and brine migration could be initiated. Consolidation is widely considered a key phenomenon for HLW disposal in salt, an evaluation that was reinforced by the consensus of the U.S./German workshop participants.

Laboratory thermal gradient testing could address the possibility for brine migration with the following approach: 1) impose a thermal gradient on natural salt cores to promote brine migration and 2) allow liberation of brine from the core as a function of stress state and deformation. There are several important aspects to this approach. First, the temperature and stress states could be controlled independently, starting with a temperature gradient and no applied stresses. Observational microscopy could document fluid inclusion migration relative to the gradient and grain boundaries. Second, an appropriate stress state could be imposed while thermal gradients are maintained. In both cases, the liberation of moisture will be estimated from weight loss, while the phenomenology of brine inclusion migration will be documented using microscopy techniques. The fundamentals of brine migration and vapor transport were also identified as critical to building the case for salt disposal.

3.2 Modeling and Simulation

Salt repository science is in an advantageous position to restart international benchmark thermal-mechanical code calculations. First, an assessment of the state of the art should be established through a benchmark exercise. This important work can begin immediately and would evaluate the "best available" salt modeling capabilities worldwide. The benchmarking process will identify the most comprehensive thermal-mechanical models and use the latest high-performance, massively parallel platforms. After the benchmark results are evaluated, a selected constitutive model could be parameterized from applicable laboratory test results obtained from particular sites. The selected model would then be available to inform a team of investigators developing a field test, regarding data quality objectives, instrument specifications and placement, expected ranges, and many other pertinent in situ test attributes and responses. In turn, the successful code/model could be validated against in situ experimental results, which adds to the credibility for long-term performance calculations.

Benchmark modeling could begin with experiments already conducted, such as the WIPP heated room experiments, and be developed in concert with international coworkers. Results of these benchmark studies allow evaluation of computational capabilities, make use of ongoing laboratory work, and inform potential design and analysis. The benchmarking program would continue to refine models, as data from the laboratory and field tests are collected. Coupled thermal-mechanical benchmark 3-D simulations could be performed in order to calculate the evolution of stresses, strains, dilatant volumetric strains, and damage around a potential repository for radioactive wastes in rock salt.

3.3 International Collaboration

International collaboration to advance salt repository geomechanics and operations has already begun by way of the U.S./German workshop in Mississippi in May 2010 [6]. The presentations by subject matter experts helped identify areas of concern with respect to HLW disposal in salt. Formal and consistent collaboration with German researchers provides immediate and ongoing technical guidance to the U.S. program in salt repository science. Much of the historic salt research was performed by German scientists, however a renewed interest by other European nations has motivated the pursuit of official EU sanction of a Salt Club. Because a generation has passed since the U.S. considered any disposal concept for HLW other than Yucca Mountain, some reassessment of the state of the art is in order. International collaboration can occur in laboratory work, with computational platforms, and in the field. Most importantly, workshops and focus areas provide the opportunity to explore issues and develop appropriate responses.

3.4 Field Tests

An in situ field test culminates the R&D agenda. Field testing provides valuable proof-of-principle demonstrations. A field test avails the opportunity to observe anticipated phenomenology, validate modeling capabilities, and evaluate design concepts. A full-scale field test could be undertaken relatively expeditiously after laboratory studies are evaluated and preliminary modeling studies are complete. In situ testing helps confirm the predictive ability of repository models, provides a range of expected parameters, and involves possible size affects associated with rock mass response. Potential exists for a full-scale heater test to provide repository-relevant heating conditions that will allow determination of the extent and properties of the DRZ, fracture healing characteristics, permeability and porosity, the thermal-mechanical response of compacted crushed salt backfill, and brine migration assessment.

4.0 CONCLUDING REMARKS

These steps focus on the geomechanics roadmap for a salt repository for heat-generating nuclear waste. A review of salt repository research has led to a clear, science-based path forward if a salt repository for heat-generating nuclear waste is pursued in the U.S. The geomechanics aspects of the salt repository roadmap are summarized from information currently available to identify research activities needed to strengthen the basis for salt disposal. Use of salt formations for nuclear waste disposal has been a widely embraced concept for more than 50 years. Salt is impermeable and deforms plastically around the waste. There is no natural water flow through a salt repository. The U.S. has vast land areas with salt formations of sufficient thickness and lateral extent to accommodate a nuclear waste repository. International nuclear waste repository programs have advanced the engineering and science sufficiently to instill confidence that such a repository could be safely constructed, operated, and sealed. The performance function of a salt repository would readily satisfy expected regulatory criteria for the safety case.

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