An Underground Laboratory in the Context of Salt Disposal Research - 15549

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ABSTRACT

Evaluating the basis of need for an underground research laboratory for salt science and engineering is imperative because of the significant commitment of time and money involved. Decades of salt repository studies, numerous experiments, and sophisticated modeling capabilities underpin the scientific database that supports safe disposal of nuclear waste in salt. The safety case for disposal of non-heat-generating waste such as transuranic waste interred at the Waste Isolation Pilot Plant is robust, with the only long-term releases to the environment projected to be by way of human intrusion. The scientific evidence also favors safe disposal of heat-generating waste. Technical evaluations for disposal of heat-generating waste in salt experienced a rather long hiatus in the United States subsequent to certification of the Waste Isolation Pilot Plant and issuance of the Nuclear Waste Policy Act Amendment that ended salt disposal research for the civilian program. Similar salt repository research in Germany was delayed by a ten-year moratorium that ended in 2010. In collaboration with German peers, the United States Department of Energy has reviewed and evaluated thermally driven processes in salt disposal and identified key technical areas in which to prioritize resources. The goal for disposal research in salt is to provide sufficient technical information to license a repository successfully. The necessity or utility of a salt underground laboratory is to be evaluated in the context of an overall research agenda that supports a license application.

INTRODUCTION

Given the long history and encyclopedic information that underwrites salt repository science, what is the role for an underground research laboratory (URL) at this stage? Salt disposal research has followed a step-wise progression toward licensing, which is nominally represented in Figure 1. As shown in Figure 1, many of the building blocks for licensing a salt repository have been accomplished. The question pursued in this document is twofold: *Does URL testing reach a high priority in today's salt research, development and demonstration program*, and if so, *how are URL tests evaluated and prioritized*? As of today, neither the U.S.A. nor any other country has an operating URL in salt. It is a widely believed that further salt testing in a URL is not required to address a perceived technical deficiency to be answered as a prerequisite to preparation of a safety case for salt disposal of heat-generating high-level waste. The technical basis for salt disposal provides strong and pervasive evidence that radionuclides in a salt repository will not migrate from the disposal horizon. Current knowledge of thermal effects supports viable concepts for disposal operations and underground evolution. The suitability of salt as a disposal medium has been recognized by national and international repository programs. Therefore, the scientific community must balance perceived necessity for field experiments with the recognition that a very strong scientific basis already exists for salt disposal of nuclear waste.

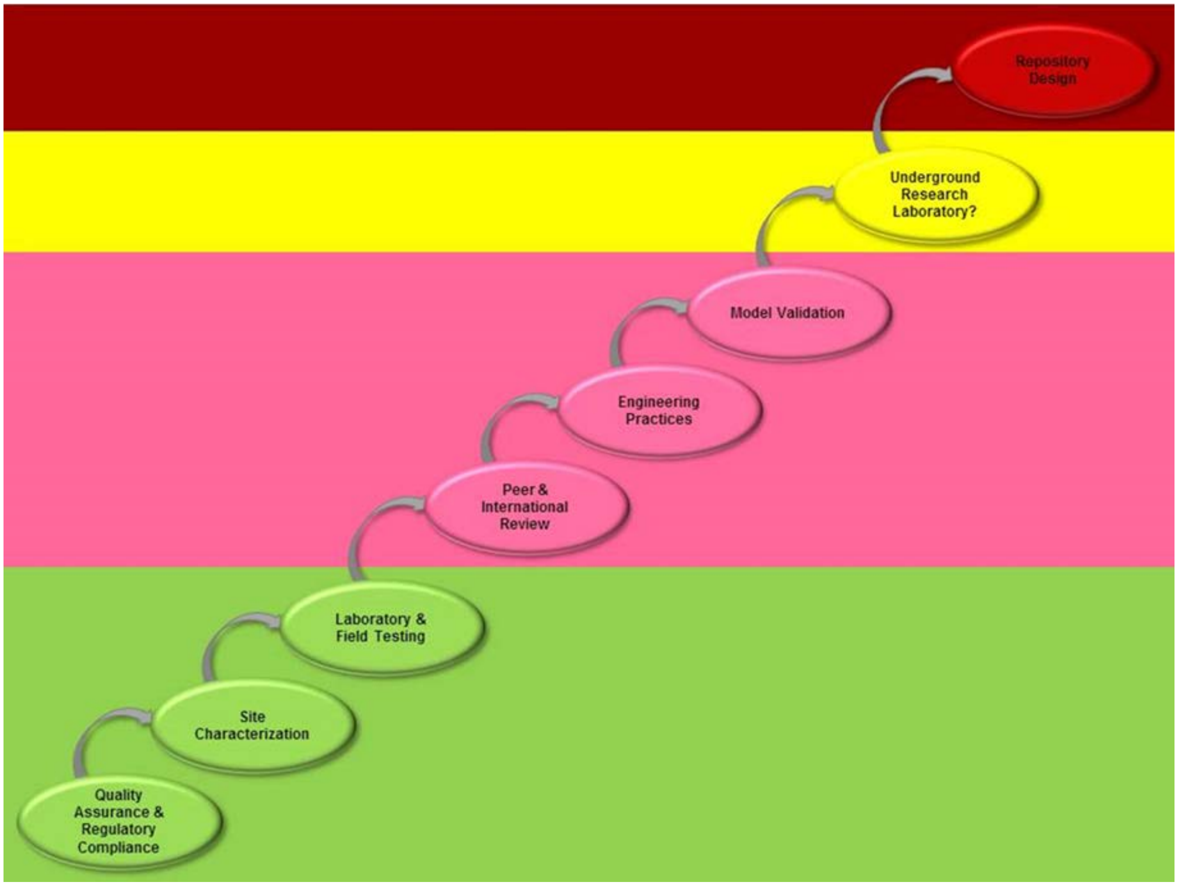

Figure 1. Progress toward a Salt Repository for Heat-generating Waste.

This document sets forth principles as well as a methodology for evaluating proposed URL activities. Because field testing is costly, any such test will necessitate commitment of money and time. Given the vast and compelling basis for successful waste isolation in salt, a choice to perform field-scale tests must be based on merit and a tangible connection to the Safety Case. Scientific investigations to support a license application are broad in scope, including laboratory tests at ambient and elevated temperature that characterize such properties as salt creep, the potential for fracture damage and its mitigation, permeability functionality of seal system components, brine accessibility via induced damage, chemical conditions in the disposal environment, and a host of other primary properties pertaining to performance assessment. The general goals for any future site characterization and laboratory or field investigations should build upon earlier work to reduce uncertainty and to enhance the safety basis for salt disposal. This document briefly discusses characteristics and modeling pertaining to waste disposal in salt. The intent is to provide a status of the U.S. national effort and assess how a salt URL fits into that effort going forward.

If salt repository research groups are to undertake a commitment to establish a URL, such action will involve a concomitant obligation of scientific resources and money. Given the well-established scientific basis for salt disposal, considerations for testing underground should include scientific rigor and transparent evaluation, implemented with formality, to establish merit and priority. This paper describes a review process (framework) to identify, justify, prioritize, and implement appropriate URL research, development, and demonstration to advance the technical basis for salt disposal.

How then will decisions be made for potential URL activities within a focused salt repository research and development program? In this paper, guidelines are put forward that outline a review and prioritization process for large-scale underground testing. Implementation principles include analysis and justification for generic testing or demonstration activities that meaningfully address technical issues in a credible manner. Implementation of demonstration and confirmation activities, integrated with other beneficial uses, could help establish an expected precondition for public and political acceptance of salt disposal of heat-generating nuclear waste.

DISCUSSION

In-depth explanation of salt attributes for permanent disposal of heat-generating waste can be found in Hansen and Leigh [1] and on the Sandia website for U.S./German collaboration [2]. A brief review of these characteristics will help clarify the foundation from which salt repository research proceeds. Long-term behavior of salt, fundamental to repository applications, requires detailed understanding of deformational processes, such that extrapolation can be made beyond human experience.

The scale of research to date ranges from a microstructural level to full-scale demonstration in the underground. Under most conditions involving elevated temperature and modest confining pressure, salt deforms plastically. The phenomenon of flow without fracture (isochoric creep) is one of the attractive attributes of salt as a disposal medium. Advanced constitutive models in the U.S. and Europe have been used to describe phenomena associated salt deformation and their dependence on different fundamental mechanisms. These constitutive models are often expressed in elegant mathematics and are currently being benchmarked in ongoing international collaborations [3]. Advanced modeling capability provides a dual purpose for field testing—modeling can be used to design test configurations at the outset and subsequently validated by test results. Regardless of proposed field activity, structural mechanics modeling has a role in defining the test bed.

Laboratory investigations in Germany and the U.S. have provided the background understanding of salt mechanical and thermomechanical responses to anticipated repository conditions. Temperature has a dramatic effect on salt deformation and, therefore, temperature and associated heat management are first-order concerns for disposal of heat-generating nuclear waste in salt. The importance of heat from radioactive decay depends on the effects that the induced temperature changes could have on mechanics, fluid flow, and geochemical processes within a salt formation.

Salt deformation in the laboratory and in the field can be accompanied by significant fracturing at room temperature, low confinement, and relatively high differential stress, conditions that occur near free surfaces of the repository openings. Under these conditions salt exhibits a measure of brittle deformation near the roof, floor and ribs, but deforms by constant volume processes at depth within the rock formation. The properties that typically define the disturbed rock zone (DRZ) include: (1) fractures ranging from microscopic to readily visible scales, (2) loss of strength evidenced by rib spall, floor heave, roof degradation and collapse, and (3) increased fluid permeability via connected porosity. Extant DRZ characteristics define boundary conditions for activities conducted within the excavated space. The general setting evolves with time and deformation; however, fracture development near excavations occurs rapidly. Evidence shows that damaged salt can heal under certain conditions, which is another important phenomenon conducive to investigations in a URL.

The Joint Project III collaboration, called *Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt* started in October 2010 [3]. This project compares modeling capability for temperature influence on deformation and for sealing and healing of damaged and dilatant rock salt. The research group is in the process of benchmarking salt mechanics codes against WIPP field tests, which were conducted during site characterization. The benchmarking study on sealing and healing comprises all phenomena that result from the elastic closure of open microcracks up to the re-establishment of chemical bonding along fracture surfaces. In the constitutive models of the partners, modeling these effects is based on a description of the healing rate as function of the current dilatancy and the stress state. Differences in the models arise from differing assumptions regarding the healing boundary. This project phase comprises performance and back-calculation of specific laboratory tests as well as simulations of selected in situ structures. At the conclusion of this collaboration, the benchmarked codes will thereafter provide analysis tools for any possible test or demonstration in a salt URL.

A salt URL could potentially host a wide assortment of tests to confirm our collective (international) knowledge on the technical basis for salt disposal. Consistent with our goals of collaboration, URL space could be used to underwrite internationally significant science and engineering, such as demonstration of sealing elements and DRZ evolution and healing. An ongoing performance confirmation program would be an integral part of a license for regulatory approval of nearly any repository and a URL setting could host an array of performance confirmation measurements associated with safety case arguments. Ongoing science made available by a salt URL holds the potential to reassure societal and political stakeholders. Due diligence also demands ongoing scientific research to confirm the licensing basis, even though the safety case for a salt repository is robust and well substantiated.

FRAMEWORK

The opportunity to set out a research strategy specific to salt disposal helps focus objectives, which can be justified in several ways. A test or demonstration might address specific features, events or processes (FEPS) to confirm our understanding and ability to model performance of a deep geologic repository for heat generating radioactive waste in salt. An activity might be proposed to build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods. A URL activity might be identified by consensus of international collaborations. Many test concepts pertain to design and operational practice, which embody model prediction and confirmation at full-scale. These particular objectives align with similar lists put forward by IAEA and NEA [4, 5]. Many objectives taken from the literature are intertwined and expressible in different descriptive forms. For example, *addressing FEPs* essentially means the same as *assessing performance of the repository system*. Building confidence by reducing uncertainty is a well-recognized basis for field testing. International collaboration is a goal and perhaps a strong justification for investing in a field activity of mutual interest.

Development of proposed testing activities will benefit considerably by integrating information from Performance Assessment into the planning and prioritization of science and engineering activities. The Performance Assessment methodology uses a hierarchy of upper tier requirements that drive data requirements to support safety case development. This structured framework can be used to prioritize activities and transparently communicate up-to-date understanding of the repository safety case. Information within Performance Assessment calculations can readily identify the nature and potential impact of remaining uncertainties, which provide measures of perceived benefit to be realized by testing. Fundamentally, activities to be undertaken in a salt URL would require justification on an objective basis, one of which is impact on Performance Assessment.

Recognizing that mined space is an expensive and limited resource, deployment of large-scale field testing comes with a significant responsibility to use the URL as strategically and cost-effectively as possible. Activities within the underground will be highly visible and carry an obligation to serve generic needs of U.S. national repository programs, international scientific interests, as well as other complementary programs. Plans for a URL must be prepared with high scientific rigor and demonstrably address issues pertinent to safe disposal of heat-generating waste. Proposals for URL research must be considered in the context of the existing body of salt science.

Given broad descriptions of objectives, how can various URL ideas be rated and evaluated? What process is available to differentiate and select URL activities? A commitment to pursue URL testing must be predicated on a structure to weigh relative merits of proposed activities. This process basically describes a simple progression from concept development to evaluation and selection in the following order:

1. Describe activity
2. Conduct independent review
3. Rank and prioritize
4. Make recommendations
5. Select, plan and budget

The framework concept is quite simple: use draft Test Plans to describe proposed URL activities and assemble a small independent review panel to evaluate merit. Use of a draft Test Plan compels the Principal Investigator to justify the activity and demonstrate connection to the safety case. A draft Test Plan also describes parameters, specifics of measurement techniques, data quality objectives, and other information in sufficient detail that objective technical review is possible. Independence of the review panel is indispensable to demonstrate objectivity to stakeholders and to provide the Department of Energy (DOE) a recognized basis for decisions leading to test selection. The deliberate review process is indispensable to the credibility and ultimate success of the URL. Not only does independent review help maximize utility of precious underground testing space, but it underlines the intended generic application of URL studies. The mission of the independent review panel is to critically evaluate and make recommendations regarding the overall mission and proposed research strategy for the URL. In response to initial reviews, the research strategy will be refined, leading to a road map for URL usage. The panel could also provide periodic review of technical progress and afford impartial input for future decisions.

Conclusions and recommendations of the review panel would then be considered by DOE to optimize available and potential research funding. Near-term and long-term temporal sequencing and spatial arrangement could be considered, which may identify initial and chronological tests in the URL. At this stage, the DOE would be able to identify functional and operational requirements from a system-level perspective in order to plan proposed activities. Development of the functional and operational requirements should include discussion of the size, shape and arrangement of openings, analysis of possible test-to-test interference, duration, power requirements, ventilation systems, data acquisition, synergistic goals and possibilities, quality assurance, records management, and other attributes of a well-considered program. These discussions should take into account potential funding sources for tests to be conducted in a salt URL, along with the differing customer expectations that may be tied to those funding sources.

Previous underground testing provides guidelines for an extensive and well documented science program. Quality Assurance procedures governing preparation of Test Plans have been used on the WIPP project for many years and several comprehensive examples exist from previous underground testing; e.g., Sandia's Nuclear Waste Management Procedure NP-20-1 covers Test Plans for field and laboratory experiments. Test Plans are reviewed and approved prior to initiation of work and describe the scientific activity in sufficient detail to allow action to be taken. Creation of a Test Plan will include objectives and describe parameters to be measured, such as deformation, temperature and stress. Data quality objectives for measurement of fundamental parameters are derived from simulations using advanced codes and models, such as thermal-structural mechanics modeling. In turn, the instrumentation and its layout, cabling, timing, power, and data channels all can be developed based on thermal-structural calculations. A Test Plan should also provide a set of post-test evaluation criteria to determine how the results of a completed test might be used to inform future testing. Depending on the location of the URL, the site owner would have operational purview. A coordination group for underground operations would take action required to implement the Test Plan details.

The framework for conduct of URL studies facilitates objective, rigorous, and transparent science. With strategic planning, investigations conducted in the underground can address a number of salt-based disposal issues while supporting generic salt studies. If undertaken with a view toward the future, operations within a URL could become a national and international centerpiece for salt repository research. Involvement of the international community would add scientific credibility and further strengthen stakeholder confidence. Operating a URL should allow participation by the next generation of students and nuclear waste management scientists through provision of a unique laboratory for basic and applied model development, laboratory testing, and field investigations.

USE OF THE URL

There are many potential uses of a salt URL [6], so it is essential to have a process to evaluate and prioritize. Furthermore, a long-term view of URL functions is vital to assess dual-purpose synergy, test-to-test interference, data acquisition, and infrastructure. Although a URL would focus on issues related to nuclear waste disposal, the overall portfolio would also include repository design and operation issues that can be isolated from heat effects, such as engineered barrier construction. This section reviews some of the proposed uses of a salt URL.

The idea of salt disposal, as well as disposal in other media, was restarted after the Yucca Mountain Project was declared unworkable in 2008. Concepts to reinvigorate salt disposal investigations were also outlined at that time, including a sequence of laboratory testing, benchmark modeling, international collaboration, and field testing [7]. Description of several large-scale tests and demonstrations has been published [6]. In addition to a series of public manuscripts describing possible tests within a salt URL, the U.S./German Workshops on Salt Research, Design and Operation examined a suite of the proposed URL activities [2, 8]. A formal, independent review—such as advocated in the framework discussion—has not been undertaken.

International collaborations between U.S. and German researchers has availed the possibility to review and discuss various salt URL test concepts. At the 4th Workshop potential URL activities were reviewed, including those previously identified in the literature [2, 5] as well as some new ideas. Workshop participants were asked to provide high-level review and feedback concerning a sense of duration, cost, and merit among several potential activities. Physical phenomena such as thermally driven creep processes or damage healing also require relatively large scale and time-dependent evolution. Considering there is no salt URL operating in the world, salt repository programs are in a position at this time to reflect deliberately upon the matter of a URL in the context of an overall research, development and demonstration agenda.

A variety of approaches can be taken toward grouping field tests in terms of information to be obtained. For example, seal system testing could involve excavation, short term DRZ evolution, concrete placement and DRZ healing. Thereby operational construction issues, model validation, first-order properties and confirmation could be integrated into one sealing demonstration. Tests could be grouped in relation to expected phenomena, such as thermally driven processes. In turn, the thermally driven processes could be ramped up from relatively low temperatures and low areal thermal loading applicable to a certain waste inventory to high temperatures associated high-burn-up used fuel. In each case, the technical basis (justification for the activity) would be different. Tests may be grouped with respect to degree of difficulty or complexity and evaluated based on cost-versus-benefit analysis. Table 1 is a high-level overview of possible URL activities. Of course, this overview and discussion is rather cursory and a more formal and rigorous review process of URL activities would be expected in order to guide development.

In Table 1, several potential URL activities are listed. Perceived technical basis is identified along with estimates of time and cost, which is abstracted as dollar signs ($ ~ 1 million, $$$$ > 10 million). In principle and considering there is no salt URL today, a balanced approach might consider what useful science and engineering could be accomplished in the first year, what could be accomplished in two years, and what would take longer and cost more. An example is given in Table 1 in terms of thermal testing. Phase 1 could involve a single heater, Phase 2 could involve multiple heaters at moderate temperature to simulate a large percentage of the waste inventory, and Phase 3 could investigate phenomena at high temperatures, which have not been approached experimentally before. Phase 1 using a single heater would allow the URL to establish protocol, develop and install infrastructure, practice data acquisition and other training elements while conducting a relatively simple test, which could be adjusted in terms of heat and orientation. In these high-level considerations benefits can usually be categorized as confirmation, demonstration, validation, and new science. There are many possible uses of a salt URL, which highlights the need for review and consensus.

Most of the proposed investigations are considered expensive and of long duration. Of course, these evaluations are high-level perspectives and more in-depth examination as conducted under the framework concept would be undertaken for proposed URL activities. These preliminary evaluations of the many potential uses for a salt URL are based upon experience, technical discussions, and lessons learned in the design and management of the original underground investigation programs that supported the technical basis for the WIPP as well as decades of salt experimental programs undertaken in Germany. International experience in salt and other geologies provide further insights into the proper design and operation of URL research programs for maximum utility.

CONCLUSIONS

The viability of salt formations to host a nuclear waste repository has been well established. Therefore, a salt repository program does not require a field-scale disposal demonstration to resolve an unknown technical issue before a license application can be prepared. This conclusion is based on a wealth of scientific information that supported both the WIPP compliance certification and the preliminary safety case for Gorleben. The former is in bedded salt and the latter in domal salt. Sufficient technical backing has therefore been demonstrated to produce a license application for a salt repository for heat-generating waste if U.S. policy is set in that direction. On the other hand, if confirmation or demonstration of performance expectations is felt to be essential for public acceptance, then it is possible that confirmation testing or disposal demonstrations could be developed to address such a societal prerequisite. The use of a salt URL could also signal that the repository program for salt disposal is committed to performance confirmation.

Examples of field testing and engineered barrier construction could further demonstrate existing ability to seal a salt repository. The state of international repository research, design and operation has been discussed and published in several annual workshops between U.S. and German researchers. International collaboration continues to advance the basis for salt disposal, with exceptional modeling of WIPP Rooms B&D and many new laboratory tests on WIPP salt. Within the context of salt R&D, the proposition of a salt URL requires justification and establishment of merit in an objective and open implementation framework. Given the likely programmatic outlay in terms of time and money, a careful assessment of the return on investment is imperative. Therefore, a framework for implementation has been provided to guide selection of the most promising uses of underground space.

Table 1. High-level Review of Possible URL Activities

Activity	**Technical Basis**	**Test Duration (years)**	**Cost**	**Considerations**
Phase 1- Low T Single heater	Process understanding Model validation	1-5	$$	Low thermal output waste (defense and commercial)
Phase 2- Medium T Single or multiple heaters In-drift or borehole	Model validation Performance confirmation	2-7	$$$$	Simulate a high percentage of used nuclear fuel inventory
Phase 3- High T Alternative disposal concepts	New science Model validation Safety issues Performance conformation	2-5	$$$$	Demonstrate disposal strategy for high burn-up fuel
Full-scale seal test	Demonstration Performance confirmation Model validation	5	$$$	Operational safety Seal design Modular closure
Wedge pillar	New science Progressive failure	2-3	N/A	High cost:benefit
Fluid differential pressure test	New science Permeability	2-3	$	Quantify uncertainities Assess model
In situ consolidation	Consolidation functions Performance confirmation	<3	$	Operational safety Modular closure
Canister movement	New science Bouyancy models	5-8	$$	Pre and post closure issues
Mine-by test	Model validation Boundary conditions	1	$$	Prerequisite for field tests

A URL in salt would provide opportunities for advancing identified U.S./German research interests and university outreach. Collaboration with Germany and other nations with salt disposal interests (The Netherlands and Poland) would help assure credibility of proposed URL activities and could promote partnering on certain ventures. No matter what activity is selected for the URL, new excavation provides a test bed for measuring evolving formation properties before, during and after the openings are made. Advanced planning allows modeling prediction of deformation and changing permeability. Thus, pre-test characterization (often called a Mine-By test) sets up a code validation/confirmation exercise in the process of defining boundary conditions for tests involving excavations.

This document provides an overview of field-scale testing in the context of the large body of information supporting salt formations as viable for disposal of heat-generating waste. Field testing almost invariably involves long times for planning, pretest preparedness, Test Plan review, readiness review, and execution. Given finite resources, consideration and selection of URL activities takes on a role proportional to its cost. Justification for field testing must be made in the context of an overall salt disposal research program.

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