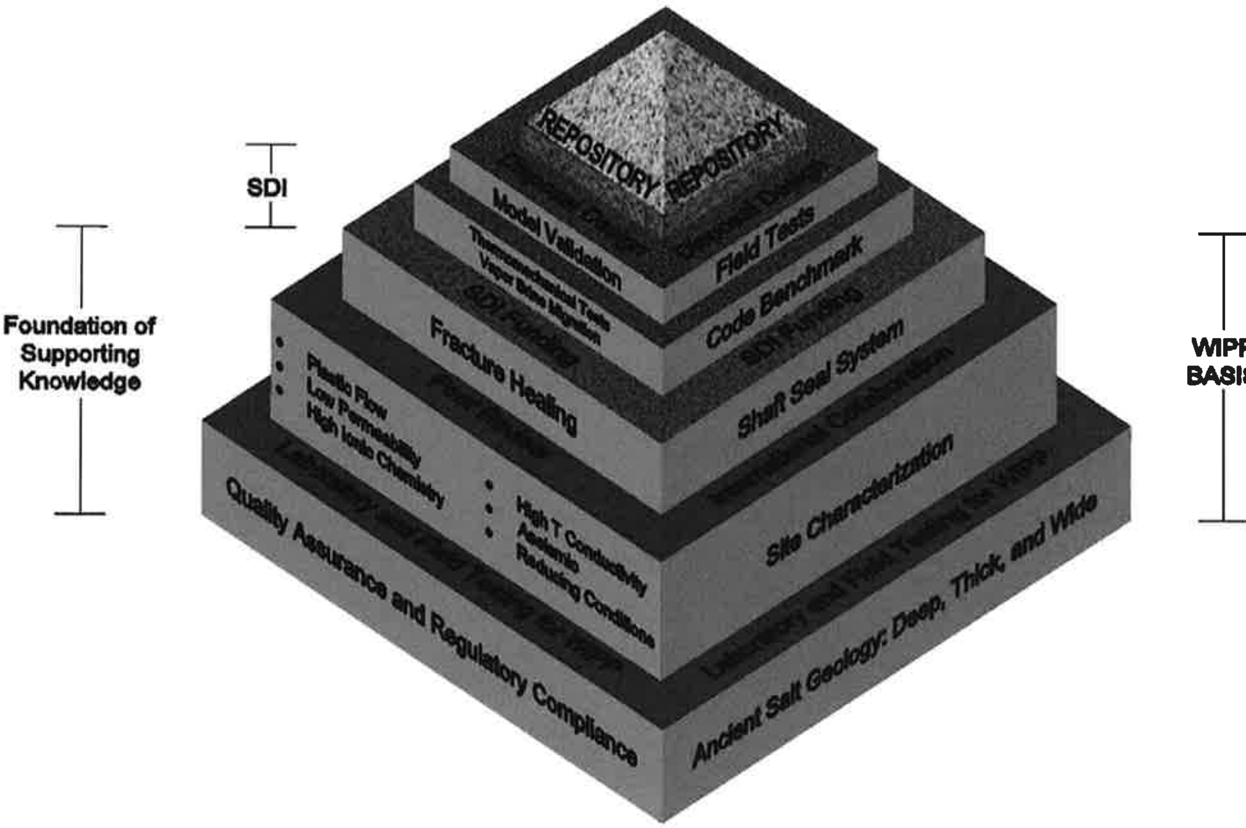
U.S. DEPARTMENT OF ENERGY
CARLSBAD FIELD OFFICE

A MANAGEMENT PROPOSAL FOR

# SALT DISPOSAL INVESTIGATIONS

WITH A FIELD SCALE HEATER TEST AT WIPP




**June 2011**

**DOE/CBFO-11-3470**
**REVISION 0**

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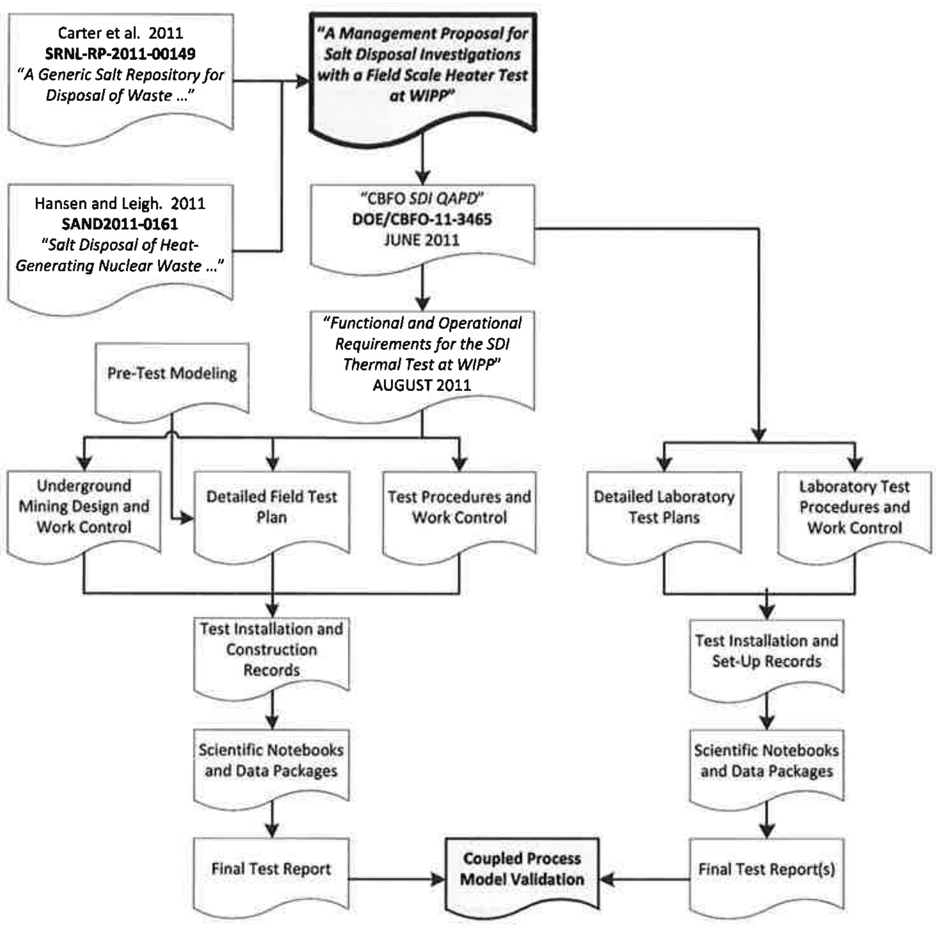
# EXECUTIVE SUMMARY
# SALT DISPOSAL INVESTIGATIONS

## PROJECT INTRODUCTION

This management proposal provides a science-based scope of work (with time and cost estimates) for a defined scope of research (laboratory work and modeling efforts) intended to establish the foundation for a proof-of-principle field test for disposal of heat-generating nuclear waste. This management proposal is considered a preliminary and internal scoping proposal meant to reach a decision-in-principle within the United States Department of Energy (DOE) headquarters. Test-specific requirements such as parameter identification, data quality objectives, instrumentation, calibration requirements, precise borehole and gauge placement, sample control, test procedures, data collection processes, and other test or modeling specific information will be provided in an ensuing field test plan to be developed in fiscal year 2012. Detailed cost estimates and schedules will be developed as a function of DOE fiscal year planning. The figure below provides a general overview of how this management proposal fits in relationship to other Salt Disposal Investigations (SDI) documents and records planned as a result of this project.

**Relationship of the Management Proposal to Other SDI Documents and Records**



Disposal of nuclear waste in salt remains a viable, yet underutilized concept in the United States. The well-recognized success of the WIPP mission for the disposal and isolation of defense transuranic (TRU) waste provides strong positive testimony in support of salt disposal for a variety of nuclear wastes. Bedded salt formations in the United States hold great promise toward solving major disposal issues for thermally and radioactively hot waste currently managed by the United States DOE Office of Environmental Management (DOE-EM).

Previous salt repository studies and operations have been adequate to demonstrate safe disposal of TRU waste in salt. However, for thermally hot waste, there are gaps in the experimental data that are addressed in this management proposal. The developmental history of the current management proposal began in 2008 when DOE assessed the need for a second repository to augment the proposed Yucca Mountain Project. As a part of that process, the DOE Office of Nuclear Energy (DOE-NE) funded a scoping study for the feasibility and efficacy of a comprehensive repository in salt, with the DOE-EM Carlsbad Field Office (CBFO) and its science and operations contracting organizations providing support.

The final report of the scoping study (Carter et al. 2011) provided a proof-of-principle layout and operational strategy for a repository that would meet the combined disposal needs for reprocessed high-level waste, low-level waste, and greater-than-Class-C wastes for the next one hundred years. The report pointed toward a near-term science-based program to gain public confidence and provide a regulatory compliance framework that would close gaps in our current knowledge for salt repositories. To strengthen the SDI proposal, DOE-EM requested a formal and comprehensive compilation of all previous work in salt, current status, and additional science necessary to fill gaps and extend our current understanding, most specifically for heat-generating waste disposal. The resulting report (Hansen and Leigh 2011), coupled with the referenced scoping study, provides the primary basis for work proposed in this SDI proposal.

Directed laboratory and field research can help reduce uncertainties regarding thermally driven processes involved with decay storage and disposal in salt and increase technical understanding for those potential missions. The research program proposed would directly test a disposal arrangement that balances heat loading with waste and repository temperature limits. It would fill information gaps in current knowledge of the thermomechanical, hydrological, and chemical behavior of salt and wastes disposed in salt and form the technical foundation for design, operation, coupled process modeling, and performance assessment of future salt repositories for heat-generating nuclear waste.

This management proposal, originally developed in February 2010, was revised in March 2011 at the request of DOE Headquarters to reflect efficiencies and cost savings realized if the test program was conducted in the area of the WIPP and not in an existing salt or potash mine. The WIPP is an operational disposal facility permitted by the New Mexico Environment Department for disposal of hazardous (mixed) waste and certified by U.S. Environmental Protection Agency for radioactive waste disposal. As such, proposed activities in this proposal will be performed in accordance with applicable regulatory requirements (Section 2.3). This will ensure that all proposed activities will not impact disposal operations or long-term repository performance. The use of the WIPP underground for the field test portion of SDI realizes significant cost savings by avoiding the development and installation of mining infrastructure at some other existing salt or potash mine of similar depth. Of course, there remain substantial costs associated with performance of SDI, as delineated in this management proposal to perform the tests in WIPP. The area to the north of the access shafts (far north of waste disposal operations) is already configured with electrical power and fiber optic cable to service basic science experiments.

Additionally, an existing trained workforce, mining infrastructure, nuclear safety bases, and a quality assurance program will make the field test component of the SDI at WIPP cost appreciably less while supporting a more defensible experiment compared to bringing these essential elements of a field test to another commercial mine.

In June 2011, the CBFO developed a QAPD specific to these SDI activities (DOE. 2011). The SDI QAPD was modeled after the highly effective and time-proven CBFO QAPD and describes an NQA-1-2008 compliant Quality Assurance Program for the science-based studies concentrating on high thermal loading effects in bedded salt. Existing WIPP procedures are adapted as appropriate to accommodate the SDI program, thereby taking advantage of the existing mature and audit-tested programmatic and technical processes established for a successful repository program.

Pursuant to the completion of the SDI QAPD, this current version of the management proposal (June, 2011) was revised to addresses technical and programmatic comments received from a review commissioned by the DOE-NE Fuel Cycle Technologies Program's Used Fuel Disposition Campaign. This process was controlled through the CBFO procedure for document review, Management Procedure CBFO-MP-4.2. Additionally, this version of the proposal reflects a funding strategy of a two million dollar annual budget for the next two consecutive fiscal years from DOE-EM, with DOE-NE contributing to the laboratory and modeling efforts (see reference 22), followed by increased budgets in subsequent fiscal years to start the heating phase in fiscal year 2015. The overall life cycle of the salt disposal investigations has consequently been extended to ten years as a result of the restrained start to the field proof-of-principle test.

## PROJECT MANAGEMENT, QUALITY ASSURANCE, AND SAFETY

The overall management of the work proposed within this SDI project will be through CBFO. The CBFO defines quality requirements through a Quality Assurance Program Document (QAPD), similar to that used for the WIPP program. The SDI QAPD describes an American Society of Mechanical Engineers Nuclear Quality Assurance 2008 Edition (NQA-1) compliant QA program for the science-based studies concentrating on high thermal loading effects in bedded salt. Those portions of the SDI investigations funded by Used Fuel Disposition Campaign (UFDC) of the DOE-NE will be managed according to the judgment of the UFDC management team.

The Los Alamos National Laboratory's Carlsbad Operations (LANL-CO) office will function as the project management organization, responsible for day-to-day test management and coordination, similar to a successful model used at the Nevada Test Site and the Yucca Mountain Project, ensuring that all test-related information and data activities are consistent and focused. In its management capacity, LANL-CO will report to the CBFO Project Manager. Sandia National Laboratories (SNL), LANL, and other potential scientific entities, will provide Principal Investigators to inform and advise test management to ensure the test is as productive, integrated, and efficient as can be achieved.

Washington TRU Solutions (WTS), the WIPP Management and Operating Contractor, will provide engineering, construction, and test support personnel to provide for the test bed (e.g., drift mining, borehole coring, electrical, ventilation) and aid in test installation.

The primary collaborators on this management proposal, predominantly from LANL and SNL, have direct salt repository experience and have conducted decades of salt research and thermal testing, both in the laboratory and the field. Experience directly relative to the types of field and laboratory activities described in this management proposal include field work at the Nevada Test Site, large in situ thermal tests at Yucca Mountain, and experimentation at WIPP. The authors have vast experience in broader repository science efforts in the areas of process and performance assessment modeling, and licensing. Appendix C provides a list of key contributors to this proposal and a summary of related experience.

Each proposal participant has extensive experience and an exemplary record of safety related to field and laboratory work activities, including a culture and value structure that promotes safety in the workplace. Each participant will conduct work safely and responsibly; ensure a safe and healthful working environment for workers, contractors, visitors, and other on-site personnel; protecting the health, safety, and welfare of the general public. This is done through an institutional framework which embodies processes that align with the principles and functions of Integrated Safety Management.

## PROPOSED RESEARCH PROGRAM

The proposed research program would substantially enhance our knowledge of the behavior of thermally and radioactively hot nuclear waste in salt and will provide fundamental data for the model validation and evaluation of concepts for disposal in salt. The program has been divided into six elements:

1. **Functional and Operating Requirements and Test Planning**
   The project benefits greatly from the fact that it can utilize existing infrastructure at WIPP and will be situated in well characterized rock salt. The test itself will require a description of functional and operational requirements (F&OR) for a field test. The work to develop the F&OR document has been funded in FY11. Detailed test plans will then be developed, reviewed, and delivered in FY12.

2. **Laboratory Thermal and Mechanical Studies to Support the Field Test**
   Elevated salt temperatures will cause accelerated salt-creep deformation, which leads to a more rapid encapsulation of the waste. Laboratory studies on the salt from the field-test site are designed to examine intact and crushed salt at the high temperatures expected for alcove disposal.

3. **Laboratory Chemical, Hydrologic, and Material Studies**
   Laboratory studies will establish the key factors that control brine migration, radionuclide solubility, and mobility at elevated temperatures. In addition, material interaction data will be obtained that can be used to evaluate waste forms.

4. **Coupled Process Modeling**
   Prediction of the behavior of the field test will initially be made using the best-available models of thermomechanical behavior, including creep, damage, healing, reconsolidation, and coupled processes. Improvements have been identified for certain elevated temperature constitutive models and brine availability including vapor phase transport. Some of the thermomechanical information will be gleaned from laboratory studies and validated as the field test progresses. The models will be updated using data collected in this study to continuously improve and validate predictive capability. Thus, a rigorously developed modeling capability will be available for use in future design and performance assessment activities for disposal in salt.

5. **Field Test Installation and Operation**
   The conceptual field test provides full-scale, real-world data for the models used to predict behavior of salt and brine at elevated temperatures. The proposed test is designed to push the limits of salt heat loading and waste temperature. One important field test design criterion is high thermal loading. If the test proceeds at a design thermal load of 40 watts per square meter ($W/m^2$), the test bed will experience temperatures in excess of 160°C in the salt mass (see section 3.4.1), above where most data have been acquired to date. Steady state creep rate of WIPP horizon salt accelerates one order of magnitude for each increase of approximately 12 degrees Centigrade (°C). The affected salt near the heater is expected to flow rapidly and perhaps decrepitate (i.e., burst owing to the pressure of fluid inclusions). Upon review of this very aggressive temperature limit, a decision to modify the test temperature in the formal review of the test configuration will be made. However these considerations will be informed early by the laboratory testing. Experimentation in the laboratory will also present significant technical challenges in terms of instrumentation survival and data acquisition. As the laboratory thermomechanical testing proceeds in advance of the field test, laboratory experience will greatly inform the field-test team. In addition, the field test will produce data directly applicable to a potential repository by testing a disposal arrangement.

6. **International Collaboration**
   Collaboration with the European Union countries (particularly Germany) will avail technical staff of the latest international developments in salt repository sciences.

## GOALS FOR CONDUCTING THIS PROPOSED WORK

The primary reasons to conduct the work described in this proposal are: 1) demonstrate a proof-of-principle concept for disposal in salt, 2) bound salt thermomechanical response, 3) investigate thermal effects on intact salt in situ, 4) apply laboratory research to intact and crushed salt, 5) develop full-scale response for dry, crushed salt, 6) observe and document fracture healing in situ, 7) characterize and understand brine liberation and migration, 8) track moisture movement and vapor phase transport in situ, 9) measure the thermodynamic properties of brines and minerals at elevated temperatures, 10) study repository interactions with waste container and constituent materials, 11) measure the effect of temperature on radionuclide solubility in brine, and 12) develop a validated coupled process model for disposal in salt for high heat-load wastes.

Information derived from the proposed field test, laboratory tests, and modeling activities will be transferable to other potential salt repositories. Transferability of experimental and analogue information forms a fundamental scientific tenet, and has been recognized in repository programs, including salt, for decades.

## COST AND SCHEDULE

The total project cost is approximately $43M over 10 years. Mining and engineering labor are included as existing WIPP resources and infrastructure; therefore, those total costs are shown, but not included in the SDI specific budget necessary to complete the work. Consumables and equipment, however, are included as direct costs. Costs (in thousands of dollars) by element and year are shown below:

| Element | FY11 | FY12 | FY13 | FY14-20 | Totals |
|---|---|---|---|---|---|
| 2.0 Management, QA, and Safety | $250 | $1,000 | $900 | $4,600 | **$6,750** |
| 2.4 International Collaboration | $0 | $200 | $200 | $1,550 | **$1,950** |
| 3.1 Operating Rqmts. and Test Planning | $200 | $0 | $0 | $0 | **$200** |
| 3.2 Laboratory Thermal and Mech. Studies | $250 | $400 | $600 | $2,200 | **$3,450** |
| 3.3 Laboratory Hydrologic, Chemical, and Material Studies | $0 | $210 | $700 | $2,600 | **$3,510** |
| 3.4 Coupled Process Modeling | $0 | $300 | $700 | $1,900 | **$2,900** |
| 3.5. Field Test Installation and Operations | $0 | $800 | $900 | $22,400 | **$24,100** |
| ** Existing WIPP Mining Resources and Infrastructure | | ($1,500) | ($1,500) | ($1,500) | ($4,500) |
| **Total SDI Budget (new) per year** | **$700** | **$2,910** | **$4,000** | **$35,250** | **$42,860** |
| **Total Cost (incl. existing resources)** | **$700** | **$4,410** | **$5,500** | **$36,750** | **$47,360** |

**Primary actions and test planning (FY11):**

- Complete the SDI Management Proposal
- Complete a Test Plan for laboratory testing for crushed salt in the laboratory to measure thermomechanical behavior across a variety of temperature, stress, and porosities
- Initiate laboratory tests on crushed salt
- Develop an NQA-1-compliant Quality Assurance Program Document and associated procedures
- Complete the F&OR document for the field test

**Test planning, initial mining and laboratory studies (FY12):**

- Begin elevated temperature tests on intact salt in the laboratory to measure thermomechanical behavior across a variety of temperatures and stresses
- Continue the laboratory tests on crushed salt
- Develop and review the detailed field test plan with equipment lists, instrumentation and borehole layouts, data quality objectives, etc.
- Comprehensively evaluate existing and available information from past thermal experiments
- Develop the criteria for the underground test design and layout
- Begin mining the underground access drifts to the test bed location
- Begin installing ventilation control and power distribution
- Write a test plan for laboratory studies of water liberation and brine migration in salt
- Begin measuring the thermodynamic properties of brines and minerals at elevated temperatures in the laboratory
- Develop a test plan and begin measuring the effect of temperature on radionuclide solubility in the laboratory
- Develop a test plan and begin studying repository interactions with waste container and constituent materials in the laboratory
- Evaluate and use coupled multiphysics modeling capability for field test configuration and analysis

**Initial studies (FY13):**

- Continue development of fully coupled TM(H) code and model for field test analysis.
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Develop test plan for intact core testing in the laboratory
- Procure test equipment and instrumentation for the field test
- Develop work control and safety basis for the field test
- Complete mining of the underground access drifts
- Develop the documented safety analysis for the field test
- Mine the field test bed

**Field test implementation (FY14):**

- Core instrumentation boreholes
- Implement the field test equipment, including data collection equipment and fiber optic communication equipment
- Investigate salt properties of test bed location
- Preparedness assessment for field test start and baseline measurements
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Continued development of fully coupled THMC code and model for field test analysis

**Conduct the proof-of-principle field test (FY15 - 20)**

- Heating start on field test – FY 15
- Investigate thermal effects on intact salt in situ
- Develop a full-scale response for dry crushed salt
- Observe and document fracture healing in situ
- Track moisture movement and vapor phase transport in situ
- Complete laboratory thermomechanical testing and chemistry experiments
- Complete laboratory studies of water liberation and brine migration
- Cool-down of field test by FY 19
- Post-test forensics, mine-back and post-test coring in FY 19 and FY 20
- Complete the final test and data reports
- Develop calibrated, coupled TM(H) model

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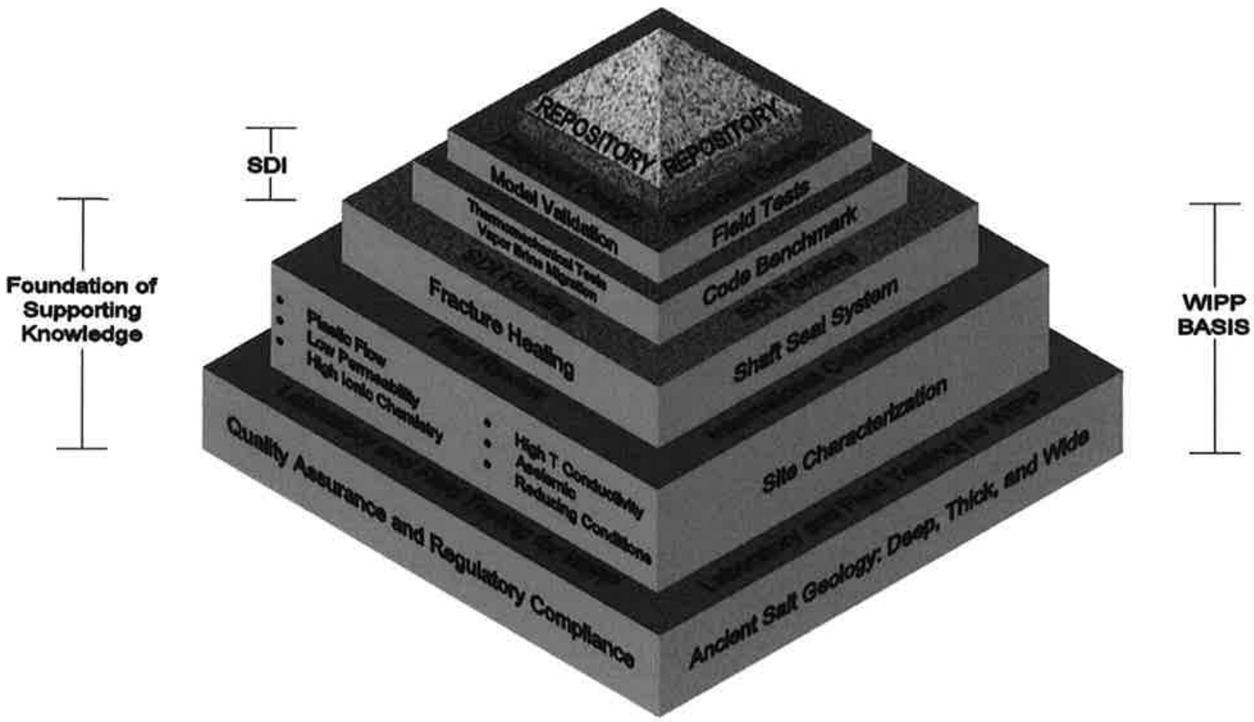
# 1. PROJECT INTRODUCTION

Long-term decay storage and permanent deep geologic disposal of heat-generating nuclear waste (such as high-level waste [HLW]) in salt lie at the intersection of research on repository performance, waste form behavior in different geologic formations, and public acceptance of the U.S. Department of Energy (DOE) Office of Environmental Management – Office of Nuclear Energy (EM-NE) Initiative for Waste Disposal Research. Public understanding and confidence in decayed storage or permanent isolation of radioactive waste in salt have improved as a result of more than a decade of successful disposal operations at the Waste Isolation Pilot Plant (WIPP). EM-NE-directed research can leverage this positive experience by reducing uncertainties regarding thermally driven processes involved with decay storage and disposal in salt, and therefore further increasing technical understanding for those potential missions. This point is explicitly included in the Memorandum of Understanding between the two offices on the topics of Used Nuclear Fuel and Radioactive Waste Management and Processing Research and Development (DOE, 2011). In collaboration with international salt repository programs, laboratory experiments, and simulated heat-generating waste/salt interaction tests, the next few years will answer remaining questions and more fully inform future repository programs. The proposed work will build upon a foundation of excellence in salt repository applications that began almost 50 years ago.

Bedded salt formations in the United States hold great promise for solving major disposal issues for thermally and radioactively hot waste currently managed by DOE EM. This management proposal involves non-mission-specific testing to evaluate the efficacy of bedded salt for thermally hot nuclear waste. The research, development, and demonstration contained in this proposal will advance the technical baseline for disposal in salt and could significantly inform future nuclear waste repository decisions.

Figure 1-1 illustrates how this management proposal builds upon an enormous base of knowledge from early test programs, many of those at WIPP (e.g., see Table 1-1, historic listing in Appendix B, and Hansen and Leigh. 2011), and that, with a relatively small and achievable incremental amount of modeling, laboratory testing, and field demonstration testing, new paths toward waste disposal designs and a future repository in salt can be realized. Information derived from the proposed field test, laboratory tests, and modeling activities will be transferable to other salt sites. Transferability of experimental and analogue information forms a fundamental scientific tenet, and has been recognized in repository programs, including salt, for decades.

**Figure 1-1: Science Based Foundation for TRU and HLW Disposal in Salt**




## The Challenging Waste Issue

DOE-EM currently manages the defense HLW from reprocessing over 160,000 tons of used nuclear fuel (UNF) in the states of Washington, Idaho, and South Carolina. Figure 1-2 compares the surface exposure rate of defense remote-handled transuranic (TRU) waste (currently being disposed of at the WIPP) and defense HLW. The defense HLW processing system in place today reflects a set of baseline technologies that, among other things, presupposed the co-disposal of DHLW (as borosilicate glass waste forms) and UNF at Yucca Mountain. A recent NAS study on waste form technology options (NAS, 2011) concluded that there is still time to improve upon the current path forward by incorporating scientific advances into the defense cleanup program to maximize efficiencies. The study highlighted the potential opportunities of developing more efficient waste form production methods, and stressed the need to match a waste form and accompanying engineered barriers to the disposal environment. The issues driving the development of waste forms have traditionally included waste loading, radiation tolerance, and long-term durability in an environment in which contact with water leads to radionuclide mobilization and transport through the natural environment. Salt is unique as a disposal medium in that, for an appropriately selected site, the amount of water contacting the waste under undisturbed conditions is expected to be minimal. This feature could be exploited by adopting more efficient, safe, and cost-effective processes upstream of HLW emplacement in the repository by relaxing the requirement that the waste form be exceptionally durable in the presence of water. Thus, research to confirm or disprove critical hypotheses on the efficacy of salt as a disposal medium for thermally hot waste is a logical next step that could lead to a viable disposal concept and to more efficient upstream options for defense waste streams.

The Nuclear Waste Policy Act and its amendments legislate that HLW eventually be emplaced in a national waste repository. However, the national repository is also intended to be a retrievable storage site during the operational phase and possible disposal site for UNF from the commercial nuclear power industry, now representing about 60,000 metric tons (MT). These two waste forms (defense HLW and commercial HLW) are radically different in radioactivity, future value, and many other attributes. Additionally, if UNF is reprocessed in the future, it is potentially limiting to connect UNF storage with either decayed storage or the deep geologic permanent disposal of HLW fractions from recycling. With the new administration's intent to rethink the issue of long-lived radioactive waste disposal in America, it is prudent that DOE research other possible geologic disposal solutions that do not directly link UNF retrievable storage with defense HLW disposal. If retrieval is less important, permanent isolation in salt potentially emerges as a robust geologic solution.

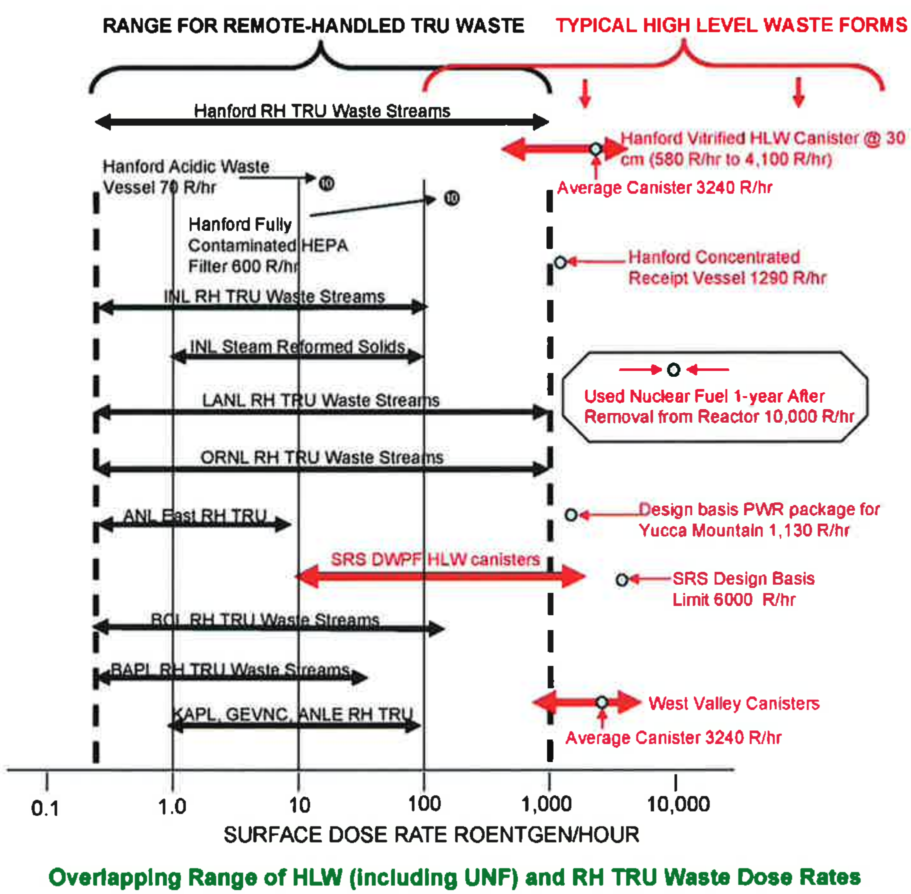
Note that retrievability to maintain ready access to a potentially valuable material is a different concept than maintaining the ability to reverse a decision to bury waste because of a flaw discovered in the safety case after disposal operations have begun. An NAS study on "adaptive staging" of repository programs (NAS, 2003) advocated retrievability from the standpoint of ensuring that decisions can be reversed, even to the extent of being able to remove wastes placed in the repository until permanent closure of the facility. In this context, retrieval of waste from a salt repository is technologically feasible, if necessary due to safety considerations, by a process of locating the waste package and re-mining to recover it. Thus, recovery of waste to reverse a decision due to safety concerns would be achievable, whereas retrieval for the purpose of recovering a valuable resource should not be considered as a viable option for salt. Therefore, the issue of retrievability should not be viewed as an impediment to proceeding with a research program for HLW disposal in salt.

The preliminary views from the subcommittees of the Blue Ribbon Commission (June 2011) noted that regardless of the future nuclear fuel cycle chosen, a geologic repository will be needed. At this point in time it is not possible to categorically state that such a future repository will be loaded with only HLW or only UNF, and it is quite likely that both waste types will be disposed of even if reprocessing is used to intercept new UNF at some future time. It is also premature to categorically state whether or not defense/government/commercial wastes will be segregated for disposal or will be disposed of together. This makes it prudent to study the disposal of disparate waste type characteristics for the higher volume wastes that may be expected. Therefore, for this proposal, the range in higher volume waste characteristics will be bounded by current descriptions of high-burnup UNF and HLW currently being produced (SRNL) and slated to be produced (Hanford) in the near term.

With respect to civilian nuclear waste, there is no technical issue related to safety or adverse environmental impact that creates an urgent need to identify a permanent disposal option. Storage in spent fuel pools and in dry casks is deemed to be an appropriate technological solution for at least 60 years beyond the licensed life of operation (U.S. NRC, 2010), and applied R&D could be conducted to enhance the technical basis for even longer storage periods. Long-term storage, with UNF stored either at reactor sites, or as recommended in a recent MIT study (MIT, 2011), in a centralized storage facility, would provide the time needed (several decades by most estimates) to assess various fuel cycle technology options before choosing the most appropriate, sustainable fuel cycle for the future. If during that period, it is determined that reprocessing would be desirable, the country would be faced with the need to dispose of a variety of waste streams, including HLW. To prepare this HLW for disposal, many of the unit operations and waste forms generated in a civilian UNF reprocessing future would be similar to those already being executed to handle DHLW. This process knowledge would be put to use should the nation decide that reprocessing of civilian UNF is desirable. Extending that concept to repositories, the proposed studies would have direct relevance to future disposal of HLW from reprocessed UNF, potentially by identifying a viable, highly cost effective disposal system. Even if it is ultimately decided that civilian UNF should be disposed of in an open fuel cycle without reprocessing, the proposed studies would provide important information on the behavior of salt under thermal loads that would be relevant to the assessment of salt as a disposal medium for UNF.

This management proposal drives directly to key technical issues common to EM-NE initiatives in waste disposal research. The program described here will vastly improve disposal options, assess waste form performance in salt, and promote public confidence — all key building blocks of the EM-NE initiative. Salt Disposal Investigations (SDI) will move forward with a science-based research program on multiple fronts, laboratory research in hydrology, chemical, and material studies, laboratory thermomechanical salt behavior, directed field testing of simulated waste/salt interaction, and full integration and collaboration with similarly motivated research centers in Europe. Deliberations on the future of nuclear energy directed toward decayed storage and disposal of commercial HLW fractions from recycling will also benefit from research proposed to resolve the key questions about thermal salt storage. This work leverages off earlier work and the substantial knowledge base concerning HLW storage and disposal in salt.

**Figure 1-2: Comparison of Surface Exposure for RH TRU Waste (Being Disposed at Waste Isolation Pilot Plant) and Defense HLW**

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**Why Bedded Salt?**

Ten years of successful operation of the WIPP have demonstrated the fiscal, operational, and compliance efficiency of salt mining and defense TRU waste disposal. Salt investigations in the United States and Germany support the concept of salt disposal for heat-generating waste as well; however, there are some gaps in our knowledge base for the mechanical behavior of salt and the hydrologic and chemical behavior of brine at higher temperatures, as well as how salt interacts with waste constituents at higher temperatures. Heat management is an overriding consideration in repository layout, and the very act of balancing the heat load underground creates ample volume for disposal of non-heat generating wastes such as greater than class C and low-level radioactive waste. Furthermore, depending on the results of this testing program and accompanying performance assessment analyses, direct disposal of calcined or other mineralized forms of waste, or other cost-effective changes to upstream processing, might be found acceptable.

The positive attributes of salt that make it an effective medium for disposal and isolation of hazardous, toxic, and radioactive materials have been recognized for over 50 years (NAS. 1957). As briefly discussed below, the attributes of salt are collectively important to its isolation capability and provide the safety basis for isolation of embedded materials.

1) **Salt can be mined easily.** Salt has been mined for millennia. A wealth of underground experience, including TRU waste disposal operations at WIPP, ensures that large-scale, safe mining can be conducted in salt.

2) **Salt flows around buried material and encapsulates it.** Salt will slowly deform to surround other materials, thus forming a geologic barrier that isolates waste from the environment. Creep or viscoplastic flow of salt has been well characterized for many applications. Research in the United States, coupled with international collaborations, has played a significant role in development of this technical understanding.

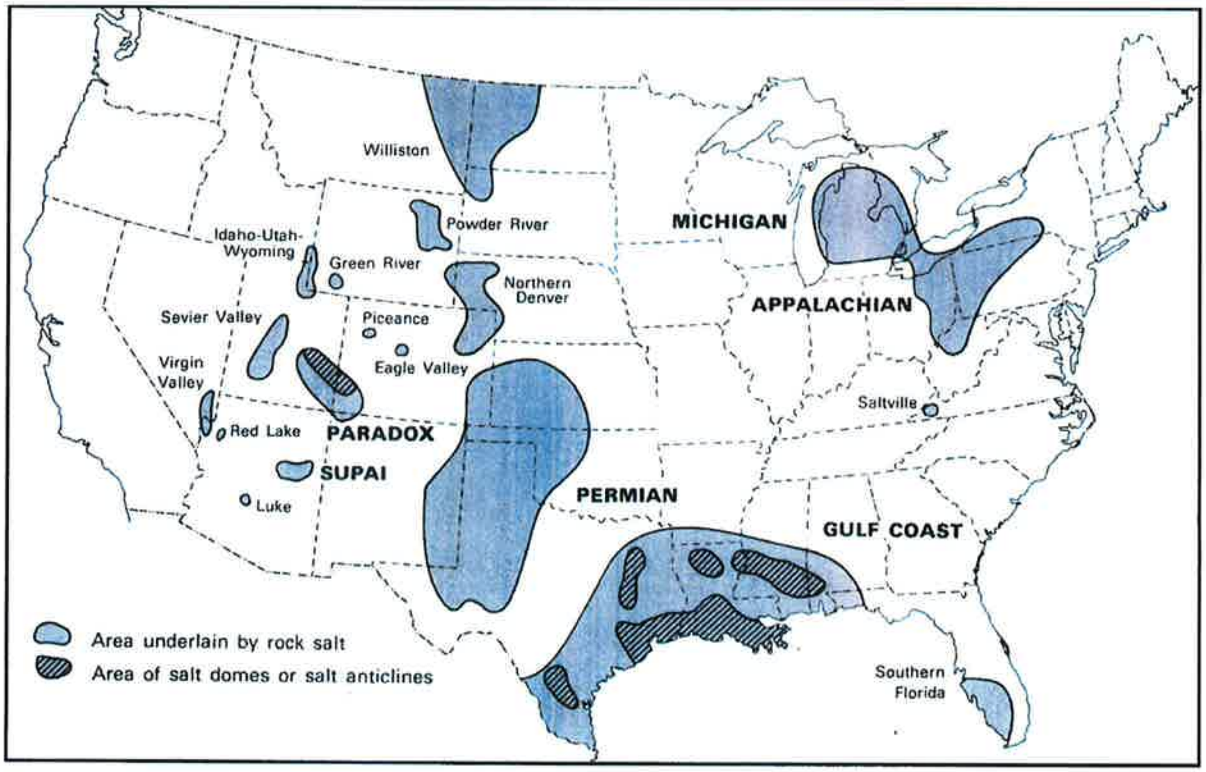
3) **Salt is essentially impermeable.** The very existence of a salt formation millions of years after deposition is proof that water has not flowed through the formation. The established values for permeability of intact salt come from many industry applications, such as the large-scale storage of hydrocarbon product in solution salt caverns. The undisturbed formation permeability of salt is essentially too low to measure using traditional hydrologic and reservoir engineering methods. In undisturbed and healed salt, brine water is not able to flow to waste at rates that would lead to significant radionuclide mobilization and transport.

4) **Fractures in salt are self-healing**. In terms of disposal, one of the most important attributes of salt as an isolation medium is its ability to heal damaged areas. Damage recovery is often referred to as "healing" of fractures. The healing mechanisms include microfracture closure and bonding of fracture surfaces. Evidence for healing of fractures in salt has been obtained in laboratory experiments and through observations of natural analogs. Fracture healing can readily restore salt to a low permeability, as noted above.

5) **Salt has a relatively high thermal conductivity**. Thermal conductivity of natural rock salt under ambient conditions is approximately 2 to 3 times higher than granite or tuff. A relatively high thermal conductivity is a positive attribute in a salt repository for nuclear waste because the heat is rapidly dissipated into the surrounding formation.

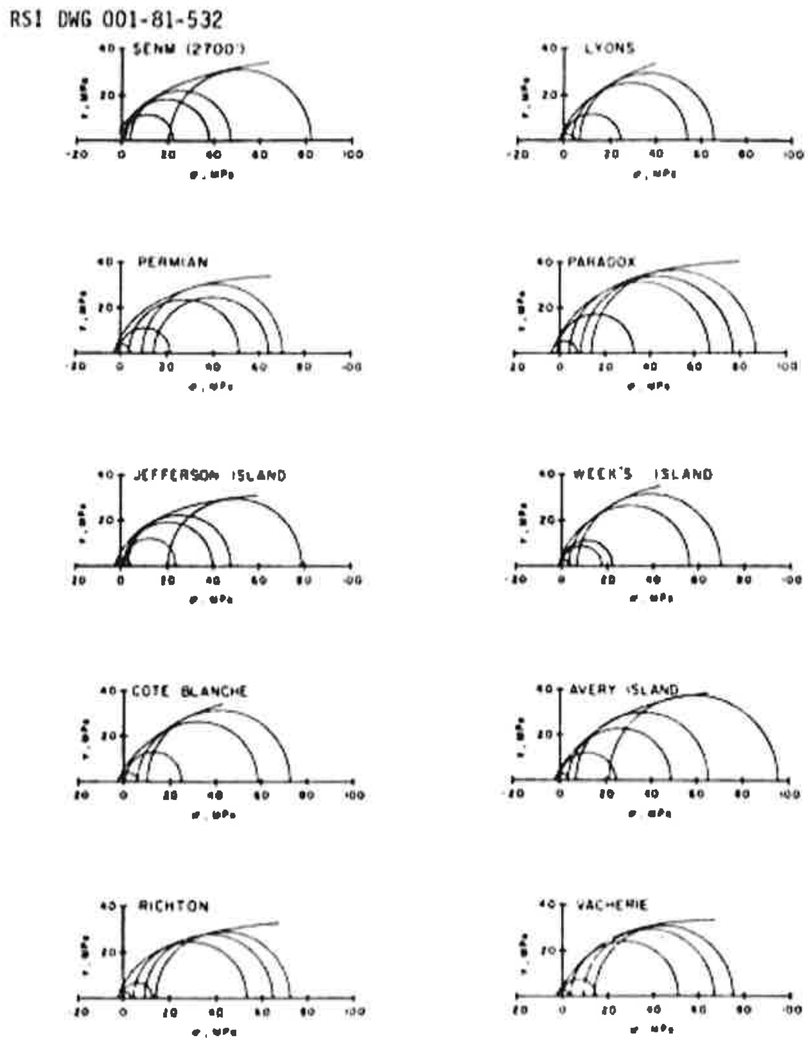
6) **Suitable salt formations exist in wide geographic distributions.** There are multiple locations with stable geologic salt formations within the 48 contiguous states (see Figure 1-3) that could host a repository. Bedded salt is preferred over domed salt due to the inherently larger areas contained in the bedded geologic salt formations, which leads to flexibility in accommodating potentially long periods of repository operations. In addition, salt formations have existed for millions of years in non-seismically active areas.

**Figure 1-3: Stable Geologic Salt Formations within the 48 Contiguous States**




Salt formations were actively studied for repository applications from the late 60's until the NWPA amendment removed the bedded salt site in the panhandle of Texas from consideration as the civilian repository for spent nuclear fuel and high level waste. In a global sense salt mechanical, thermal, and hydrological properties are fundamentally similar. In the early years of site investigations, basic properties of many salts were measured. For example, in Figure 1-4, the failure envelopes for ten natural salts including both bedded and domal formations with a variety of impurities show the similarity of strength and pressure sensitivity (Hansen et al., 1980). Some of the other basic phenomena, such as dilatant response and plastic deformation mechanisms, have commonality across a wide range of natural salt. These points are made to emphasize that the fundamental studies encompassed in the SDI will be applicable to all salt repository studies.

**Figure 1-4: Mohr's Circles of Stresses at Failure for Ten Rock Salts at Room Temperature**




## Why Study Bedded Salt at Higher Temperatures?

Laboratory and field studies of intact salt and crushed salt and the chemical interactions of salt with waste packaging, waste forms, and waste constituents received a considerable amount of attention in the 1980s. However, the upper temperature limit for the thermomechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests have been conducted predominantly at room temperature. These past studies have been more than adequate to demonstrate that disposal of TRU waste in salt is safe and efficient. However, for thermally hot waste there are gaps in the experimental data that are addressed in this management proposal. The proposed research, development, and demonstration of salt efficacy for the safe and efficient disposal of thermally hot waste proposed here will provide the basis for a single repository that can readily isolate large quantities of nuclear waste material, a key component of a safe and secure nuclear future for the nation.

The main goals for conducting this work are:

- **Demonstrate a proof-of-principle concept for disposal in salt.** WIPP experience has demonstrated that placing waste in a pre-drilled borehole is cumbersome and difficult. This disposal concept — proposed as a result of previous DOE-funded work (Carter et al. 2011 – see section 3.5.1) — obviates the need for pre-drilled holes, as well as the difficult phase of waste alignment and insertion into the pre-drilled hole. The proposed disposal concept is simple, safe, and expedient. The outcome of this proposed testing, in concert with the WIPP and analogue repository experience, will allow a more objective evaluation and optimization of proposed future repository designs.

- **Bound the salt thermomechanical response.** This test will push the envelope in terms of individual canister heat load and the average bulk salt temperature, thus ensuring that the thermomechanical phenomena experienced in the test for disposal in salt encompasses all likely thermal loads associated with future disposal.

- **Apply laboratory research to intact and crushed salt.** The fundamentals of high-temperature intact salt response and hot, dry reconsolidation will be studied in the laboratory. Information derived will inform field test planning and underpin the coupled process models of the large-scale response.

- **Investigate thermal effects on intact salt in situ.** Elevated temperature in the near-field environment will give rise to salt decrepitation (bursting caused by expansion of trapped brine) in addition to stress-induced fracture. Note that these phenomena may be negative or positive in terms of long-term performance, depending on the fate of liberated water and the ability of fractures in salt to heal. High temperatures, fracture states, and brine liberation drive important performance phenomena that will be investigated at repository scales in the field test.

- **Develop full-scale response for dry, crushed salt.** Whereas the reconsolidation processes of ambient crushed salt with a small amount of moisture are well understood mechanistically (e.g. Brodsky et al. 1996), the large-scale reconsolidation of hot and dry salt is less well documented. Understanding crushed salt reconsolidation in this setting is essential to establish room closure response, thermal conductivity, and near-field temperatures.

- **Observe and document fracture healing in situ**. Fracture healing is an important attribute for disposal in salt. This experiment will allow evaluation of creation and healing of a disturbed rock zone.

- **Characterize and understand brine liberation and migration.** Small amounts of brine exist in natural bedded salt, trapped there since its ancient deposition, millions of years ago. The brine exists in three forms: fluid inclusions, grain boundary brine, and hydrous minerals. Laboratory experiments will be conducted to quantify brine migration and characterize mineral reactions relevant to the water budget.

- **Track moisture movement and vapor phase transport in situ.** Because brine is considered a key to the evolution of the disposal setting, its movement in this testing milieu will be documented. Liberated brine will derive from the disturbed rock zone as enhanced by the thermal pulse. Samples of various materials associated with the full-scale test will allow determination of what chemical reactions and transport might take place with the brine movement.

- **Measure the thermodynamic properties of brines and minerals at elevated temperatures.** Precise measurements of the pressure, volume, and temperature (PVT) properties of brines are required for coupled process and performance assessment models.

- **Study repository interactions with waste container and constituent materials.** Evaluation of the chemical interactions of a broad range of materials (see Table 3-4) and waste forms in the laboratory will provide a scientific basis to evaluate waste form strategies and engineer waste forms and packages to limit or preclude the migration of radionuclide species in a salt based repository.

- **Measure the effect of temperature on radionuclide solubility in brine.** Radionuclide solubility will control the source term of any thermally hot waste repository for scenarios in which water contacts the waste. These studies will quantify the magnitude of the temperature effect on radionuclide solubility (U, Th, Tc, and Cs) and both guide and focus future performance assessment work.

- **Develop a validated coupled process model for disposal in salt for high heat load wastes**. Iterative field observations and model development will lead to a model that can be used with confidence in future repository design and performance assessment analyses.

- **Evaluate environmental conditions post facto**. After the heating cycle is complete, the test will be allowed to cool sufficiently to allow for the performance of forensic studies of the healed fractures, the consolidated salt, and corrosion coupons as the heaters are disinterred.

Underlying the research is the hypothesis that heat-generating waste may be advantageous to permanent disposal in salt. Under the conceptual model leading to this favorable result, the approximately 300-year thermal pulse introduced by the defense HLW would dry out a moisture halo around emplaced waste and thereafter accelerate entombment by thermally activating the creep processes. Note also that the thermally hot UNF recycling fractions (notably cesium (Cs)-137 and strontium (Sr)-90) will simply decay away in approximately 10 half-lives or 300 years. Thus, thermal decay storage in salt of these elements, which might otherwise be separated and stored, would favorably affect the disposal environment for the remaining very long-lived isotopes. These long-lived isotopes would be permanently encapsulated in a geologic formation that is demonstrably hydrologically inactive for hundreds of millions of years, thereby potentially precluding the need for engineered barriers in a repository design. As an example, a currently proposed engineered barrier is vitrification, a waste form modification for HLW.

The directed research will inform, guide, and ultimately validate capabilities for the next generation of coupled multiphysics modeling. The current state-of-the-art models will be instrumental for layout of the large-scale in situ field tests and continue to provide bases for performance assessment in the future. Next generation coupled TM(H) codes developed concurrently with the planning phase of the field test would then be benchmarked against current codes and validated using the field test data. This research will identify specific requirements for a viable long-term decay storage and deep geologic disposal concept in salt. These key elements would translate into parameters and phenomena to be measured in a proof-of-principle field test. The validated conceptual and numerical models resulting from the effort can then be used in future design calculations or performance assessment analyses. Appendix B, written as a short memorandum in June 2010, provides a brief recap of some of the reasons that salt research is timely and of national interest.

The investigators are well aware of the significant challenges to established boundaries presented in this proposal. The very reason for this proposal is that this work substantially advances the basis for the design, analysis, and validation of disposal in salt. The work embodied in this proposal is transformative. It is not proposed to repeat what others have done before; from the existing body of knowledge, the intent is to push forward the technical basis for disposal in salt. Cognizance of the scientific baseline has allowed the proposal team to establish the limits identified in this work, which will further the scientific limits in the address of unanswered questions. Because this is a science-based research proposal, which explores and advances the substantial foundation of salt science, the work, by necessity, rests at the forefront of technology, knowledge, and experience. This work is proposed because it explores the frontier and addresses questions that when answered, will set the future direction for disposal options in salt for the nation. Execution of elements of this management proposal, therefore, presents daunting challenges. Laboratory thermomechanical testing, for example, will include tests at high temperature and pressure, because understanding the physics under these conditions is vital to operational concepts, design, safety, and long-term isolation.

One of the important field test design criteria is high thermal loading. If the field test goes forward at a design thermal load of 40 W/m$^2$, the test bed may experience temperatures in excess of 160°C in the salt mass (see section 3.4.1), above where most data have been acquired to date. Steady state creep rate of WIPP horizon salt accelerates one order of magnitude for each increase of approximately 12°C. The affected salt near the heater is expected to flow rapidly and perhaps decrepitate. Upon review of the field test plan, the team may modify the very aggressive temperature limit, decide to modify the test temperature, or otherwise adjust the test and instrument arrangement. These considerations will be informed early by the laboratory testing and modeling. Experimentation in the laboratory will also present significant technical challenges in terms of instrumentation survival and data acquisition. As the laboratory thermomechanical testing proceeds in advance of the field test, laboratory experience will greatly inform the field-test team.

**Applicability of this proposed work to other salt sites**

There is a solid foundation of work conducted in salt, both for thermally cool and thermally hot wastes, providing confidence that a directed research program could lead to an expeditious path forward for thermally hot HLW disposal. This foundation, summarized in Hansen and Leigh (2011) and embodied in the WIPP technical basis documents, consists of 1) WIPP site-specific characteristics such as the geology of the Salado Formation (the salt host rock for the WIPP repository), the hydrochemistry of the repository fluids, the hydrogeology of the adjacent formations, and seismic stability; and 2) fundamental physical processes such as salt creep behavior, rock salt damage due to the mining operation, the hydrologic characteristics of intact and damaged salt, the healing of fractures in salt, radionuclide solubility and speciation in high-ionic-strength solutions, and the ambient-temperature consolidation of crushed salt (studied extensively in the context of the WIPP shaft seal system design).

At this stage of development of a HLW repository in salt, site-specific considerations in item 1 that enable the WIPP safety case to be made are not relevant because the science gaps being addressed in this management proposal are basic issues that are independent of any specific site. However, inasmuch as studies conducted at the WIPP site contribute greatly to the foundational knowledge of salt repositories, the rock characteristics and processes studied at the WIPP site are relevant, especially given that the logistically optimal next step for field testing would be to conduct in situ experiments at the WIPP facility. Because the location of a future repository will likely be based on a voluntary siting process (as suggested by MIT, 2011, among others), science-based investigations conducted before site selection must be focused on addressing fundamental issues that will be present at any potential salt repository site. Information gained from *in situ* studies must be transferable to other sites, either through direct analogy or through the use of validated numerical models. Furthermore, the observations made at the specific field study site should provide information useful to the site selection process by highlighting the properties and conditions that are either conducive or deleterious to repository performance. In suggesting the need for testing in an underground research laboratory (URL) at this stage, this proposal draws upon a long precedent in international repository programs (e.g. IAEA, 2001) for an approach involving research at URLs in advance of or in parallel with a site selection process, including the Swedish Aspo Hard Rock Site (Lundqvist, 2001) the Grimsel and Mont Terri sites in Switzerland (McKinley et al., 2001) and the Asse salt mine in Germany; the wisdom and efficiency of this approach appears to be borne out in the successful progress of the Swedish program.

With respect to this effort, the proposed research and development will build upon a foundation of excellence in salt repository applications that began with the 1957 National Academy of Science recommendation to use salt for permanent isolation of radioactive waste from the biosphere. As summarized in Table 1-1, various programs at different times and places have shared their results, which accounts for the large foundation for understanding salt properties over a wide range of applications. The proposed SDI will further add to the scientific basis for disposal in salt.

Table 1-1 summarizes the history of in situ salt thermal tests both in the U.S. and internationally over the past 50 years. The need for additional, science-based testing to fortify the technical baseline supporting HLW disposal builds upon a considerable data base deriving from historical experiments. For example, field heater tests in salt were conducted in Project Salt Vault in Kansas in the 1960s and in WIPP in the 1980s. Building upon past experiences and taking advantage of advanced technology allow the formulation of a solid, task-oriented, progressive proposal to address the remaining issues for HLW disposal in salt.

**Table 1-1: Summary of In situ Salt Thermal Tests**

| Year | Project | Location | Description |
|---|---|---|---|
| 1965-1969 | Lyons mine, Project Salt Vault | Lyons, KS | Irradiated fuel & electric heaters |
| 1968 | Asse salt and potash mine | Germany | Electric heaters |
| 1979-1982 | Avery Island | Louisiana | Brine migration |
| 1983-1985 | Asse (U.S./German Cooperative) | Germany | Brine migration under heat & radiation |
| 1984-1994 | WIPP | Carlsbad, NM | 1) DHLW mockup<br>2) DHLW over-test<br>3) Heated axisymmetric |

It is worth noting that the heated experiments conducted at WIPP were undertaken after the agreement was made not to place heat-generating waste at WIPP. The collective science community agreed that the results obtained at WIPP would be applicable to the civilian program, which was investigating salt in the Texas panhandle. Thus, the justification for continuing field tests at WIPP was recognition of the transferability of information. The basic material properties, effects of stress and temperature, and phenomenology at a field scale were thought to be applicable and transferable between sites (see Figure 1-4, for example). In addition, salt programs have collaborated internationally for the purpose of understanding the fundamental physics. Indeed, the transferability of salt investigations reaches across the ocean, as the US civilian program sponsored brine migration experiments at the Asse mine in Germany. The salt science community has been building the technical baseline collectively for decades, utilizing lab and field test results from many different sources (Sandia National Laboratories. 2010. US/German workshop http://www.sandia.gov/SALT/SALT_Home.html.).

The following synopsis includes field experiments that started as early as 1965 with Project Salt Vault near Lyons, Kansas, as well as nearly contemporaneous field testing and demonstration at the Asse salt mine in Germany.

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 WIPP site near Carlsbad, New Mexico. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits.

These field tests imparted a relatively modest thermal load in a vertical borehole arrangement and did not use crushed-salt backfill or explore reconsolidation of salt. These tests were primarily focused on the mechanical response of the salt under modest heat load. Although the results can be used, for example, to validate the next-generation high-performance codes over a portion of the multiphysics functionalities, the SDI disposal concept is intended to explore the interactions created by higher heat loads, a horizontal placement and crushed-salt backfill. The Heated Axisymmetric Pillar test conducted at WIPP in the 1980s (Matalucci. 1987) involved an isolated, cylindrically shaped salt pillar and provided an excellent opportunity to calibrate scale effects from the laboratory to the field, as well as a convenient configuration for computer model validation over a small part of the thermomechanical range of interest. These experiments were conducted at temperatures that are at the lower temperature range than that of which the SDI investigations are expected to test.

The very concept of analogues for repository performance is predicated on transferability of information from one site to another. Analogues are used in all geologic repository programs, regardless of the geology. Considerable qualitative support for permanent isolation in salt derives from pertinent analogues. For example, the unique sealing capability of salt has been dramatically demonstrated by containment of nuclear detonations in salt horizons, one at the Gnome Site near WIPP and two at the Salmon Site at Tatum Dome in Mississippi (Rempe. 1998).

In addition to anthropogenic evidence from mining experience and nuclear detonations, nature itself showcases the encapsulating ability of salt formations penetrated by high-temperature magmatic dikes. Salt formations in New Mexico and Germany have been intersected by magmatic dikes. Despite the severe nature of such magmatic intrusions, there are only very thin alteration zones at the contact between the high-temperature igneous intrusion and the salt. No evidence of significant fluid (inclusion) migration toward the heat source has been reported from field observations. Analogues over a wide range of conditions provide qualitative evidence that salt formations have the capacity to permanently contain a wide variety of severe conditions. This type of analogue information is commonly used in repository sciences and transferability of such observations is a fundamental tenet of the safety case.

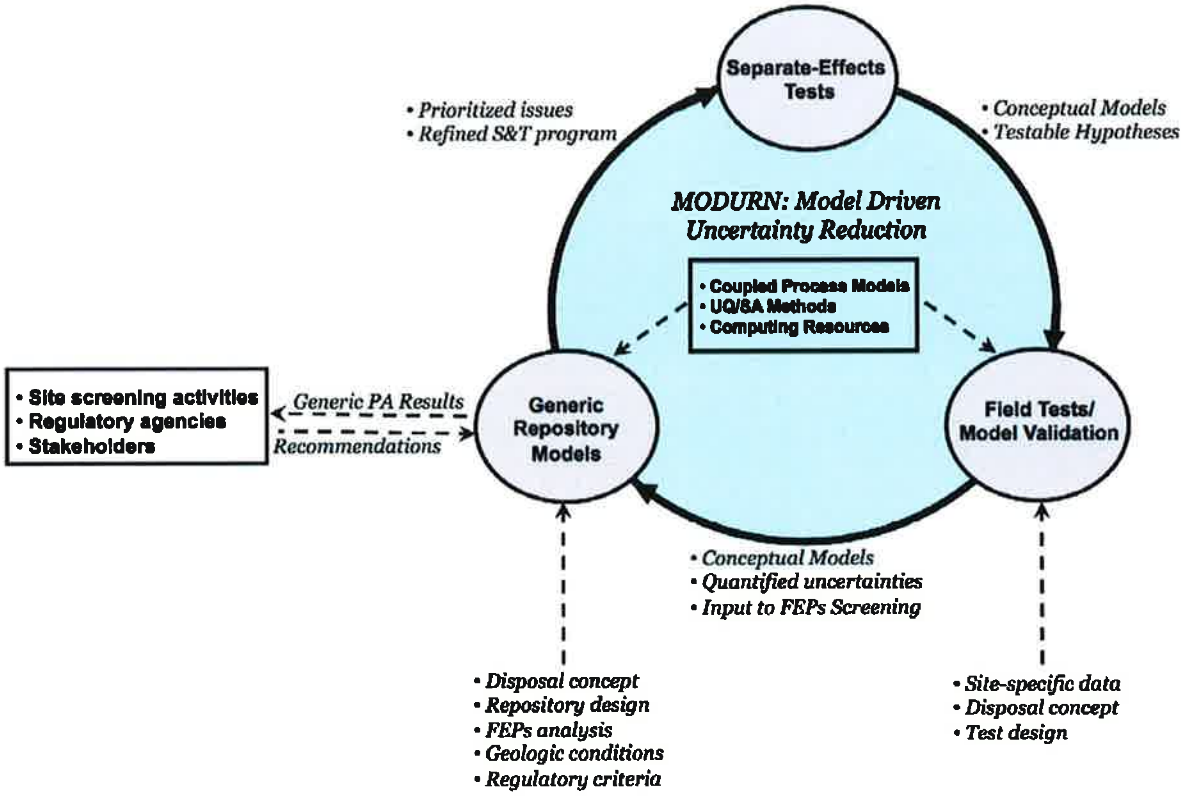
It is for these reasons that SDI investigations, as defined in this management proposal, will further add to the scientific basis for disposal in salt and that these proposed studies at WIPP are applicable to other salt sites.

**Relationship of this Work to Broader Repository Science Efforts**

After the Presidential decision to eliminate Yucca Mountain from consideration as the host site for a U.S. High-Level waste and spent nuclear fuel repository, the U.S. needs to rethink its approach to the disposition of defense high-level waste and civilian used nuclear fuel. The Presidentially appointed Blue Ribbon Commission for America's Nuclear future is chartered to "*conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities.*" (DOE, 2010). The likely outcome of such an evaluation is a set of recommendations regarding potential technological and policy alternatives that would provide direction for the U.S. in its efforts to deal with legacy nuclear waste, hopefully putting the U.S. on a path that enables cleanup of legacy waste sites and the sustainable utilization of nuclear energy to meet our growing need for low-carbon energy sources. Thus, there is a need to develop a logical set of research and development activities, informed by knowledge of the current national need, which would help the nation to craft a robust repository program. To that end, a set of scientific investigations that will provide clarity regarding the strengths and limitations of the use of salt as a host medium for the deep geologic disposal of high-level and other classes of radioactive waste is identified herein. In reaching this conclusion, no attempt to perform a comprehensive trade study is made, and it is probable that there are other technically viable choices for permanent geologic disposal available to the nation. Nonetheless, it is believed that the research program advocated herein, which proposes to address gaps in the knowledge of the behavior of salt as a disposal medium for thermally hot waste, represents one promising direction with both near term and long term benefits.

To understand our long-term perspective, consider Figure 1-5, which illustrates the role of field tests for model validation in the context of a broader set of investigations required to build a science-based safety case for disposal. The schematic is generic: it is not specific to any disposal concept or host medium, nor does it presuppose that a site has been selected for suitability investigations. The core concept is the systematic reduction of uncertainty in models through the iterative process of model development, experimental studies, and repository modeling to assess geologic disposal viability. Separate-effects tests, which typically study one or a few processes in great detail under controlled conditions, are re-examined in an integrated fashion in an underground research laboratory (URL), and models of the field test are developed. No matter how faithful an in situ test is to an actual disposal concept, it is still only a test of limited duration and spatial extent, rather than an actual repository. Therefore, residual uncertainties propagated through a generic model of a repository must be quantified, bringing in other relevant considerations and processes (e.g. scenario development, regulatory criteria, subsystem models) in order to fully define a Performance Assessment analysis. These results, vetted at regular intervals with stakeholders, are used to inform modification of the science program as new knowledge is incorporated and critical uncertainties are identified. Models are central to this vision, and are used to drive a process of systematic learning, adaptation, and communication that is the recommended path to ultimate success of a repository program (e.g. NAS, 2003). This figure depicts the process at the relatively early stage of development that the U.S. program currently finds itself, in advance of site selection. As the process evolves, site screening would be replaced by site-specific investigations, including field tests at a proposed repository site, PA analyses would no longer be generic, and interactions with stakeholders and regulators would become more regular and formal.

**Figure 1-5: Conceptual Schematic of Model-Driven Process for Repository Investigations**




***Note: Figure Acronyms: FEPs – Features, Events, and Processes; PA – Performance Assessment; S&T – Science and Technology; SA – Sensitivity Analysis; UQ – Uncertainty Quantification.***

Successful implementation of this process requires a suite of modeling capabilities, from coupled thermal/mechanical/hydrologic/chemical process models to higher-level systems models of repository performance. The current U.S. program, through the Used Fuel Disposition campaign, has efforts underway to develop repository performance assessment modeling systems, and general-purpose subsurface modeling and simulation capabilities that will significantly enhance our capabilities in the future. Meanwhile, a combination of existing codes and incremental model development will enable us to implement this process.

The understanding of different geologic media and disposal concepts is at different levels of maturity. In the U.S., salt is one of the most mature, with the iterative loop of Figure 1-5 having been traversed in the past through the combination of laboratory scale experiments (called "separate-effects tests" in the figure), field investigations under ambient conditions, PA modeling of the WIPP repository, and field-scale heater tests. As opposed to other media and disposal concepts, the current needs and requirements of a research program for salt are well known and quite specific, and can be satisfied through an integrated program of laboratory experiments, model development, and a validation field test to fill gaps in knowledge for assessing for the disposal concept presented herein. Separate-effects tests include thermal/mechanical studies on crushed and intact salt to extend the range of temperatures for which phenomena are known to approximately 300°C, and brine migration, mineral dehydration, and phase transformation reaction studies to investigate the potential fate of water. Additional laboratory investigations relevant to repository modeling (i.e. inputs to the "Generic Repository Models" portion of Figure 1-5) include studies of interactions of fluids with typical engineered materials at repository temperatures, solubility, speciation, and redox states of key radionuclides in high-ionic strength solutions at elevated temperatures. In other words, a field-validated thermal model of salt behavior relies on thermal/mechanical/hydrologic lab studies, whereas the generic repository modeling performed to put the field results into context for the purpose of building a repository safety case requires additional data inputs related to radionuclide and engineered materials behavior in the repository environment.

Armed with this additional suite of separate-effects tests, a thermal test conducted in the field (represented by the "Field Tests/Model Validation" portion of the figure) is required to complete another iterative loop of the R&D cycle to reduce uncertainties associated with the disposal of HLW in salt. To better understand the rationale for this statement, consider that the behavior at the repository scale is governed by a complex set of interrelated processes at multiple scales. For example, water movement is tightly coupled to the mechanical behavior of the rock as well as the thermal evolution of the decay heat in the waste form, crushed salt backfill, and surrounding salt, both damaged and intact. On the one hand, there is an impressive set of scientific studies which will be used (and additional laboratory studies are proposed) to understand the processes that might control the behavior of salt as a disposal medium for thermally hot waste. However, in the case of repository modeling, different small-scale effects (each of which are relatively well understood) interact with and influence one another, and their impacts on large-scale observables wax and wane over time as the system evolves. Fundamentally, in a complex system, emergent behavior is likely to arise when individual processes interact in this way. The reductionist approach of studying individual processes or characteristics of a salt specimen at the laboratory scale is insufficient to allow, for example, the prediction of the thermal-mechanical evolution of the rock mass and the fate of liberated water. Only through integrated tests are the operative controlling mechanisms able to be fully assessed; large scale, in situ measurements in a repository disposal setting are required to build confidence in a disposal concept, repository design, and safety case.

While the relative merit of conducting this work versus performing R&D in other media is beyond the scope of this management proposal, these proposed activities fit nicely within the broader goal of reconsidering multiple options for permanent geologic disposal. The fact that the logical next step involves field testing is a consequence of the large investments made by the U.S. to study salt for TRU waste disposal, and previously when salt was considered as a host medium for HLW before Yucca Mountain was chosen for intensive investigation. Taking an international perspective to the nuclear waste disposal issue, granite and clay disposal concepts are at a similar stage of development to salt, in that field investigations are being conducted and generic and site-specific activities are being pursued, in many cases in advance of site selection. If the U.S. program follows suit by initiating its own field investigations in salt, and aggressively pursues international collaborations in salt and other media, ongoing repository science activities around the world will be maximally exploited the for the purpose of defining future options for disposal of U.S. wastes. Furthermore, establishing a U.S.-based URL for repository science in salt will help facilitate international collaborative R&D, and will maintain and enhance a critical capability to perform large-scale, subsurface R&D or repository science that was established in the Yucca Mountain and WIPP projects.

# 2. PROJECT MANAGEMENT, QUALITY ASSURANCE, AND SAFETY

## 2.1. TEST MANAGEMENT STRUCTURE

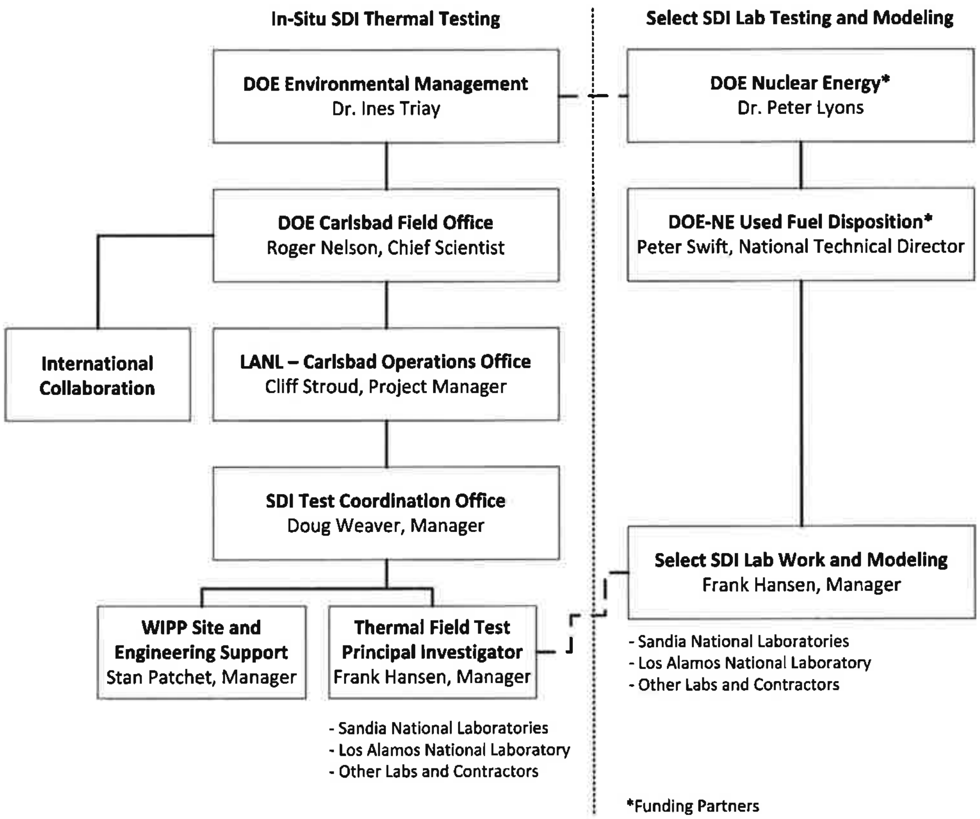
The overall management of the work proposed within this SDI project will be through the CBFO. The CBFO defines quality requirements through a QAPD similar to that used for the WIPP program. The SDI QAPD describes an NQA-1-2008 compliant QA program for the science-based studies concentrating on high thermal loading effects in bedded salt. DOE-NE will manage work packages designated in fiscal year 2012 for select laboratory testing and modeling efforts (see reference 22). DOE-EM is funding efforts largely related to the planning, design, and initial construction of the in situ thermal test at WIPP (see Table 4-2 for specific budget breakdown).

LANL-CO will function as the project management organization, responsible for day-to-day test management and coordination, similar to a successful model used at the Nevada Test Site and the Yucca Mountain Project, ensuring that all test-related information and data activities are consistent and focused. In its management capacity, LANL-CO will report to the CBFO Project Manager. SNL, LANL, and potentially other scientific entities, will provide Principal Investigators to inform and advise test management to ensure the testing program is as productive, integrated, and efficient as can be achieved. Those portions of the SDI investigations funded by Used Fuel Disposition Campaign (UFDC) of the DOE-NE will be managed according to the judgment of the UFDC management team.

WTS, the WIPP Management and Operating Contractor, will provide engineering, construction, and test support labor to provide for the test bed (e.g., drift mining, borehole coring, electrical, and ventilation) and aid in test installation.

Participants in this research will include personnel from LANL, SNL, and WTS. Personnel at these organizations bring many years of direct salt repository experience and have conducted decades of salt research and thermal testing, both in the laboratory and the field. Experience directly relative to the types of field and laboratory activities described in this management proposal include field work at the Nevada Test Site, large in situ thermal tests at Yucca Mountain Nevada, and experimentation at WIPP. Additionally, the primary collaborators bring the experience of many years of public interactions, which sharpen an appreciation for public understanding. Public outreach will be integrated with our international collaborators and build upon elements of their success as well. Appendix C provides a list of key contributors to this management proposal and a summary of related experience. Figure 2-1 illustrates the organizational structure of this testing program with the funding partnership between DOE-EM and DOE-NE.

**Figure 2-1: SDI Organizational Structure with Funding Partnership**




## 2.2. QUALITY ASSURANCE AND SAFETY

CBFO, in support of this project, developed an SDI QAPD modeled after the highly effective and time-proven CBFO QAPD. The SDI QAPD describes an NQA-1-2008 compliant Quality Assurance Program for the science-based studies concentrating on high thermal loading effects in bedded salt. Existing WIPP procedures are adapted as appropriate to accommodate the SDI program, thereby taking advantage of the existing mature and audit-tested programmatic and technical processes established for the repository program.

Each program participant assigned responsibility for performing the SDI work described in this proposal (primarily LANL, SNL, and WTS) is currently working under and maintaining compliance with the CBFO QAPD for WIPP activities. The CBFO, for current WIPP work, is responsible for defining quality requirements and applicability, developing appropriate plans and procedures to attain quality, and supporting project participants in pursuit of quality. Where applicable, project participants are responsible for developing and following plans and procedures that effectively implement the requirements described in the CBFO QAPD. Project participants are also responsible for compliance with requirements contained in other relevant CBFO planning documents. Those elements of the SDI funded by DOE-NE will be performed consistent with requirements of the Fuel Cycle Technology QAPD, which governs Quality Assurance for research under DOE-NE.

The combined experience and track record of the national laboratories, WTS, and CBFO in successful implementation of rigorous QA programs in a regulatory environment are exceptional. The primary national laboratories expected to participate in this work (LANL and SNL) have extensive NQA-1 experience in repository sciences associated with WIPP. Each has participated in the successful compliance certification (and two 5-year recertifications) of WIPP with the U.S. Environmental Protection Agency (EPA) as a regulator and the Resource Conservation and Recovery Act (RCRA) permit issuance and recent 10-year renewal by the New Mexico Environment Department (NMED).

Additionally, as with quality assurance, each proposal participant has extensive experience and an exemplary record of safety related to field and laboratory work activities, including a culture and value structure that promotes safety in the workplace. Each listed participant will conduct work safely and responsibly; ensure a safe and healthful working environment for workers, contractors, visitors, and other on-site personnel; and protect the health, safety, and welfare of the general public. This is done through institutional frameworks and processes that align with the principles and functions of Integrated Safety Management.

## 2.3. WIPP REGULATORY COMPLIANCE CONSIDERATIONS

The WIPP may only dispose of the nation's defense-related transuranic radioactive waste, however, there are processes to evaluate the use of WIPP for underground experiments. The use of the WIPP underground for the field test portion of SDI is based on saving costs by avoiding the development and installation of mining infrastructure at some other existing salt or potash mine of similar depth. There will be some costs to perform the tests in WIPP. However, the area to the north of the access shafts (and far north of waste disposal operations) is already configured with electrical power and fiber optic cable to service basic science experiments. An existing trained workforce, mining infrastructure, nuclear safety bases, and an NQA-1 quality assurance program already in place will make the field test part of SDI cost less than bringing these essential elements of a field test to another commercial mine.

The cost effective and efficient use of WIPP for the field tests is offset by the need to gain regulatory approval to conduct the tests there. WIPP's compliance envelope is complex, with multiple state and federal agencies involved. The two most important regulators that are involved in WIPP operations are the NMED and the EPA. In addition, DOE itself must ensure that any tests performed at WIPP are in compliance with the National Environmental Protection Act (NEPA).

In response to multiple basic science inquiries made by researchers across the country after WIPP opened, DOE conducted an Environmental Assessment (EA) under NEPA guidelines in 2001. That EA analyzed impacts from a variety of possible experiments that might be performed using the unique underground setting at WIPP. One of the bounding experiments was a test very similar to the scope of the proposed SDI. That potential experiment involved using electrical heaters in specially mined alcoves to measure the response of the salt medium to the effects of heat-generating materials emplaced for disposal in salt. A Finding of No Significant Impact (FONSI) was reached as a result of the EA, and this management proposal assumes that no additional analyses are necessary under NEPA to allow the SDI field tests to be performed in WIPP (Marcinowski to Triay. 2003).

The NMED regulates the disposal of hazardous waste at WIPP under the provisions of the RCRA. Much of the transuranic waste destined for disposal in WIPP also contains hazardous components regulated under RCRA. However, none of the specific actions proposed in the SDI field test will involve hazardous materials. Therefore, no modification of the permit issued to WIPP by NMED should be necessary. However, since the SDI tests will use the common infrastructure that is regulated under the permit for waste disposal, DOE will inform and consult with NMED as the tests are designed and conducted.

WIPP's primary purpose is the permanent isolation of transuranic waste resulting from defense activities. EPA's regulations promulgated under 40 Code of Federal Regulations (CFR) Parts 191 and 194 require that DOE ensure isolation and compliance with the standards for a 10,000-year period. The conduct of SDI field test is unrelated to waste emplacement operations (other than the use of common infrastructure) and will not change the characteristics of the overall disposal system within the land withdrawal area for WIPP. DOE will prepare analyses that demonstrate the effects of the additional mining and heating of the test area footprint (well north of the waste disposal operations) will not compromise long-term repository performance. These analyses will be submitted to EPA under a Planned Change Notice for their review and concurrence, similar to the process both agencies have successfully used for other basic science experiments that have been, and continue to be, conducted in the north part of the WIPP underground. This review and approval process has typically required about 3-6 months to complete and will be initiated in mid FY 2011 to support the start of mining.

## 2.4. INTERNATIONAL COLLABORATION

CBFO will establish a program that will re-engage research and operating entities in Germany and other European Union (EU) member nations. This proactive re-engagement with primarily European counterparts will enhance the DOE's scientific program and protect against loss of knowledge and personnel from salt repository enterprises. Elements of the international outreach will provide consistent support for workshops devoted to repository research topics, which will provide a forum for documenting technical advances that accompany an expanded publication effort.

Salt disposal remains a leading permanent disposal option and it is well established internationally. (Sandia National Laboratories. 2010. US/German Workshop on Salt Repository Research, Design, and Operation, May 25–27, 2010. <http://www.sandia.gov/SALT/SALT_Home.html>). As one of the most advanced repository options in the world, the science community has a definitive grasp of what has been done and what still needs to be done. Much of the experience gained from United States repository development, such as seal system design, coupled process simulation, and application of performance assessment methodology, helps define a clear strategy for a heat-generating nuclear waste repository in salt. The authors worked closely with German salt repository scientists and engineers to identify the research challenges ahead of us.

The recent summary of the US/Germany workshop proceedings issued by Forschungszentrum Karlsruhe GmBH (KIT. 2010) acknowledges that implementation of a repository for heat-generating waste in rock salt is feasible. This German agency supports research and development in rock salt that parallels the work identified in this proposal. Full-scale field studies in the United States include Project Salt Vault at Lyons, Kansas; the Avery Island, Louisiana, heater tests; and WIPP thermal structural investigations. Salt repository programs in Germany include a proposed HLW site at Gorleben, the research facility at the Asse Mine, the nuclear waste storage facility at Morsleben, and a bedded salt storage facility for chemotoxic wastes at Herfe-Nerode. In today's environment, large-scale salt studies have been pursued by EU members. Collaboration with EU countries (with Germany, in particular) would avail technical staff of the latest international developments in salt repository sciences. Possible goals for international collaboration include:

- Create collaboration and technical alliances between CBFO and international partners (first Germany, then other EU member nations).
- Preserve and advance technical applications of salt sciences, specifically focusing on international interests that compliment U.S. interests.
- Perform fundamental research into areas where understanding deformational behavior of salt is incomplete.
- Partner with EU countries (Germany and Poland as a start), through the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, to support a working group on "Safe Disposal of Long-Lived Radioactive Waste in Rock Salt as Repository Host Rock Formation" (Salt Club).
- Develop position papers on vital salt repository issues, such as brine and vapor transport.
- Utilize technology and instrumentation developed and demonstrated in salt applications in Europe.
- Provide an educational basis for and knowledge transfer to next-generation researchers.
- Transfer methods and tools for salt storage facilities and mining operations to ensure safe, secure, long-term functionality of the underground structures.
- Expand existing international collaboration with Karlsruhe/INE on actinide speciation in brine.
- Make technology available to support the nation's future energy supply and infrastructure needs.
- Afford technical experts access to the latest international developments in salt mechanics sciences.
- Develop a central library of acquired salt data and other information, with broad access provided via the Internet.

# 3. PROPOSED RESEARCH PROGRAM

The proposed research program describes areas that would substantially enhance our knowledge of the behavior of thermally and radioactively hot nuclear waste in salt and would provide fundamental data for the evaluation of concepts for disposal in salt. The program has been divided into the following major elements:

1. Functional and Operating Requirements and Test Planning (including Project Management, QA, Safety and Regulatory Compliance activities as described in section 2.0)
2. Laboratory Thermal and Mechanical Studies to Support the Field Test
3. Laboratory Hydrologic, Chemical, and Material Studies
4. Coupled Process Modeling
5. Field Test Installation and Operation
6. International Collaboration (described in section 2.4)

The first task establishes the functional and operational requirements for the field test. The experimental investigations are divided into laboratory testing, modeling, and in situ testing. Laboratory research in support of the field test includes thermomechanical and hydrologic testing of intact and crushed salt and chemical and physical properties of the brine as a function of temperature. Chemical and material studies consistent with salt repository performance will also be pursued in the laboratory. Some of these areas received a considerable amount of attention in the 1960s to 1990s; however, the upper temperature limit for the thermomechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests were predominantly conducted at room temperature. The laboratory studies will build upon previous work and enhance these efforts by reinvigorating international collaborative research. Furthermore, the proactive reengagement with primarily European counterparts will enhance our scientific program and protect against loss of knowledge and personnel from salt repository enterprises. A carefully designed field test in bedded salt will serve as a proving ground for concepts of disposal in salt and provide data for modeling validation and refinement that is needed for a repository design or performance assessment model. The in situ heater test in out years will provide a full-scale mock-up of a generic salt repository design concept and will provide data (temperature, deformation, and environment) for thermomechanical calculation confirmation, backfill consolidation, moisture movement, and waste form/brine chemical interactions. Forensic analyses of the re-mined material after the in situ heater test will provide performance validation and confirmation in years beyond the current proposal. All of this information will be used to support an integrated modeling and simulation effort for the evaluation of concepts for disposal in salt.

Elements of this management proposal are technically integrated and build a solid science basis for disposal options. The proposed testing and modeling will be conducted under a QA program. The QA obligation includes development of test plans, calibrations, and record capture and storage.

## 3.1. FUNCTIONAL AND OPERATIONAL REQUIREMENTS AND TEST PLANNING

This task will be determining F&OR for a field test. CBFO will collaborate with the technical team in the development of the F&OR, as well as assuring the appropriate breadth of scientific studies is included. The F&OR document will be a deliverable to CBFO in late FY 2011 and will be used to provide the basis for the test bed location, layout, and operational requirements such as specifics related to providing proper ventilation, power, and access. Test-specific requirements such as instrumentation characteristics, precise borehole placement, instrumentation calibration requirements, data quality objectives, and other detailed test information will be provided in a field test plan to be developed, reviewed, and delivered in FY 2012. Laboratory testing and modeling activities will have specific test plans scaled to the level of activity complexity, in accordance with the applicable QAPD. As part of these detailed test plans, existing and available information from past thermal experiments in salt will be comprehensively evaluated.

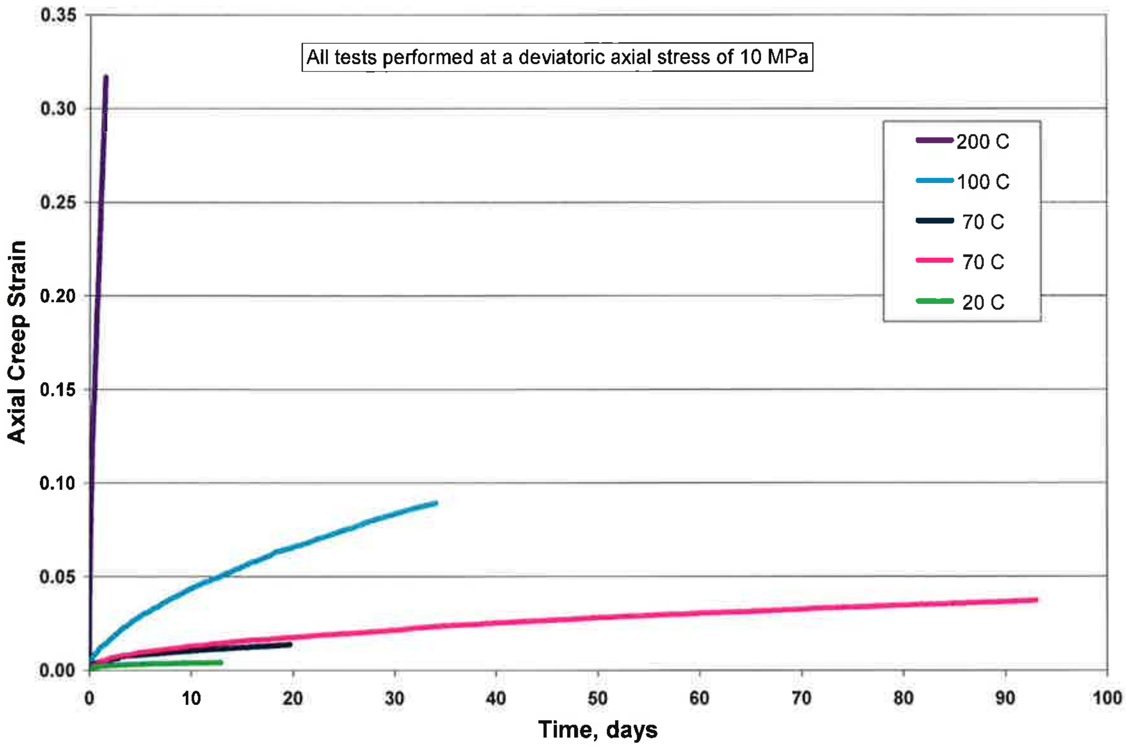
## 3.2. LABORATORY THERMAL AND MECHANICAL STUDIES

Laboratory studies of salt are proposed and described in the following sections. The laboratory studies are intimately related to the needs of the modeling program. Experiments to evaluate consolidation of hot, dry, run-of-mine salt, will yield a stress/temperature/porosity function needed for modeling the disposal proof of principle. In addition, an assessment of thermal conductivity as a function of porosity is needed to properly account for the transient evolution of the disposal area. Deformational phenomenology of exceptionally hot intact salt tested uniaxially is fundamentally important before the final design parameters are assigned for the disposal concept field test. These thermomechanical (TM) laboratory results are essential for modeling and therefore need to be conducted as early in the program as possible. These TM inputs are used directly for modeling the proof-of-principle disposal concept, which includes liberation of accessible brine.

Laboratory studies on WIPP salt are designed to provide a phenomenological examination of intact salt at high temperatures and stress states that the near-field salt is expected to experience. Consolidation of hot, dry crushed salt will provide important data for performance and detailed modeling of the disposal concept. Salt immediately surrounding a simulated waste package (heater) will consist of run-of-the-mine salt (backfill) used to bury the heater. Both laboratory experimental programs involve mechanical compression at temperatures as high as 200°C to 300°C to observe the change in deformational behavior as the temperature increases. Earlier Office of Nuclear Waste Isolation (ONWI) and WIPP experience and knowledge of salt's thermomechanical response provide an initial basis for this applied rock mechanics work. The personnel performing these studies will share information with international collaborators.

For purposes of the field test, it is anticipated that the underground salt environment will be heated to temperatures well above those for which current salt experimental data exist. In a general sense, the thermally driven response of salt is the controlling element of the concept of disposal in salt. Elevated salt temperatures will cause accelerated salt-creep deformation, which leads to a more rapid encapsulation of the waste. Therefore, these laboratory-based intact-salt studies will provide key field-test information for evaluating the disposal concept and testing the hypothesis that the thermal pulse imparted by the waste leads to this rapid encapsulation.

**Figure 3-1: Strong Influence of Temperature on Creep of Natural Rock Salt**




Salt deformation is dominated by plastic behavior at elevated temperatures. Figure 3-1 illustrates strain-versus-time curves for creep tests on rock salt performed at the same stress condition but at different temperatures. Temperature has a dramatic influence on the creep rate of intact salt specimens owing to thermally activated deformation mechanisms. Relatively little elevated temperature mechanical testing has been conducted for crushed salt consolidation, an important element of the concept of disposal in salt. Crushed salt testing has two parts. First consolidation testing will derive a relationship between temperature, stress states and porosity. The second test series will determine thermal conductivity as a function of porosity and temperature.

### 3.2.1. Intact Salt Studies

All testing will be performed under an approved test plan developed in accordance with appropriate QA requirements discussed earlier in this management proposal. A preliminary test matrix is identified here for schedule and cost estimates. Test conditions described push the threshold of laboratory experience on natural salt. The Principal Investigator will reserve flexibility in the test plan to change the preliminary test conditions if results warrant it. The intact salt will be tested in an unconfined condition at a constant axial strain rate using solid cylinders. Uniaxial stress loading will continue until the specimen exhibits either failure or extreme deformation (~20% strain). It is well known that salt deformation, even at room temperature, is dominated by plastic deformation mechanisms. Crystal plasticity will be greatly enhanced as temperature increases, such that extensive plastic deformation will accompany fracture formation. As a preliminary basis of estimate, a total of nine tests (Table 3-1) will be conducted comprising a triplet of tests at each of three temperatures: 200°C, 250°C, and 300°C.

Inelastic creep processes will dominate the deformation of the specimens even in a quasi-static load application, with the creep response being ever more pronounced as the temperature increases. Rather than specimen failure, extreme deformation is expected to cause the tests to be stopped.

**Table 3-1: Uniaxial Compression Test Matrix**

| Test Number | Salt Type | Test Type | Temperature | Loading Condition |
|---|---|---|---|---|
| 9,10,11 | Intact | Uniaxial stress | 200°C | Constant Strain Rate |
| 12,13,14 | Intact | Uniaxial stress | 250°C | Constant Strain Rate |
| 15,16,17 | Intact | Uniaxial stress | 300°C | Constant Strain Rate |

The tests at 200°C will overlap with historical databases and provide a point where predictive models based on those databases can be checked for the current work. The tests at temperatures above 200°C will provide new data so that extrapolation outside the actual test database will not be necessary. The field test (and actual alcove disposal) is expected to involve temperatures much greater than 200°C (at the heaters), thus this high-temperature research is needed for the design and evaluation of the in situ experiment. An assessment of the need to run triaxial experiments at these temperatures will be made based on the results of these uniaxial tests. The schedule and budget do not include triaxial testing.

### 3.2.2. Crushed Salt Studies

The laboratory tests on crushed salt include consolidation as a function of stress and temperature and thermal conductivity as a function of bulk density and temperature. Here "crushed" salt means run-of-mine salt that is sieved to separate out large aggregate. Consolidation of the sieved run-of-min salt can be performed in two ways: either using an oedometer arrangement or an isostatic pressure vessel. Thermal conductivity of the backfill salt will be measured on reconsolidated salt specimens produced during the consolidation studies. The thermal properties will be measured over a temperature range from the mine temperature to 300°C and at a variety of porosities.

Because of greater opportunity for experimental control, most consolidation research will be done using an oedometer. Oedometer consolidation involves uniaxial compression of circumferentially constrained granular salt within a hollow steel shell. The large scale apparatus for consolidation under heat and load will have to be fabricated. Consolidation is measured using axial displacement measurements, and the measured change in volume represents the reduction of pore space in the run-of-mine salt and an accompanying increase in bulk or fractional density. A total of eight individual tests (as listed in Table 3-2) are proposed. Two replicates will be performed at each of four temperatures: 100°C, 150°C, 200°C, and 250°C. The stress application and deformation of these tests is expected to be short term; however, the pre-test heating and the post-test observational work (petrographic analyses) will require additional time.

**Table 3-2: Oedometer Consolidation Test Matrix**

| Test Number | Salt Type | Test Type | Temperature | Loading Condition |
|---|---|---|---|---|
| 1,2 | Backfill | Uniaxial compaction | 100°C | Biaxial Stress |
| 3,4 | Backfill | Uniaxial compaction | 150°C | Biaxial Stress |
| 5,6 | Backfill | Uniaxial compaction | 200°C | Biaxial Stress |
| 7,8 | Backfill | Uniaxial compaction | 250°C | Biaxial Stress |

The consolidation of granular salt will also be examined using hydrostatic (uniform triaxial) compression. In this style of testing, stress control is provided by two independent systems: an axial loading ram and fluid pressure applied radially to the specimen. The loading ram is a standard hydraulic actuator driven by a servo valve, and either the ram position or the load on the ram can be used as the feedback control variable. Fluid pressure in the vessel is controlled by a constant-pressure intensifier, which also functions as a dilatometer, making it possible to measure volume changes of samples.

The isostatic compression method can be modified to produce deviatoric compression where the axial and confining pressures are not equal. This test condition is a more realistic representation of the consolidation expected in alcove disposal, where the roof-to-floor closure is expected to be faster than the rib-to-rib closure. A series of deviatoric consolidation tests will be performed to compare to the isostatic and oedometer consolidation results.

Thermal conductivity tests will be performed over a temperature range from room temperature to 300°C at known values of fractional density (porosity). The specimens for the thermal conductivity tests will be created in a manner similar to the way uniaxial consolidation tests are conducted. The major difference in the thermal conductivity specimen creation test will be that the test will be terminated at specific targeted values of fractional density. Additionally, the specimens might have to be sized differently than the mechanical test specimens for thermal conductivity test purposes.

The thermal conductivity test method will most likely be the comparative cut-bar method (ASTM E1225, Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique) to measure axial thermal conductivity. In this test, the crushed salt specimen is placed between two sections of a material with known thermal properties, and then a heat flux is passed through the assembly. Comparison of the temperature gradients is then used to determine the thermal conductivity of the test specimen. Depending on specimen size requirements for run-of-the-mine crushed salt and the anticipated relatively low values of thermal conductivity compared to the value for intact salt, the guarded hot plate method (ASTM C177, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus) may be used for some crushed salt thermal conductivity measurements. This method is more commonly used for materials requiring large specimen sizes with low thermal conductivity values.

The individual thermal conductivity tests to be performed in this initial laboratory effort are outlined in Table 3-3. The tests will be conducted on a range of porosity values from 35% (estimated mine-run value) to porosities approaching those of intact salt. The thermal conductivities will be determined at average specimen temperatures of mine temperature, and at 50°C degree increments from 100 to 300°C — shown as 25°C–300°C in Table 3-3.

**Table 3-3: Thermal Conductivity Test Matrix**

| Test Number | Salt Type | Test Type | Porosity (%) | Six Temperatures |
|---|---|---|---|---|
| 1–6 | Backfill | Steady-Flow Conductivity | 35 | 25°C–300°C |
| 7–12 | Backfill | Steady-Flow Conductivity | 30 | 25°C–300°C |
| 13–18 | Backfill | Steady-Flow Conductivity | 25 | 25°C–300°C |
| 19–24 | Backfill | Steady-Flow Conductivity | 20 | 25°C–300°C |
| 25–30 | Backfill | Steady-Flow Conductivity | 15 | 25°C–300°C |
| 31–36 | Backfill | Steady-Flow Conductivity | 10 | 25°C–300°C |
| 37–42 | Backfill | Steady-Flow Conductivity | 5 | 25°C–300°C |
| 43–48 | Backfill | Steady-Flow Conductivity | ~1 | 25°C–300°C |

Design, development, fabrication, and qualification of test equipment and techniques are included in the estimates found in Table 4-1. Each testing program would be conducted under a reviewed and approved test plan. Test conditions may be changed by the Principal Investigator as research progresses; however, the test matrix provided sufficiently defines the research effort for proposal purposes.

## 3.3. LABORATORY HYDROLOGIC, CHEMICAL, AND MATERIAL STUDIES

During the field test, it is anticipated that the underground salt environment will be heated to temperatures for which current experimental data do not exist. Two interrelated components of the system involve the nature and fate of brine as well as the geochemical interactions of the salt/brine/engineered materials/radioactive waste.

Understanding the mobilization of native brine is essential to establish the evolution of the underground setting of the disposal concept. Migration of small amounts of water present in fluid inclusions within the intact salt, as well as the potential liberation and transport of brine derived from dehydration of hydrous minerals within the interbeds of a halite deposit, must be characterized in order to assess such parameters as the basic amount of brine available to the system and its ability to influence deformational processes such as fracture healing and granular salt consolidation. In addition, as the potential carrier of radionuclides, the brine source and transport represent essential components of the repository source term for scenarios in which brine-waste interactions are evaluated.

Closely related to the source and transport of brine is the chemical and material behavior of the brine/salt/engineered materials/waste form system. Laboratory studies on salt and brine will build upon the scientific basis developed for WIPP, and bounding brine and salt formulations will establish the key factors that control radionuclide solubility and mobility at elevated temperatures (as discussed in the chemistry sections of this proposal). The data obtained will be used to fill knowledge gaps in models for radionuclide release for the range of hypothesized intrusion conditions that could be encountered in the disposal of thermally hot waste (such as EM defense HLW) in a salt repository. In addition, material interaction data from both the laboratory studies and the field test site will be analyzed, providing data that could be used to assess the compatibility of various waste forms, if warranted.

The next two subsections present the laboratory brine liberation/migration tests and chemical/material studies proposed to fill gaps in data needed to support the field test and model development. In each area, a detailed test plan will be written, reviewed, and approved prior to initiating the laboratory experiments. Thus the concepts put forward below are consistent with the science basis for disposal in salt and will be rigorously reviewed in the process of implementation.

### 3.3.1. Hydrologic Studies

The foundational data needed to assess the sources, rates, and migration mechanisms for brine fall into two categories: brine migration in intact (or dilated) salt, and water liberation from accessible brine, such as hydrous minerals or grain boundary brine. These two experimental investigations are detailed below.

**Brine Migration**

The fate of water trapped as inclusions within salt crystals and in hydrous minerals present along with the halite is important to understand when assessing performance of a salt repository. Typical quantities of water present in salt fluid inclusions is on the order of 0.1 to 1% in bedded salt (e.g. Permian salt from the WIPP site ranged from <0.1% and 1.7% and is highly spatially variable – Roedder and Belkin, 1979a), and much lower in domal salts (e.g. on the order of 0.003% in several Louisiana salt domes – Knauth and Kumar, 1981; Knauth et al., 1980). Historically, fluid inclusions in salt have been used forensically to study the paleoenvironments relevant to the location of petroleum reservoirs. Pursuit of the concept of using salt for nuclear waste disposal led to a series of investigations employing fluid inclusions in geologic studies to shed light on the environment and subsequent evolution of the salt deposit, as well as to consider the possibility that this water might negatively impact repository performance (Roedder, 1984). A recognized and well-studied mechanism by which salt can potentially migrate up a temperature gradient toward the nuclear waste canister is the process of dissolution of salt on the high-temperature side of the inclusion, solute diffusion within the fluid to the low-temperature side, where deposition occurs from the supersaturated solution. The net effect of this process is migration of the inclusion from lower to higher temperatures. If significant water contacts the waste canisters, corrosion could occur, including the possibility of exposing the waste to direct contact by water should a portion of the repository later become inundated due to natural processes, failure of repository seals, or an inadvertent human intrusion episode. Beyond these potential failure mechanisms, the role of water in facilitating fracture healing must be understood in order to predict the evolution of permeability and rock deformation properties in the DRZ. Relatively steep gradients of the order of 2°C/cm or higher are required to mobilize fluid inclusions in salt.

U.S. Geological Survey (USGS) experiments (Roedder and Belkin, 1979; 1980) indicate that an increase in ambient temperature and/or gradient increased the inclusion mobilization rate, in approximately direct proportion. The migration rates for inclusions in different parts of a given sample, however, were found to vary by a factor of three, for as yet unknown reasons. The three major controlling variables seem to be inclusion size, ambient temperature, and temperature gradient. Theoretical considerations and some experimental studies suggest that the migration rate may also be related to the fluid composition, the presence (and volume) of a gas bubble, the gas pressure in such a bubble, mechanical strain in the host salt, dislocation abundance and nature, and crystallographic direction.

While numerous laboratory studies have been performed to investigate the mechanisms by which fluid might mobilize and contact waste canisters, significant uncertainties remain. The details of movement of fluid inclusions even within a single salt crystal are very complex, depending on temperature gradient, inclusion size and shape, the presence or absence of a gas bubble, stress, and surface tension effects within the inclusion (see Carter and Hansen, 1980 for a summary discussion). Furthermore, the fate of brine at grain boundaries is also complex and variable: in many cases, migration of inclusions is observed to cease at grain boundaries, with the fluid spreading into microcracks at the boundary. However, in some instances, the inclusion is observed to traverse the grain boundary (Jenks and Claiborne, 1980) and continue to migrate within the adjacent grain. Decrepitation has also been observed to liberate relatively large quantities of water from inclusions (Roedder and Belkin, 1979a). As temperature rises, water from either inclusions or mineral dehydration reactions that is present in microcracks and other discontinuities in the rock mass will tend to be mobilized through vapor transport, at rates that are proportional to the permeability of the fractured salt medium. This permeability will, for some period of time, be orders of magnitude higher than that of intact salt; it will exhibit directional dependence (e.g. Beauheim and Roberts, 2002); it will depend on distance from the mined opening (Hansen and Leigh, 2011); and it will vary in time as fractures undergo stress-induced healing (Pfeifle and Hurtato, 1998). The nature of this interplay of various processes is currently unknown and requires further study, starting with laboratory tests and progressing to examination of the integrated effects in the field.

To perform these essential experiments, these rather extreme conditions shall be examined in the laboratory by way of some innovative tests on both natural intact and disturbed salt. Laboratory thermal gradient testing could address the possibility for brine migration with the following approach: 1) impose a thermal gradient on natural salt cores (both intact cores and with a mechanically stressed zone within the core) 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 both weight loss and fluid capture, while the phenomenology of brine inclusion migration will be documented using microscopy techniques. The fundamentals of brine migration and vapor transport, especially at the intact/disturbed rock zone interface, are identified as central to building the case for disposal in salt. Brine migration studies will be reinitiated in the laboratory for a specific range of conditions diverse set of conditions (temperatures, gradients, and levels of damage, which will be measured as volumetric strain) in order to further develop the conceptual model for brine migration behavior.

**Clay Dehydration and Phase Transformation Studies**

Hydrous minerals, in particular clay, produce the most brine at WIPP. Clay interbeds in the Salado Formation (repository layered salt horizon at WIPP) can attain a thickness of up to one meter. Therefore, in the process of the thermal gradient testing described above, the weight loss of the clays will be examined specifically. Clays (smectite/illite layered phyllosilicates) are important in a repository environment as their volumes, water contents and stability can be affected by even small variations in temperature and partial water pressure, thereby resulting in changes in water amount in the environment and potentially in the host rock strength, porosity and permeability. In a repository, emplacement of waste will increase temperature and thus will change the water vapor pressure. In such a geological system, the partial water pressure is typically lower than the total pressure and dehydration of clays might occur below the boiling point of water (Koster van Groos and Guggenheim. 1986). Different behaviors are expected depending on whether the rocks are unsaturated (disturbed salt) or saturated (intact salt).

The thermal behavior of clays may involve several phenomena: 1) reversible collapse/expansion of the smectite layers due to loss/gain of interlayer water at water vapor pressures < 1 atm (Wu, et al. 1997); 2) irreversible collapse of the smectite layers due to loss of interlayer water and migration of interlayer cations into the layers (Meunier, et al. 1998); 3) irreversible reduction of the osmotic swelling capacity of smectites in a steam atmosphere (Koster van Groos and Guggenheim. 1986); and 4) inhomogeneous transformation of smectites into interstratified illites/smectites at temperatures > 300 °C (Mosser-Ruck et al. 2010). Of these four types of thermal reactions, reversible collapse and collapse in a steam environment probably play more important roles in a repository environment. Such dehydrations may create transport pathways as those volume contractions are accommodated under in situ conditions.

For clay dehydration, because there are gaps and discrepancies in experimental data, the partial dehydration of clays over the relevant temperature and partial water pressure range will be quantified, clay phases analyzed and characterized, and the potential impact on the water source term and stability of the altered minerals assessed. Along with geochemical modeling and thermodynamic constraints (Vidal and Dubacq. 2009), the phase transition from smectite to illite will be mapped out in repository P, T space. Because data will be provided from basic measurements and to close gaps in knowledge, the data would then be incorporated in coupled THMC models to properly account for the impact of these mineral reactions on water liberation and migration. The high pressure experimental lab at LANL (presently performing research on geothermal tracers, carbon sequestration, and natural analogue nuclear waste forms) is well suited to perform such experiments in Dickenson autoclaves and cold seal assemblies at potential repository maximum temperatures (350°C) and lithostatic pressures (600 bar). Furthermore, the LANL experimental lab is now certified to the new DOE pressure standards.

### 3.3.2. Chemical and Material Studies

This overall approach encompasses experiments and fundamental research that identify and analyze the components and characteristics of the waste that could impact repository performance. The work will be divided into five tasks:

1. ***Measure the thermodynamic properties of brines and minerals at elevated temperatures.*** Precise measurements of the pressure, volume, and temperature (PVT) properties of brines are required for hydrologic and chemical benchmark modeling and future development of performance assessment models.

2. ***Study repository interactions with waste container and constituent materials.*** Evaluation of the chemical interactions of a broad range of materials and waste forms with a salt-based repository will provide a scientific basis to evaluate waste form strategies and engineer waste forms and packages.

3. ***Measure the effect of elevated temperature and ionizing radiation on brine chemistry.*** The results of these experiments will bracket the potential changes in brine chemistry due to temperature and radiolysis, as well as provide a measure of the extent that these changes are controlled by waste package constituents.

4. ***Measure the effect of temperature on radionuclide solubility in brine.*** Radionuclide solubility will determine the source term of any thermally hot waste repository for scenarios in which brine contacts the waste. These studies will quantify the magnitude of the temperature effect on radionuclide solubility in brine and both guide and focus future performance assessment work.

5. ***Measure radionuclide oxidation distribution and redox control at elevated temperatures.*** The lower oxidation states of key radionuclides (U(IV) and Tc(IV)) will be less soluble, and it is important to establish the effects of elevated temperature and ionizing radiation on the processes that generally lead to the creation of a reducing environment in a salt repository.

The motivation for these tasks is discussed in more detail below. Details regarding the laboratory apparatus, experimental techniques, and ES&H requirements will be described fully in detailed test plans written upon commencement of the laboratory testing program.

### 3.3.3. Measure the Thermodynamic Properties of the Brines and Minerals at Elevated Temperatures

PVT properties of brines are required for both radionuclide source term model and benchmark model development. Precise, specific heat capacities of brines from the site are required to predict the thermal history of brines according to different thermal loading scenarios. These properties for complex brines are not available in the literature. To determine the range of conditions under which thermodynamic properties are required, both undisturbed conditions in which the intact salt is under lithostatic load will be considered, and disturbed conditions in which the presence of the mined opening or, for example, a borehole being inadvertently drilled through the repository, will be considered. Under the undisturbed scenario, the lithostatic pressure (brine pore pressure) for a salt repository at a depth of 650 meters is about 15 megapascals (MPa). In such a case, the pressures for the brines at elevated temperatures will be dominated by the brine pore pressures. Under the disturbed scenarios, the pressures for the brines at elevated temperatures will be the saturated vapor pressures, which are a function of both temperature and brine composition.

For purposes of this management proposal, the host rock is the Salado Formation. The following tests will be performed on samples from the Salado Formation:

1. ***Determine the saturated vapor pressure of brine in equilibrium with halite–polyhalite–anhydrite at temperatures up to 300°C.*** Saturated vapor pressures of complex brines at elevated temperatures are not known. This property is important for calculating the pressure dependence of chemical equilibrium.

2. ***Determine the PVT properties of brines up to 300°C at constant pressures (1 to 20 MPa) and saturated vapor pressures.*** The ultimate goal of this subtask is to produce adequate experimental data to develop equations of state for brines.

3. ***Determine viscosity and thermal conductivity of brines up to 300°C.*** These fluid properties will affect the heat and mass transport processes affecting brine movement at the pore scale, and therefore must be known under a wide range of conditions.

### 3.3.4. Study Interactions with Waste Container and Constituent Materials at Elevated Temperatures

Laboratory tests specifically targeting the disposal field test proposed (see section 3.5) are shown in Table 3-4 and will provide laboratory data under controlled conditions that will be used to interpret the results obtained on coupons placed in the in situ heater tests. The test matrix is focused on a broad range of materials and waste forms that might be considered for a salt-based repository disposing thermally hot waste and will provide a scientific basis to evaluate waste form strategies and material selection in waste package design. The key test parameters are:

- Temperatures from 25°C to 300°C
- Humidity, low brine-inundated conditions
- Presence and absence of air/oxygen
- Brine composition
- Pressure, ambient to 20 MPa
- Ionizing radiation

Table 3-4: Test Matrix for Alcove-Specific and Bounding Material Interaction Tests

| Material | Environmental Conditions | | | |
|---|---|---|---|---|
| | Temperature | Humidity | Atmosphere | Ionizing Radiation (γ) |
| Actual In Situ Heater Test Container Materials | 25°C - 300°C | Low, moderate, and high humidity | Air and Inert at 1 and 20 MPa | 0 - 10,000 rad/h |
| Salt and Interbed Material from the Site | 25°C - 300°C | Low, moderate, and high humidity | Air and Inert at 1 and 20 MPa | 0 - 10,000 rad/h |
| Possible Repository Metals | 25°C - 300°C | Dry, low, moderate, high humidity; brine inundation | Air and Inert at 1 and 20 MPa | 0 - 10,000 rad/h |

These tests will build on past studies in salt (German HLW canister underground tests, U.S. ONWI program, and WIPP) to provide a more robust understanding of material performance in salt for the range of environmental conditions possible in a repository where thermally hot waste is disposed.

The expectation in salt is that it is not necessary to design a container or waste form as a barrier against radionuclide transport so it is not the intent in this proposal to give the impression that these materials are required or that additional containment is necessary. There are advantages to using certain materials, such as iron or stainless steel, for maintaining a reducing environment which can provide defense in depth against transport. The use of steam reforming, vitrification, or encapsulation in glass can reduce solubility of the waste matrix but it is the contention, when burying in salt, that none of these are required. The plan is testing the materials that make up defense HLW.

A wide range of analytical techniques are available to establish the reaction products and overall reactivity. G-values (i.e., the number of molecules produced per 100 eV of ionizing radiation absorbed) for gas generation in the salt irradiations will be established by measuring gas composition and pressure as a function of time. Water content will be determined as a function of the experimental conditions for materials that initially contain water (e.g., salt, some waste forms). For the inundated tests, changes to the brine chemistry will be determined to establish the appropriate range of brine chemistry for the radionuclide source term studies.

The temperature range up to 300°C was chosen as a bounding value for the temperature in the bulk salt formation. This temperature is used for the brine studies and the material interaction studies. Temperatures near the canister heater could exceed this value and the lab test may be modified through the test plan to reflect the higher temperature. Local temperatures near the canister would be expected to gradually decline by the time significant quantities of water could possibly contact the canister and the waste.

### 3.3.5. Measure the Effect of Elevated Temperature and Ionizing Radiation on Brine Chemistry

High temperatures and levels of ionizing radiation present in thermally hot waste will affect brine chemistry. Increased temperature will lead to changes in the solubility of the major cations and anions present in brine, causing compositional changes in the brines at the point of saturation, as well as shifts in the system redox potential (Eh) and acidity-alkalinity (pH). These compositional changes could impact radionuclide solubility. Radiolysis could lead to the buildup of oxidizing and/or reducing species that would change the redox potential of the brine system. Gamma irradiation using self-contained Cs source cells will be used in the laboratory to establish general radiolytic trends that tie into the existing literature of established redox trends. The most important potential impact of these radiolytic effects is on the redox distribution of radionuclides. The proposed experiments to study and understand these effects are outlined in Table 3-5.

**Table 3-5: Test Matrix for the Effects of Temperature and Radiation on Brine Chemistry**

| Brine | Environmental Conditions | | | |
|---|---|---|---|---|
| | Temperature | Ionic Strength | Atmosphere | Ionizing Radiation |
| NaCl | 25°C -150°C | 0.1 M - 5 M | anoxic | 0-10,000 rad/h (γ) Variable isotope (α) |
| $MgCl_2$ | 25°C -150°C | 0.1 M - 5 M | anoxic | 0-10,000 rad/h (γ) Variable isotope (α) |
| Simulated* Brine A | 25°C -150°C | Alone, Excess Salt, Waste Package Materials | anoxic | 0-10,000 rad/h (γ) Variable isotope (α) |
| Simulated* Brine B | 25°C -150°C | Alone, Excess Salt, Waste Package Materials | anoxic | 0-10,000 rad/h (γ) Variable isotope (α) |
| Simulated* Brine C | 25°C -150°C | Alone, Excess Salt, Waste Package Materials | anoxic | 0-10,000 rad/h (γ) Variable isotope (α) |

*Brines A and C are "bracketing" simulated brine formulations that cover the range of expected brine compositions; Brine B is an intermediate formulation brine. Final detailed compositions will be provided in the test plan for the laboratory work.

For all experiments proposed, changes in the brine chemistry (cation/anion composition, Eh, pH) will be monitored as a function of temperature and irradiation condition. The results of these experiments will bracket the potential changes in brine chemistry due to temperature and radiolysis, as well as a measure of the extent that these changes are overwhelmed by waste package constituents. Recovered precipitates will be analyzed to establish their elemental and phase composition.

The thermal model performed for the generic salt repository (Carter et al. 2011) produced peak bulk salt temperatures of approximately 150°C. This is the value that formed the basis for the temperature selection for the chemical studies since the higher temperatures are localized near the canister.

### 3.3.6. Measure the Effect of Temperature on Radionuclide Solubility

The oxidation-specific solubility of key radionuclides will be established as a function of temperature, using oxidation state-invariant analogs. This overall approach has been used successfully in room temperature studies at WIPP and avoids the experimental complexity of uncontrolled changes in oxidation state during the experiments. The overall goal of this study is to establish the magnitude of the temperature effect on radionuclide solubility to guide future performance assessment models. These data would become important in any repository scenario in which water contacts the waste and mobilizes radionuclides. It is likely that in any future repository program, these scenarios will need to be investigated regardless of how robust the scientific evidence is for encapsulation of the waste by the deforming salt medium.

The test matrix for the radionuclide solubility experiments is given in Table 3-6. Waste package materials will be included in some experiments to account for sorption effects and solid/liquid interface interactions.

**Table 3-6: Test Matrix for the Effect of Temperature on Radionuclide Solubility in Brine**

| Radionuclide | Environmental Conditions | | | |
|---|---|---|---|---|
| | Temperature | Brine | Atmosphere | Waste Package Materials |
| U(VI) | 25°C - 150°C | Brine A, B, C | anoxic | Fe, Glass, TBD |
| Th(IV) | 25°C - 150°C | Brine A, B, C | anoxic | Fe, Glass, TBD |
| Tc (IV) | 25°C - 150°C | Brine A, B, C | anoxic | Fe, Glass, TBD |
| Cs | 25°C - 150°C | Brine A, B, C | anoxic | Fe, Glass, TBD |

### 3.3.7. Measure Radionuclide Oxidation Distribution and Redox Control at Elevated Temperatures

Radionuclide speciation under the conditions possible in a high thermal load, salt-based repository has not been studied extensively, and further research is needed. There is currently very little empirical data on the speciation of many radionuclides for the range of pH conditions likely to occur in these subsurface brines. For a salt-based repository that will experience elevated temperatures, it is especially important to obtain data on the effects of temperature on redox distribution and radionuclide speciation.

Some key actinides (uranium (U), neptunium (Np) and plutonium (Pu)) and fission products (technetium (Tc)) can have multiple oxidation states in brine depending on the redox potential of the brine system. The lower oxidation states of these key radionuclides (U(IV), Np(IV), Pu(III/IV) and Tc(IV)) should be less soluble. It is important to measure the effects of elevated temperature on the processes that generally lead to the creation of a reducing environment in an anoxic salt repository, which keeps these radionuclides in lower oxidation states.

The central objective of this subtask is to measure and quantify the effect of elevated temperature on processes known to establish reducing conditions at room temperature. The most important of these processes are pH/Eh variations, bioreduction, and reaction with reduced metals (e.g., iron, manganese, others). The overall experimental approach is to prepare the radionuclides in their higher-valent oxidation state, establish anoxic conditions in a range of brine systems, and evaluate the effectiveness of reduction as a function of temperature and self-irradiation effects (auto-radiolysis). The test matrix for these experiments is given in Table 3-7.

**Table 3-7: Test Matrix to Establish the Key Factors that Control Radionuclide Oxidation State**

| Process | Environmental Conditions | | | |
|---|---|---|---|---|
| | **Temperature** | **Brine** | **Atmosphere** | **Components** |
| Varying pH | 25°C - 150°C | Brine A, B, C | anoxic | U and Tc will be evaluated |
| Fe reduction | 25°C - 150°C | Brine A, B, C | anoxic | U and Tc will be evaluated |

## 3.4. COUPLED PROCESS MODELING

Prediction of the thermomechanical and hydrologic response of the in situ experiment will initially be made by benchmarking calculations using the best-available codes and models. It is anticipated that at least the two major national laboratories will participate in the benchmark calculations, and the international collaborators will be invited to model the benchmark as well. Benchmarking computational capability is common practice in repository programs, and was done on the WIPP program many years ago, on an international parallel calculations exercise, and more recently by the European Commission for calculations on the BAMBUS II experiment. The benchmark parameters will be established by a technical team. The benchmark modeling cases will assume that the initial modeling structure and the parameter values are understood and certain. However, it is known that there are differences in the constitutive models adapted for the state-of-the-art codes. The performance will be assessed in the benchmark exercise. The benchmark model will be used to inform the field test personnel with regard to placement of instrumentation and sample coupons, as well as establish the data quality objectives for the main test parameters.

The benchmark models will be refined (validated/calibrated) using field test data to match and predict the behavior of the actual system at the alcove scale. This work proposes to benchmark and then refine calculational capability for design and analysis of a salt repository. Because there is no current unified predictive model for thermomechanical, hydrologic, and chemical behavior in bedded salt, the modeling will be performed in two separate tasks, defined in the subsections below.

### 3.4.1. Thermomechanical Benchmark Modeling

The overall objective of this modeling effort is to inform the field test design and to assess the current capabilities of the thermomechanical computational codes available to solve several complex initial/boundary value problems, which represent heaters, excavations, and back-filled crushed salt of the in situ experiment.

This benchmark exercise will use codes that are appropriate for application to salt repository calculations. Hopefully, several of the most developed constitutive models for thermomechanical behavior of salt can be brought to the benchmark studies through our proposed international collaborations. The advanced salt mechanics codes used by research centers in Germany that are being considered for these analyses are summarized in the *Final Individual Report Joint Project: Comparison of Current Constitutive Laws and Procedures Using 3-D Model Calculations for the Mechanical Long-Term Behavior of Real Underground Rock Salt Mines* (FZK 02C1587, 2010).

The calculations will be explicitly defined, such as a benchmark analyses of the Room H test conducted at the WIPP horizon. Code-specific details (such as mesh refinement, error bounds on iterative processes, and time step sizes) will be left to the modeler's judgment. The type of output requested would include temperature distribution, deformation at certain locations, and stress states. With the addition of the crushed salt constitutive model and porosity-specific thermal conductivity relationship, these models will be applied to specific numerical aspects of the field test.

Fully coupled thermomechanical modeling will provide information on temperature distribution and room and drift closure. These calculations require constitutive laws for deformation of intact salt, reconsolidation of granular, mine run salt, and thermal conductivity of granular salt as a function of porosity. The state of the art to perform these calculations will be assessed. Constitutive models will be enhanced by the thermomechanical testing previously described. This management proposal acknowledges that an essential part of the field test is to determine, at full scale, the liberation processes and fate of the native brine. Therefore, a module for these processes will be added to the coupled thermomechanical code. Considerations include evolution and devolution of the disturbed rock zone, temperatures experienced in the disturbed zone, permeability creation and healing, reduction in permeability of crushed salt as density increases, and temperature distribution at a large enough scale to ascertain if a condensation zone is possible. The fate of accessible brine is fundamental to chemical considerations.

A preliminary assessment of the disposal concept has already been completed by Sandia SIERRA Mechanics (Stone et al., 2010). These example calculations used the SIERRA Mechanics code suite that is comprised of application codes that address specific physics regimes. The two SIERRA Mechanics codes which are used in thermal-mechanical coupling are Aria and Adagio (Stone et al., 2010). The suite of physics currently supported by Aria includes the incompressible Navier-Stokes equations, energy transport equation, species transport equations, as well as generalized scalar, vector and tensor transport equations. A multiphase porous flow capability is a recent addition to Aria. Aria also has some basic geochemistry functionality available through embedded chemistry packages. The solid mechanics portion of the thermomechanical coupling is handled by Adagio which solves for the quasistatic, large deformation, large strain behavior of nonlinear solids in three-dimensions. Adagio has some discriminating technology that has been developed at Sandia involving the use of matrix-free iterative solution algorithms that allow extremely large and highly nonlinear problems to be solved efficiently. This technology also lends itself to effective and scalable implementation on massively parallel computers. The actual thermal-mechanical coupling is done through a flexible solution controller within SIERRA Mechanics called Arpeggio. Additional features that need to be added include the temperature, stress, reconsolidation model for the hot run-of-mine salt and a relationship between thermal conductivity and porosity, both of which are elements of this proposal described earlier.

Fully coupled thermomechanical models involve three-dimensional details that will allow prediction of the expected field test results. As improved modules for reconsolidation and thermal conductivity are developed in the early stages of this proposed research, very informative calculations can be executed. As noted in this management proposal, the state-of-the-art codes and models, including SIERRA Mechanics, will be evaluated for their ability to simulate the concept of disposal that will be demonstrated in the field test. Preliminary examples of output are shown in the following Figures 3-2 and 3-3, which are very similar to the results discussed by Stone et al. (2010). These preliminary calculations show temperature distribution and run-of-mine salt consolidation that simulates the alcove disposal configuration (thermally activated creep deformation enhanced by an 8.4 kW canister). These calculations were run with a second canister of hulls and hardware (approximately 10 meters from the back of the alcove) in addition to the high-level waste canister located at the back of the alcove. Because the canister of hulls and hardware produces no heat, it is not planned to be included in the SDI thermal test.

**Figure 3-2: Preliminary Temp Distribution for the Proof-of-Principle In Situ Field Test**

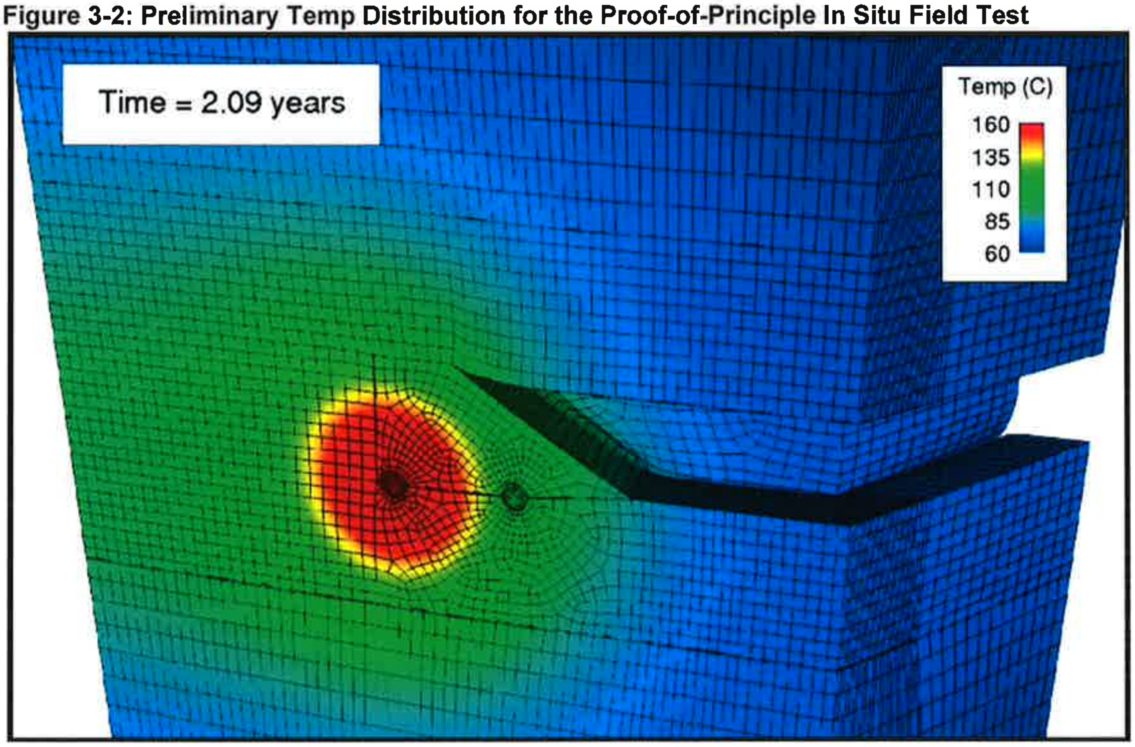
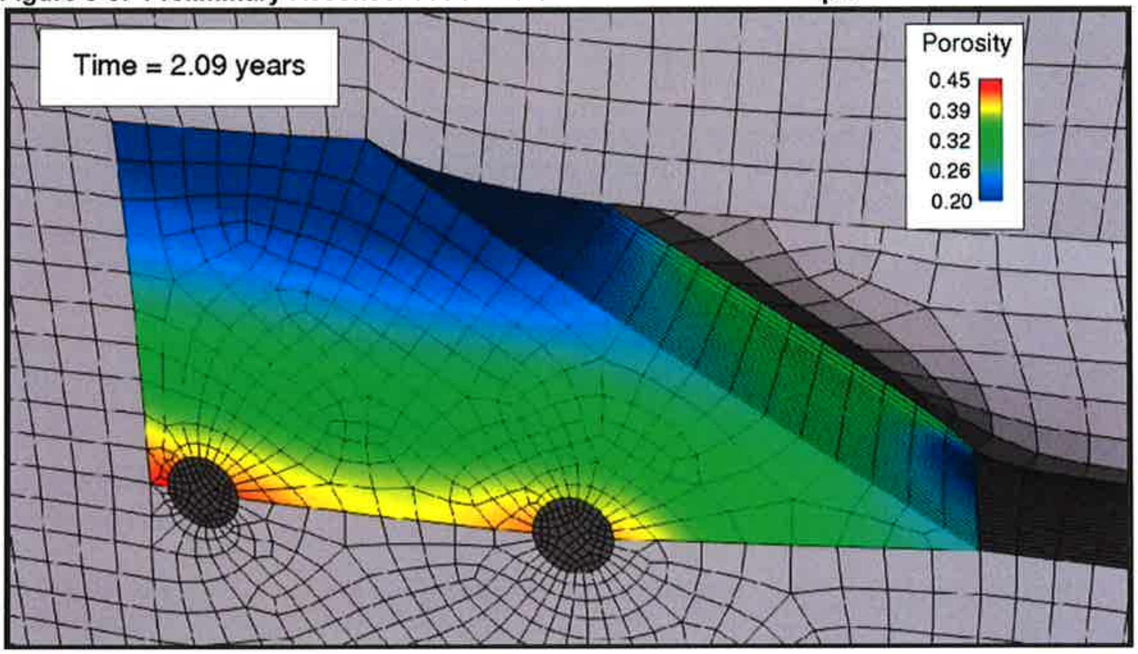


**Figure 3-3: Preliminary Reconsolidation Calc for the Proof-of-Principle In Situ Field Test**




As noted, the primary focus of the benchmark calculations is to inform the field test design personnel with regard to expected full-scale in situ results. This information will be useful for placement of gauges and density of coverage for certain measurements. The benchmark calculations simultaneously allow ongoing assessment of the state of the art for models and codes, while providing preliminary results that guide field testing. To model the proof-of-principle field test as accurately as possible, the initial testing of intact core at high temperature and the tests associated with reconsolidation need to be completed and evaluated. The modeling process will involve continued refinement as field and laboratory results are acquired, which will allow for improved modeling capability. These results will be periodically reported in technical publications as the project collects information. At the completion of the field test, a general model of the thermomechanical behavior of the field test will be calibrated and published.

### 3.4.2. Hydrologic and Chemical Benchmark Modeling

Prediction of the thermal, hydrologic, and chemical conditions of the in situ experiment will be made by benchmarking calculations using the best-available codes and models. The overall objective of such a study would be to assess the current capabilities of the thermal-hydrologic-chemical computational codes available to solve several complex initial/boundary value problems, which represent idealizations of real drifts/rooms and waste/backfill of the in situ experiment.

This benchmark exercise will use codes that have been developed for other thermal, hydrologic, and chemical applications and apply them to salt repository calculations. The calculations will be explicitly defined. Code-specific details (such as mesh refinement, error bounds on iterative processes, and time step sizes) will be left to the modeler's judgment. The type of output requested might also be much different from that typically requested for drift design calculations and, in fact, the output data requested will include specific numerical aspects of the field test application.

This task will also seek to refine a modeling capability to predict the brine chemistry and associated radionuclide solubility/concentration in high ionic strength brine systems at the elevated temperatures expected in a high thermal load salt repository. The overall modeling approach will extend the approach used at WIPP and will rely heavily on the extensive experience gained from the WIPP and Yucca Mountain projects. The empirical nature of this modeling approach makes it challenging to accurately predict the effects of temperature without the availability of experimental results over the temperature range of interest (25°C -150°C). Initially, simulation of the behavior of high ionic strength solutions will be conducted using the best available databases and information. An assessment will be made to determine if there are significant gaps in the available data, and if so, the uncertainties will be parameterized and considered in the subsequent modeling exercises. Then, as the project progresses, the prediction of radionuclide solubility/concentration will rely heavily on the data collected in the laboratory studies and temperature data from the in situ test. As a result of these efforts, a modeling approach that accounts for higher temperature and a wide range of brine composition will be configured. This model will provide needed concentration data to define the radionuclide source term in subsequent transport and release calculations, which may be required for future performance assessment calculations.

As noted, the primary focus of the benchmark calculations is to inform the field test design personnel with regard to expected full-scale in situ results. The hydrochemical calculation might be useful for placement of gauges and density of coverage for certain hydrologic and chemical measurements. The benchmark calculations are exercises that simultaneously allow ongoing assessment of the state of the art for models and codes, while providing preliminary results that guide field testing. Also as noted, the modeling process will involve continued refinement as field and laboratory results are acquired, which will allow for improved modeling capability. These results will be reported in technical publications as the project collects more and more information. At the completion of the field test, a general model of the thermal, hydrologic, and chemical conditions of the field test will be calibrated and published. Assuming that a fully coupled THMC modeling capability is available during the project, this code would also be employed for this purpose.

## 3.5. FIELD TEST PROOF OF PRINCIPLE

This section describes a preliminary, high-level plan to conduct a field test in salt to evaluate its behavior under thermal loads representative of those that would be experienced if HLW were disposed in salt. To set the stage for this proposed field test program, first, the motivation and the basis for selecting the geometry and conditions of the test is described. One of the most important elements affecting the design of a HLW repository is heat management. A disposal safety case, properly conceived and elucidated, relies on well-understood processes attesting to the stability and durability of the geologic barriers to radionuclide migration over geologic time scales. Perturbations caused by the installation of a mined opening or the emplacement of waste must be carefully considered. As such, the decay heat from the waste places limits on the maximum possible areal density of waste, with a significant impact on utilization efficiency of the subsurface facility. Consequently, the management of waste before it is emplaced in the repository, and the configuration of waste packages underground, must be conducted such that critical thermal design criteria are met.

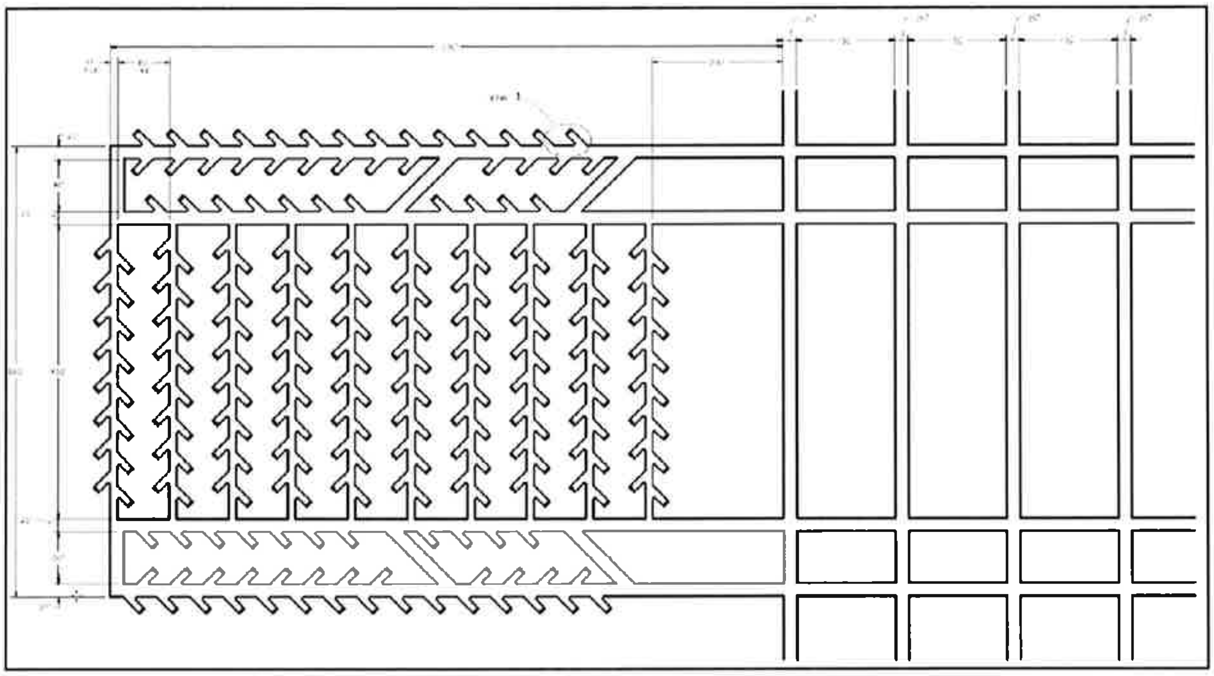
Another requirement affected by heat is that of predictability: models used for repository design and performance assessment calculations must be demonstrated to be valid for their intended purpose, to provide assurance that the repository will perform as expected during operations and in the post-closure period. During operation, the stability of the mined facility and the temperatures and radiation environments to which workers will be exposed must be well understood and operations conducted so as to minimize risk to workers and the public. During operations and after permanent closure, parameters such as the maximum allowable temperatures experienced by the waste form, engineered waste package, and the surrounding medium must be established to ensure that the isolation capability of the repository system is not degraded as a result of decay heat. Because heat is a disturbance from the natural state of the geologic medium, a comprehensive understanding of those changes must be demonstrated, and those changes reflected in validated models of the physical/chemical system, in order to support the safety case for geologic disposal. If it can be shown that salt behaves in a predictable way (as demonstrated by a validated numerical model) and that the waste isolation capability of the salt host medium is not degraded relative to isothermal disposal conditions, then important strides will have been made in expanding the safety case for salt to include disposal of thermally hot wastes.

### 3.5.1. Preliminary Work: Conceptual Disposal Concepts

To conduct meaningful, focused research in geologic disposal, an appropriate starting point is a disposal concept describing the physical configuration of wastes in the underground, and the operations that would be conducted to load the repository. For salt, the favored approach is to select a disposal concept that is reasonably bounding in terms of local and areal-average heat load, is feasible and efficient operationally, and is likely to result in a solid safety case provided that issues identified as uncertainties are addressed. A study of a generic salt repository for disposal of thermally hot HLW (Carter et al., 2011) documents the basis for the disposal concept adopted in the present study. That study, which proposed a conceptual design of a repository from a future closed fuel cycle producing large quantities of heat-generating borosilicate glass HLW, presented a subsurface and surface facility design and disposal strategy that, in principle, can be practically realized using proven mining operations. The study assumed that waste with significant radionuclide mass loadings, including Cs, Sr, and other heat-generating elements, would be buried with minimal decay storage, thereby providing an aggressive, bounding case with respect to the thermal load.

The design concept is based on a disposal strategy in which a series of repository panels, each of which is a subsurface cell consisting of individual rooms and a total of 236 alcoves, are constructed underground (see Figure 3-4 for the configuration of a single panel). The disposal operation, detailed in the insets in the figure, would consist of placement of one HLW canister at the end of each alcove. Mining operations would be performed on a "just-in-time" schedule such that the waste would be emplaced soon after the mining of a particular area is completed. Carter et al. (2011) determined that, for the assumed repository layout, operating conditions, and waste streams, that HLW from a facility reprocessing 83,000 Metric Tons Heavy Metal of UNF, operating for a period of 40 years, could be disposed of in a repository of 96 panels covering an area of 2.1 by 2.5 miles, or 3,350 acres. In addition, because the layout and linear distances of mined repository are controlled by the need to spread HLW out to distribute the heat load, ample space would also be available to co-dispose of other radioactive waste streams such as GTCC and LLW that would be generated in a reprocessing plant. The HLW package and potentially remote-handled (RH) waste being co-disposed in the same alcove would be covered by crushed salt backfill to provide radiation shielding for workers conducting operations in the vicinity. This strategy is intended to enable a simpler disposal operation than the emplacement methods into the intact salt than those in which boreholes are drilled into the intact salt, making it easier for the disposal operation to "stay ahead of" the heat from previously disposed waste.

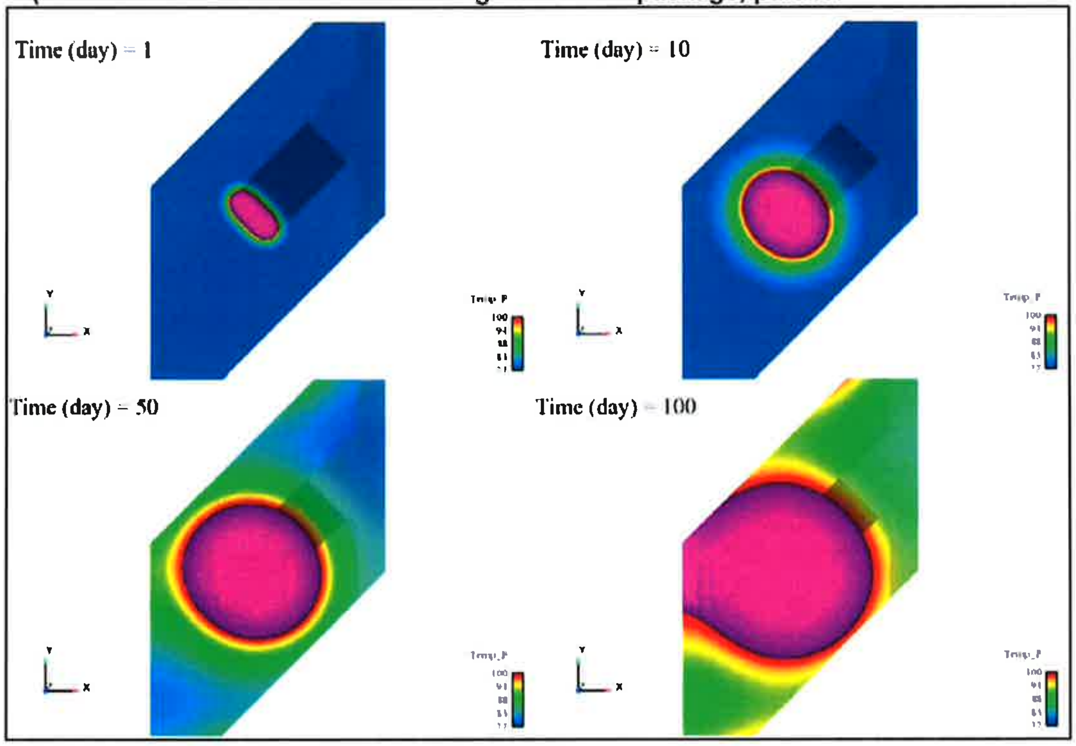
**Figure 3-4: Disposal Concept of Carter et al. (2011) Used as the Basis of the Proposed Field Testing Program**



***Note: Figure reproduced from Carter et al. (2011)***

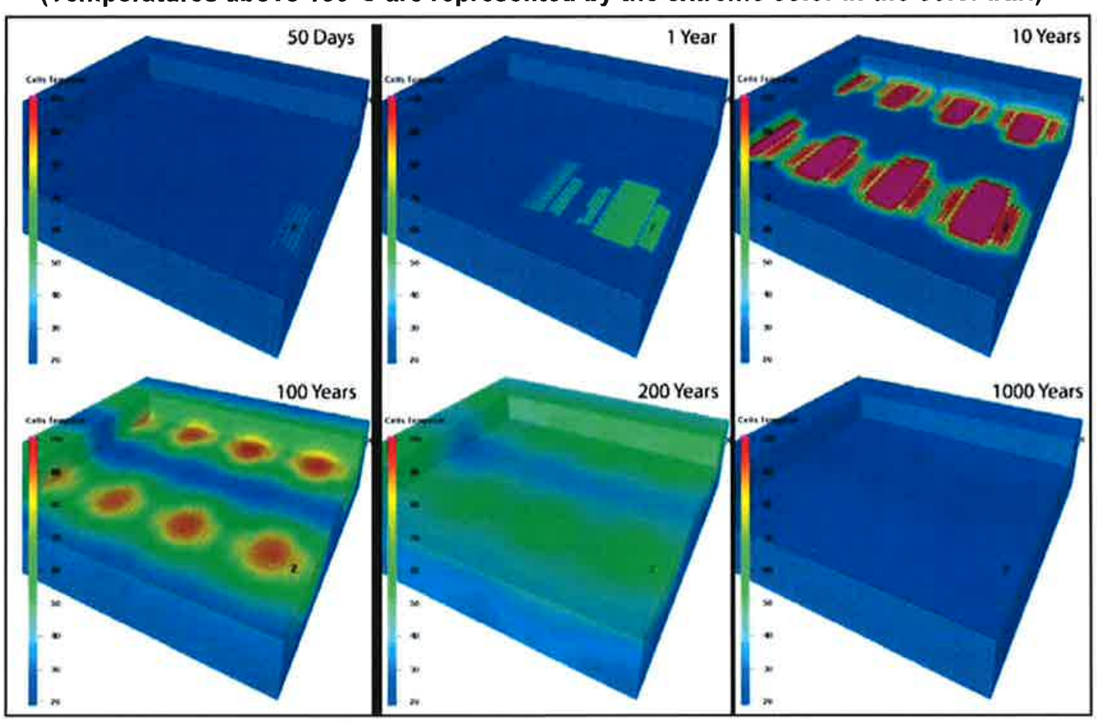
To provide a framework for understanding and addressing thermal issues, modeling studies were conducted (Clayton and Gable, 2009; Gable et al., 2009) to illustrate the likely thermal behavior of the system and to quantify the magnitude of uncertainties, including simulations assessing the level to which uncertainties can be reduced with a thermal field test. These studies reported heat transport modeling results at both the alcove and repository panel scales. The thermal calculations were performed in the absence of direct consideration of mechanical effects. Instead, the potential impact of these effects on temperatures within the waste form and the surrounding medium was assessed indirectly by varying thermal parameters in ranges that reflect the uncertainties brought on by unknown mechanical effects. Given that caveat, results from both the panel-scale (Figure 3-5) and alcove-scale results (Figure 3-6) confirmed that the base case disposal concept as outlined in Carter et al. (2011) is sound from the standpoint of avoiding operational difficulties accompanying the propagation of the thermal pulse to adjacent alcoves, which takes 75 to 150 days, or to adjacent panels, which takes 7 to 12 years. This conclusion is relatively insensitive to details of the thermal and mechanical processes occurring at the alcove scale.

**Figure 3-5: Alcove-Scale Thermal Simulation: 100°F Isotherm as a Function of Time. (Plots are for a horizontal slice through the waste package, parallel to the alcove floor.)**




*Note: figure reproduced from Clayton and Gable (2009)*

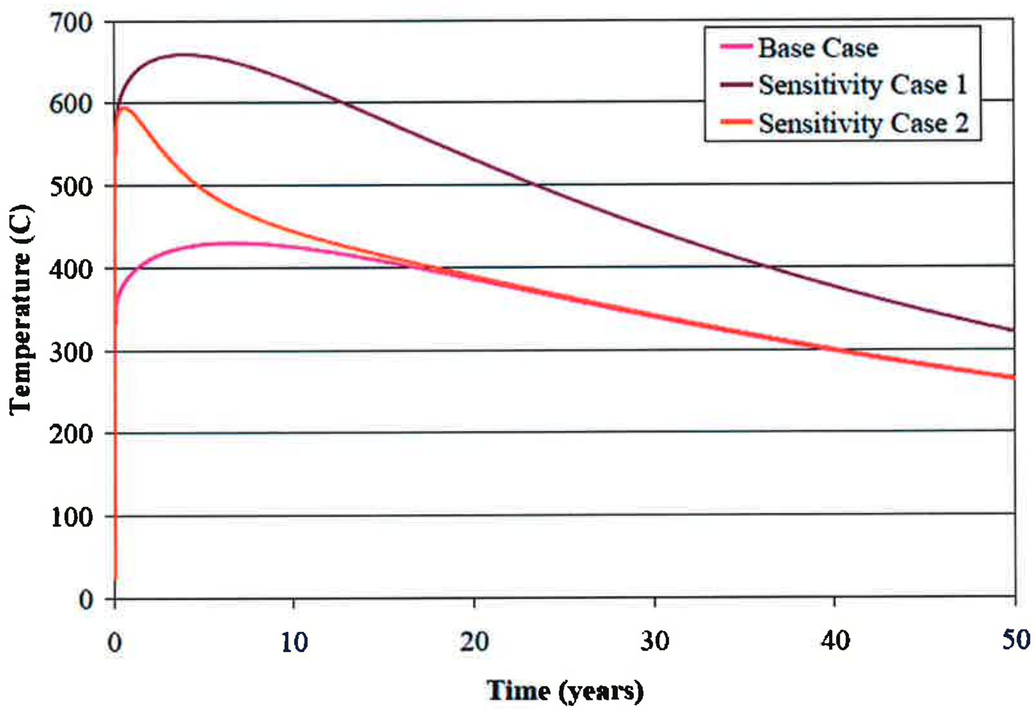
**Figure 3-6: Repository-Scale Thermal Simulation. (Temperatures above 100°C are represented by the extreme color in the color bar.)**




*Note: figure reproduced from Clayton and Gable (2009)*

However, details at the alcove scale, including processes for which there is insufficient knowledge, have a strong bearing on the local conditions experienced by the waste and surrounding salt. For example, one hypothesis pertinent to this disposal concept is that the crushed salt will rapidly reconsolidate when compressed due to alcove closure, and that this process will be accelerated due to heat, relative to room-temperature salt creep processes. However, Figure 3-7, reproduced from Clayton and Gable (2009), shows that if the crushed salt reconsolidates either gradually (Sensitivity Case 2) or not at all (Sensitivity Case 1) within the first 50 years after disposal, the average temperatures experienced by the waste would be much higher than if the crushed salt rapidly consolidates and attains the thermal properties of intact salt (the Base Case). Unconsolidated crushed salt has a very low thermal conductivity compared to intact salt, leading to an insulating effect on the waste package and contents until the crushed salt consolidates. Thus, the mechanisms and timing of the crushed salt consolidation process must be understood and incorporated in a model that can be used to iteratively develop a robust repository disposal concept.

**Figure 3-7: Average Waste Temperatures Versus Time for Different Assumed Behaviors of the Crushed Salt Backfill**




***Note: figure reproduced from Clayton and Gable (2009)***

Note that slow reconsolidation of the crushed salt would not be a "showstopper" issue: a disposal concept that would mitigate the impacts of insulation of the waste package could be devised that would keep waste temperatures lower, all other things equal. Clayton and Gable (2009) discussed several viable solutions, including: aging the waste; disposing of waste with lower loadings in a greater number of alcoves; or designing the shape of the waste form to facilitate heat transport away from the canister. Nevertheless, answering this scientific question would enable a robust disposal concept design to be devised that supplies a high degree of assurance that the waste would remain within specified limits of temperature.

### 3.5.2. Conceptual Field Test Design

The alcove waste-disposal concept of Carter et al. (2011) described in the previous section innovatively balances safety, ease of operation, and heat management. This configuration is different than the configurations tested at Lyons, Kansas; Avery Island, Louisiana; or the thermal/structural interaction tests at WIPP. In these earlier tests, live nuclear waste packages (at Lyons) and electrical heaters (at WIPP, Lyons, and Avery Island) were placed in vertical boreholes drilled into the floor of the mine. The proposed field test consists of seven alcoves with five of the alcoves containing an electrical heater to simulate a disposed waste package. Each electrical heater will be placed on the floor near the back of the alcove and covered with crushed salt. Thus, the waste-disposal configuration for the field test is a full-scale mock-up, with heat loads and spacings that are intended to bound thermal conditions for disposal operations. The field test, laboratory tests, and modeling activities will produce data directly applicable to a potential repository, reduce the uncertainty of current predictive models, and allow improvement to the scientific bases of the models.

The test will incorporate measurements of temperature changes imposed on the intact salt surrounding the alcove (roof, floor, and pillars) and mine-run salt placed as backfill over the waste. Closure and entombment processes will be measured directly by various deformation gauges, as well as post facto forensic reconnaissance. Hydrologic effects will be determined through the monitoring of moisture/brine movement in and around the test alcoves, as well as down-drift in the exhaust air. In addition, chemical effects on various metal coupons and radionuclide analog elements will be assessed during the forensics stage. The test bed is expected to see temperatures in excess of 160°C in the salt mass (see section 3.4.1). The alcove tests will be complemented by laboratory tests on dry mine-run salt to determine its deformation characteristics at elevated temperatures (200–300°C) and on intact salt specimens to obtain creep rates above 200°C. The pre-test and post-test chemistry and environmental parameters will also be evaluated and compared to laboratory test results under more carefully controlled environmental conditions. The underground experiment measures the imposed transient temperature field, the accelerated deformation in the intact salt and backfill, and the movement of moisture/brines in the salt. Figures 3-8 and 3-9 illustrate in a perspective view, the general layout and architecture of the field test and a typical heated alcove. Note that Figure 3-8 only shows the thermal test area and adjacent access drifts. It does not show the cross cuts and outer most ventilation and access drifts that are shown on Figure 3-10.

**Figure 3-8: Perspective View of the Mining Layout for the SDI In Situ Thermal Test**

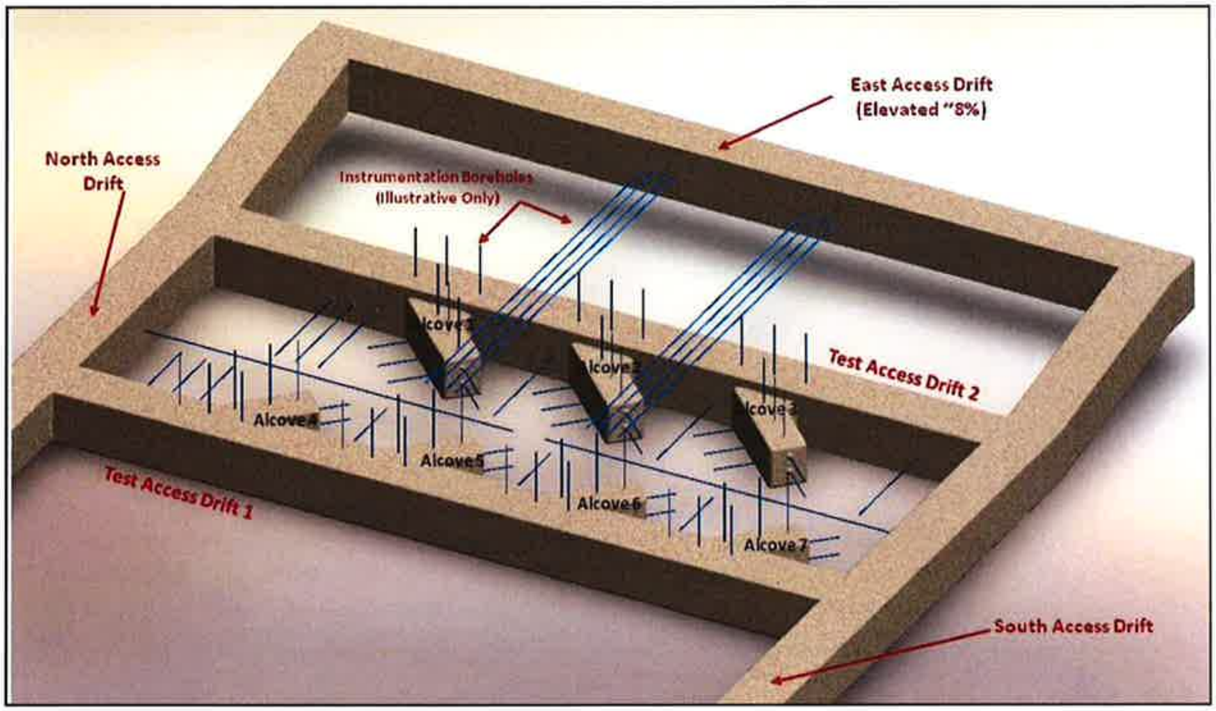



**Figure 3-9: Areal View of a Typical SDI Alcove**

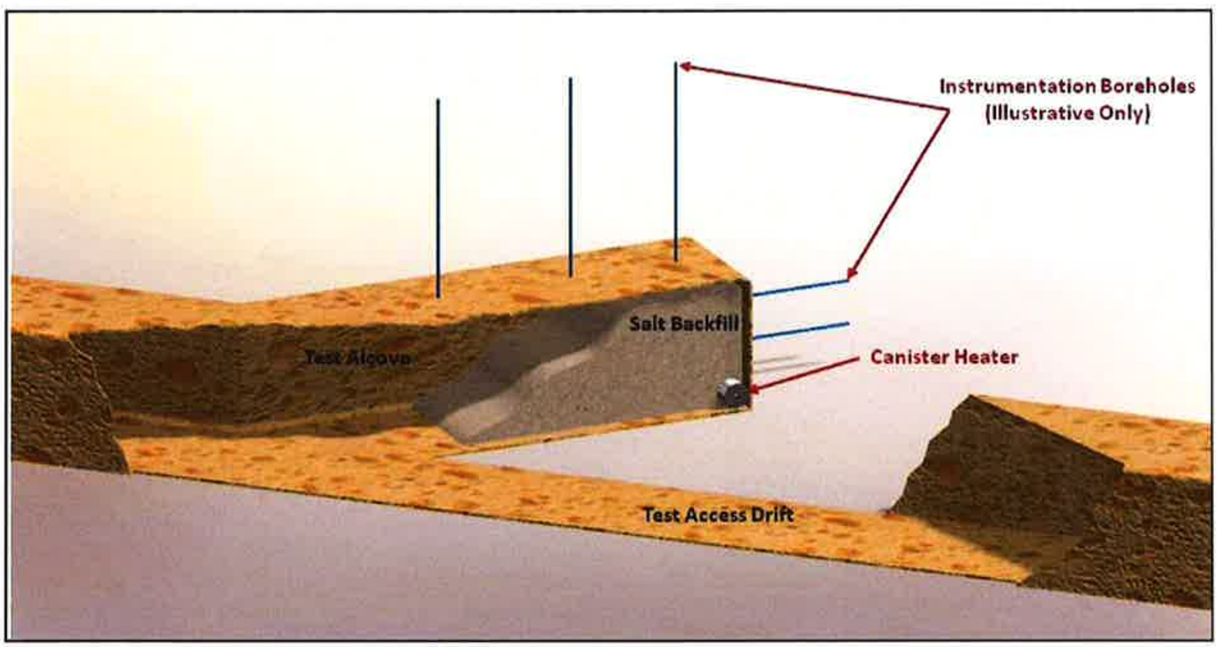


Figure 3-10 illustrates the approximate area within the WIPP that would most logically support the field test. Some of the major considerations to the exact placement of the test within the WIPP are: 1) this test will not interfere with WIPP operations, 2) the test should be located to the north, as far from waste handling operations as possible, and outside the shaft pillar area, 3) the test should not interfere with existing scientific testing occurring in the northern part of the facility, and 4) the test should exhaust directly to the exhaust shaft.

A concept that would address each of these criteria sites the test bed a few hundred feet south of the N-1100 drift in the WIPP facility and outside the shaft pillar area. Approximately 9,500 linear feet of mining would be required to implement this concept. A two-drift access drift, one originating from N-780 and the other from N-1100, with cross cuts would provide ample ingress/egress as well as sufficient controlled ventilation for accelerated forced cool-down of the test bed. The ventilation return would be directly to the exhaust shaft. This arrangement allows for accelerated cooling for access to the test bed to conduct post-test forensics. Additionally, it allows for rapid cooling of the test area if required.

The test will be located in a representative selection of salt, characterized during the early mining stages prior to turn out for the test bed. The test bed would be located approximately mid-way between WIPP Marker Beds 138 and 139 in the facility. Specific details related to test bed criteria and placement will be documented and transmitted to the construction support organization by way of the F&OR document and detailed field test plan.

Figures 3-11 and 3-12 illustrate the general layout of the waste-alcove type salt repository to be demonstrated in the field test. The primary objective of this full-scale demonstration is to provide thermal, structural performance, and hydrological data for the alcove configuration. In detail, the objectives of the in situ heater test are to:

- Measure temperatures to confirm heat transfer calculations.
- Monitor salt movement (alcove deformation) to validate salt creep calculations.
- Impose reconsolidation on the crushed salt to test the salt-reconsolidation model.
- Determine brine and vapor movement for initial information on moisture effects.
- Validate far-field thermal modeling capability by having several interacting alcoves.
- Provide a specific problem and detailed in situ test data for three-dimensional computer code validation and benchmarking.
- Evaluate chemical effects on coupons of various materials placed in proximity to canisters and associated changes in the in-field chemistry and environment.

Details of the in situ heater test will be developed in a formal field test plan based on the F&OR document. After the test plan is written, CBFO will review and provide final acceptance of the test plan. The concepts displayed here are sufficient to allow reasonable estimates for cost and schedule.

Figure 3-10: Proposed Area within WIPP for the SDI Heater Test

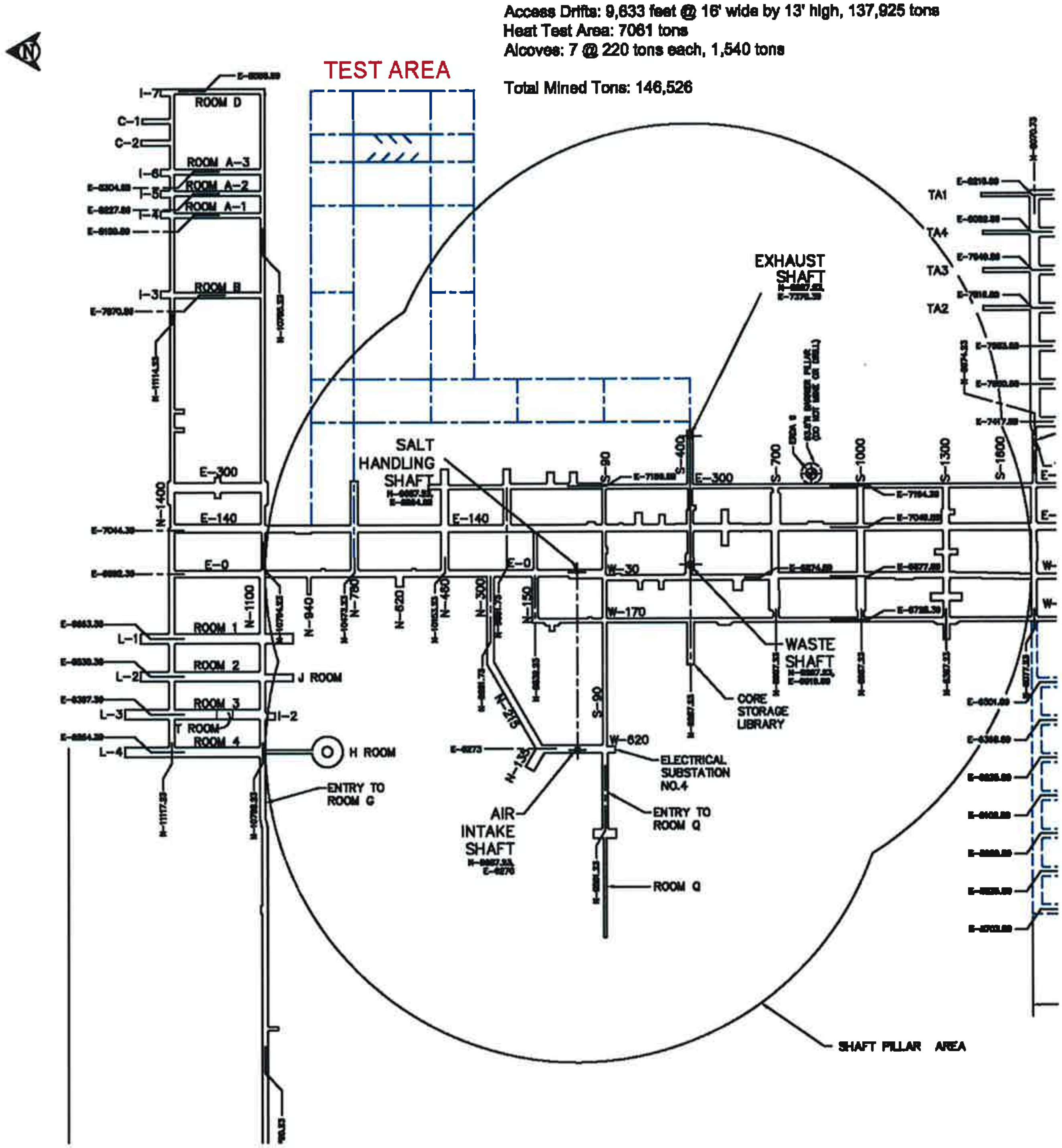


**Figure 3-11: Plan View of the Mining Layout for the SDI In Situ Test**

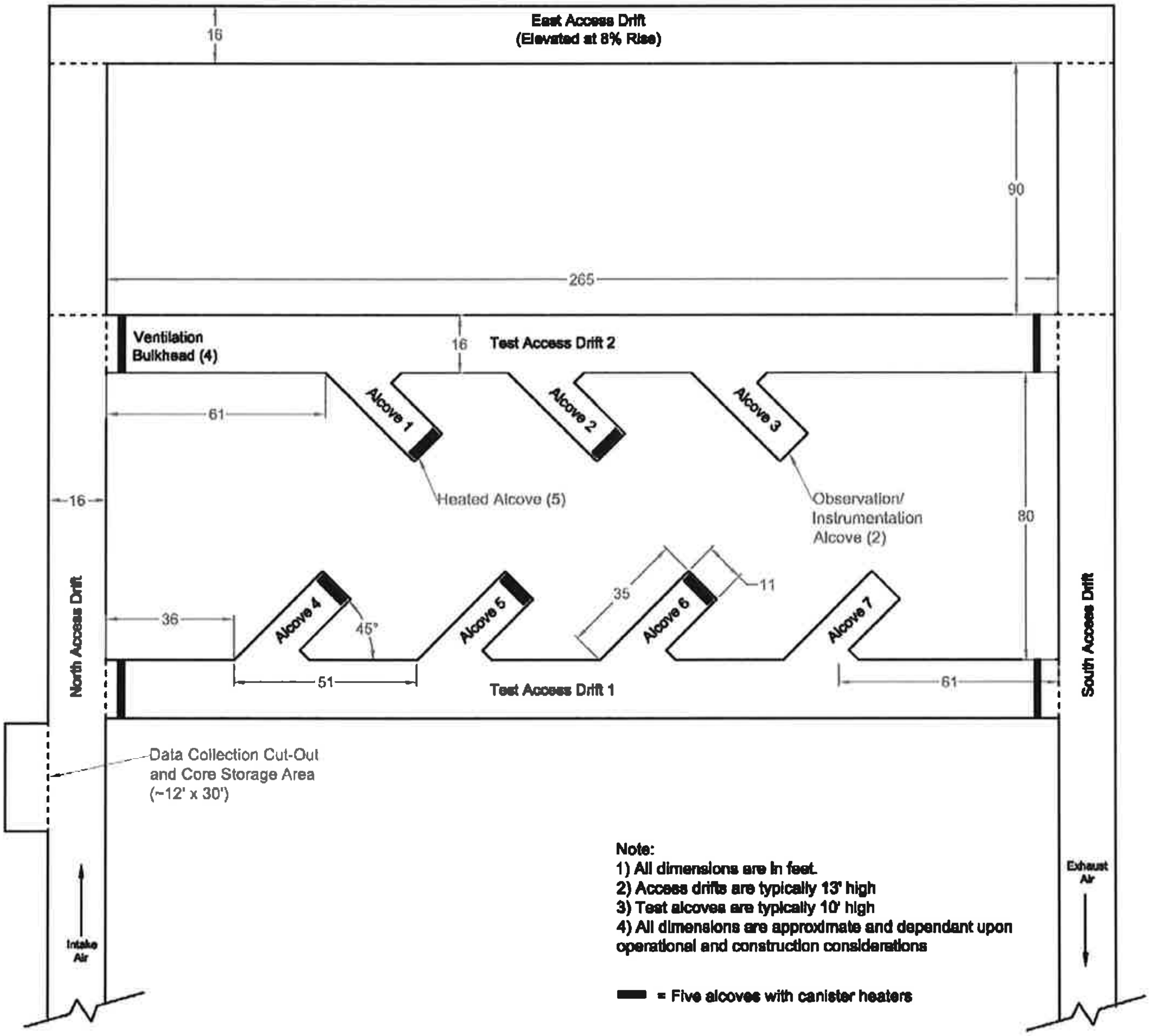
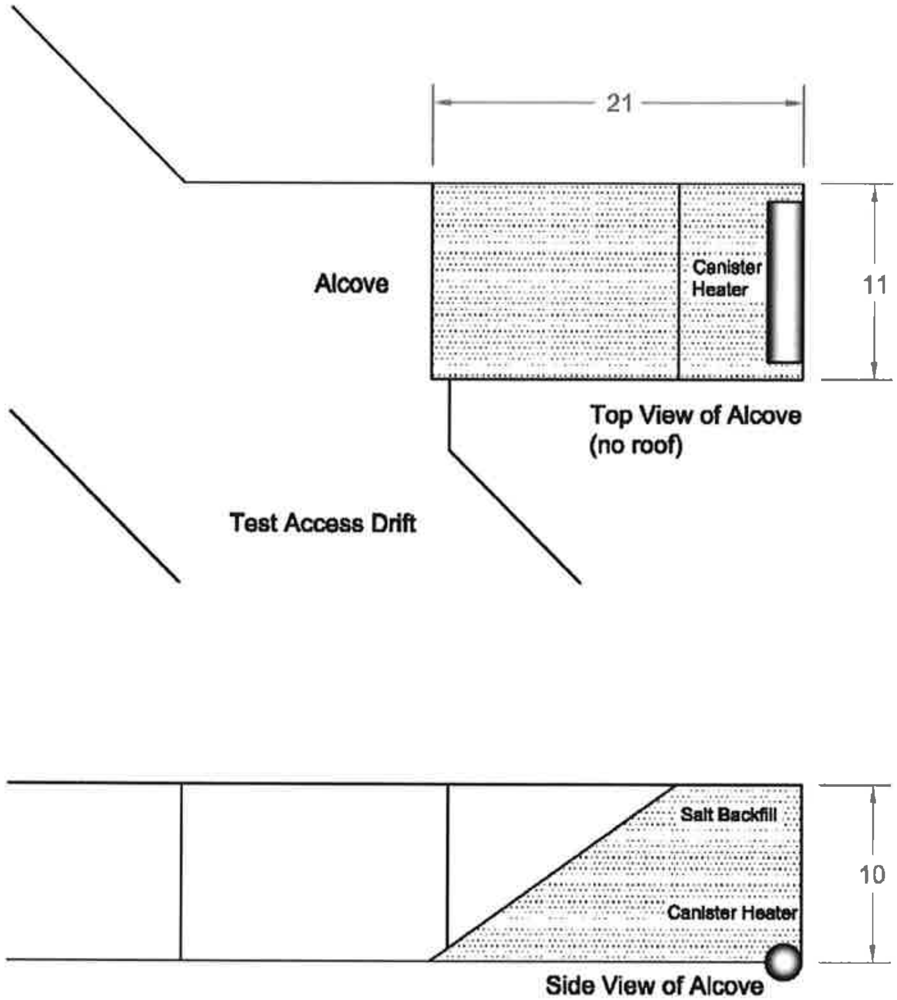


**Figure 3-12: Plan and Profile View of a Typical Alcove**




NOTE: Dimensions are in feet. Dimensions are preliminary, not to scale, and for planning purposes only. Angle of repose of the salt is for illustration. Exact layout and dimensions will be documented in the F&OR document and the detailed field test planning documentation. Cylinder shown at the back of the alcove is the canister heater simulating the thermally hot waste canister and will be placed in a notch at the back of the alcove for stability and enhanced heat transfer.

Seven alcoves will be instrumented to measure brine and vapor movement, temperatures, deformation, closure in and around the alcoves, pressure in the crushed salt, and ventilation conditions. Because of the large deformations and brine conditions expected during the test, redundant instrumentation from observation drifts as well as from within the test alcoves themselves will be deployed. Robust signal wiring, including wireless signal transmission, will be investigated and deployed if suitable. Geophysical techniques as described in section 3.5.3 will be used to assess test conditions. Remote visual monitoring through high temperature camera systems will also be deployed. The proposal team intends to include our international peers in review of this test arrangement.

The field test will use electrical heaters to simulate the waste packages. The concept at this stage includes 8.5 kW heaters that should bound the thermal output of any waste placed in each alcove. This thermal loading pushes the areal heat density to approximately 40 W/m$^2$, which will produce temperatures well above 100$^\circ$C, (temperatures above where most data have been acquired to date) in the nearby undisturbed salt. The heaters will have sealed (welded) ends with high-temperature potted electrical leads. The electrical controller will use a step-down transformer to regulate heater power. These values will be validated and specific heater wattages and areal heat loading values will be specified in the field test plan.

**Electrical Heater Stability During Testing**

The concept of buoyancy includes the notion that the waste will either "melt" its way downward or float upward, and the heated volume of salt may move upward as a result of its reduced density. The planned field test instrumentation includes surface surveys that are part of the performance confirmation monitoring program for WIPP. Thus, any uplift will be measured from these very accurate surveys. Measurement of buoyancy in situ will be investigated if practical geophysical and instrumentation techniques can be identified.

The movement of canisters containing heat-generating nuclear wastes buried in a salt formation has been hypothesized. The existence of buoyant forces due to thermally produced density differences suggests the possibility of initiating convection cells in a plastic medium like salt. A proper assessment of this motion includes considerations of the temperature dependence of the effective viscosity and thermal conductivity of the salt, as well as the decreasing thermal output of the heat-generating wastes with time.

Analyses performed in the 1970s indicate that very little canister movement will result during the heat-producing life of the waste canisters. The transient analyses show that initially the canister will sink. Then, due to the formation of a convective cell in the salt from heating by the wastes, the canister will rise. Eventually, as the convective cell diminishes, the canister begins to sink again. Predicted displacements are less than a canister length during this process. The steady-state analyses provide upper bounds on the magnitudes of upward velocity possible during heating. In all cases, the velocities are sufficiently small to indicate that very little movement will occur while the canister is capable of producing heat.

**Field Cost Estimates**

Cost estimates are developed on a "per alcove" basis, using the fully instrumented alcove. There will be modifications to the instrumentation arrangements, particularly in the two alcoves without heaters. And the final design will almost certainly add to and otherwise change some of the detail exhibited here. The precise instrumentation configuration will be developed in a detailed field test plan. Nonetheless, the array of instruments provides a reasonable overview of the in situ test for estimating purposes. Table 3-8 provides a breakdown of the measurement types, measuring devices, and estimated quantities, along with cost estimates for the in situ heater test. Table 3-9 represents the additional total equipment purchase costs for the in situ heater test. Some select instrumentation and equipment will be developed and/or purchased in FY12 and FY13. The data acquisition system, the heaters and controllers, and the remainder of the equipment will be purchased in FY14 in preparation for a heater start in mid FY15.

**Table 3-8: Instrument Costs per Alcove for the In Situ Thermal Test**

| Measurement | Sensor Type | Estimated Number per Alcove | Estimated Installed Cost ($K) |
|---|---|---|---|
| Roof-Floor Closure | One-meter range, spring loaded pull-wire potentiometer, temperature compensated | 4 | $30 |
| Salt Displacement and Deformation | Multiple Point Borehole Extensometer (MPBX) with invar rods and four displacement transducers | 5 | $90 |
| Temperature | Thermocouples/RTDs | 40 | $70 |
| Crushed-Salt (Backfill) Pressure on Heaters | Temperature-compensated load cells between buried loading plates | 4 | $30 |
| Heat Flux to Salt | Flexible high conductivity heat-flux meter mats with precisely positioned thermocouples | 4 | $30 |
| Water Vapor Movement | Systems for monitoring of vapor movement within the test bed (e.g., air volume, temperature, humidity, sonic velocity, electrical-resistivity) | 1 | $40 |
| **Estimated Instrument Cost per Alcove** | | | **$ 290** |
| **Estimated Total Instrument Cost for 7 Alcoves** | | | **$2,030** |

**Table 3-9: Equipment Costs for the In Situ Thermal Test**

| Equipment & Hardware | Description | Quantity | Estimated Installed Cost ($K) |
|---|---|---|---|
| Heaters with Controller | Rod heaters (redundant leads and elements), 10kW capacity in 24-inch diameter casing, sealed both ends, potted high-temp leads | 5 | $750 |
| Data Acquisition | Multi-channel DCS | 1 | $350 |
| Fiber optic communication system | Communications cable data hub and system to communicate data to the DCS and the surface | 1 | $250 |
| Cameras & Recording | 10 digital video cameras and video station | 1 | $200 |
| **Estimated Total Equipment Cost** | | | **$ 1,550** |

A 24-month heating interval is anticipated, followed by an 18- to 24-month cool-down period. Information to be gathered after the heating period includes sampling the reconsolidated crushed salt for forensic studies, including optical and scanning election microscopy and limited physical and mechanical testing. The heaters and any attached metal coupons will be recovered and evaluated.

A team responsible for experimental operations consisting of a test coordinator and field testing support staff will be required to perform equipment testing, shakedown, technical operation, monitoring, maintenance, data collection, data reduction, operational assurance, and reporting. Additionally, the Principal Investigators and field test scientific management is required for the duration of the test once it begins heating in FY15.

### 3.5.3. Mining and Construction Support

The proposed in situ testing effort requires salt mine access. To aid in determining relative costs, a division of responsibilities has been developed for this proposal and as shown in Table 3-10, which delineates the anticipated work breakdown.

**Table 3-10: Partitioning of Responsibilities - Construction & Operations Support and Testing**

| Activity | Pre-Test Planning | Const. and Ops Support | Testing |
|---|---|---|---|
| Prepare mine layout and specifications | X | | |
| Define infrastructure needs (air, electrical, comm) | X | | |
| Develop detailed field test plan | X | | |
| Excavate the defined openings (access and alcoves) | | X | |
| Install ventilation structures | | X | |
| Drill/core instrumentation boreholes | | X | |
| Install instruments in boreholes (e.g., MPBXs, thermocouples) | | | X |
| Install data collection system (DCS) | | | X |
| Connect instruments to DCS | | | X |
| Run fiber-optic cable from DCS to surface | | X | |
| Connect fiber optics to transmitter | | X | X |
| Install electric power distribution | | X | |
| Install electric control panels and heater controllers | | X | |
| Install heaters | | X | |
| Provide underground compressed air | | X | |
| Routine supply delivery (aboveground to test area) | | X | |
| Special equipment delivery | | X | |
| Facility management and science program interface | | X | |
| Test coordination, oversight and facility interface | | | X |
| Install ventilation monitors | | X | |
| Install instrumentation | | | X |
| Install heaters in alcove | | X | |
| Cover heaters with mine-run salt | | X | |
| Install instruments in mine-run salt | | X | X |
| Daily heater power inspection/regulation | | X | |
| Instrumentation and DCS maintenance | | | X |
| Collect and analyze test data | | | X |
| End of test forensics, recovery & decommissioning | | X | X |

The estimates for mining and infrastructure are estimated from direct mining experience at WIPP. The operating WIPP facility provides advantages in terms of operating infrastructure, Mine Safety and Health Administration (MSHA) qualification, equipment, and resources. The field experiment will not interfere with the WIPP operations or the greater WIPP mission.

It is estimated that the savings for mining and infrastructure costs exceed 50% of those in the original proposal from February 2010. The infrastructure at WIPP, as well as mining equipment and machinery, has already been purchased by the DOE. WIPP personnel and equipment would facilitate mining, mucking and trucking, utilities, transport, surveying, craft support, facility operation, and safety. Estimates are shown in Table 3-11. The labor and infrastructure associated with mining and engineering at the WIPP are existing WIPP resources and will not require new SDI budget. However, those total costs are accounted for, but not included in the new SDI specific budget necessary to complete the work. Consumables and equipment (e.g., ventilation control, power distribution, the purchase of a new core rig) are included as direct costs requiring new SDI budget. The cost estimate also includes forensic back-mining in the last year of the project to retrieve coupons, salt samples, and the heaters for laboratory analysis and determination of in situ alcove environmental conditions, mineralogy, and brine chemistry. As before, the total costs are shown, but not included in the roll-up of necessary new SDI budget to conduct the work. As there are no mining or infrastructure costs in FY11, the following table begins in FY12.

**Table 3-11: Mining and Infrastructure Costs (in thousands of dollars)**

| Activity | FY12 | FY13 | FY14 – FY18 | FY19 | FY20 |
|---|---|---|---|---|---|
| Mining, Surveying, Salt Disposal, and Management (existing WIPP resources) | ($1,500) | ($1,500) | | | |
| Core Rig Purchase & Coring | | | $1,700 | | |
| Ventilation Control | $250 | $250 | $50 | | |
| Power Distribution | $200 | $200 | $600 | | |
| Safety Case & Work Control | $50 | $50 | $50 | | |
| Ops Support | | | $3,000 | $700 | $500 |
| Test Forensics, Mine Back | | | | | ($1,500) |
| **Total SDI Budget (new) per year** | **$500** | **$500** | **$5,400** | **$700** | **$500** |
| **Total Cost (incl. existing resources)** | **$2,000** | **$2,000** | **$5,400** | **$700** | **$2,000** |

The total distance mined for test access rooms and alcoves for the basis of estimate is approximately 750 linear feet at approximately 11 feet wide by 10 feet high. Approximately 9600 total linear feet of mining (approximately 16 feet wide by 13 feet high) will be required in the north section of the WIPP in order to gain access and properly ventilate the test area. Each alcove will be backfilled with run-of-mine salt after the heater is placed in the alcove as shown in Figure 3-9. Whereas the detailed field test plan will have exact layouts and dimensions, it can be expected that there will be approximately 20 boreholes per alcove (cored from both inside and outside the alcove). If each borehole were an average of 20 feet long, an approximate total of 4,000 linear feet of precisely placed boreholes will be required to field this test.

The five heaters at 8.5 kW will require a power load of 43 kW. Assuming a 25% load factor, this would be 53 kW of power. The instrumentation, equipment, lighting, and general power will require 10 kW clean 110V/220V single-phase power.

### 3.5.4. Geophysical Assessment and Monitoring of the Field Test

A key test parameter associated with this experimental work is brine and vapor movement in the salt formation during heating and cool-down. These measurements are generally not as straightforward to make as is monitoring for temperature or ground movement. Additionally, the large ground movements and brine conditions expected to be seen during the test will make it imperative that measurement techniques not dependent upon hard wired gauges down a borehole be used where feasible. As such, new or more advanced techniques are likely to be developed and employed in this field test to measure, at a minimum, vapor and brine movement. These techniques are also anticipated to provide three-dimensional information regarding mechanical changes and physical closing of alcove openings to complement more direct measurement methods.

Geophysical techniques (in addition to the more traditional instrumentation listed in Table 3-8) are expected to be developed, demonstrated, and potentially deployed to monitor salt alcove properties important to the test. These categories of salt alcove properties, features, and behavior may include: 1) fluid migration, 2) alcove interface rheology and structural changes, 3) thermally induced seismicity, and 4) electrical properties. A two-year duration period at the beginning of the time-line is set aside to develop and demonstrate these techniques such that measurement techniques sufficient to monitor salt alcove properties important to the test, in particular for vapor movement, are achieved. All of these methods are proven but are site- and application-specific. They are low risk in that they are well established, but some may not be appropriate for this problem due to such issues as minimum spatial resolution and limited sensitivity to contrasts between solid, fluid and vapor phases. For these reasons, higher risk is associated with applying these techniques to fluid and vapor migration. The demonstration period will be used to develop advancements that address the resolution and sensitivity issues. The following section discusses some of these techniques.

Near real-time (four-dimensional (4D)) interrogation (using repeated active and passive seismic and active resistivity measurements) may be made at sufficiently large standoff distances to avoid the potential damage to the sensor networks that could occur due to high temperatures and major structural changes in and immediately surrounding the test alcoves. Two primary thermally induced physical processes associated with the salt heater test may be monitored: 1) thermomechanical evolution and deformation of the alcoves, backfill, and surrounding formation, and 2) migration of fluids (brine) within and between these same structural components. As with the more detailed description of the thermomechanical instrumentation, the geophysical monitoring layout would be integrated with the field test plan and reviewed by internal technical teams. Stand-off in situ seismic and electrical resistivity experiments are proposed for the salt heater tests to quantify: 1) the thermomechanical evolution of targeted structural components, and 2) the migration of brine within these same structures. The work would also build on and provide support for the point measurements of salt alcove deformation (extensometer) and temperature (thermocouple) outlined in earlier sections by providing full 3D time-lapse measurements of the entire volume surrounding and including the alcove, backfill, and heaters. Furthermore, the seismic and resistivity arrays would survive major alcove deformation or collapse that might damage the extensometer and thermocouples. The following geophysical techniques are proposed.

- **Active time-lapse in situ seismic wave transmission measurements and monitoring.** Active seismic methods are the primary tool that could remotely, noninvasively detect subtle thermal/mechanical changes within the test area. Reflection imaging and transmission imaging could provide complementary information of the test area.

  The velocity at which seismic waves travel through solid material varies with density, temperature, and pressure. The density, wave scattering properties, and energy dissipation of the material also change with temperature. Thus, spatial variations in the travel time, scattering, and attenuation of seismic waves can be used to map changes in seismic wave velocities, material density, heterogeneity, and viscoelastic properties caused by temperature gradients in and around a heated region of salt and/or brine and vapor movement. One method that may be used is known as seismic tomography and is similar to techniques used in medical X-ray diagnostics. Full 3D coverage of the region surrounding heated alcoves with appropriate seismometers or accelerometers would allow detailed 4D tomograms to be obtained using active seismic data acquired at different times, which would illustrate how the spatial temperature profile around the heaters evolves. 3D ray tomography and 3D double-difference waveform tomography are proposed to obtain high-resolution 3D images showing where temperature changes occur. When the source frequency is in kilohertz, the anticipated spatial resolution of 3D images would range from approximately 0.5 m to a few meters (or half wavelength to 2-3 wavelengths), depending on tomography algorithms. It might be possible to attain .25 m resolution or better with higher frequency sources, since the experimental layout is very compact (Schuster, 1996).

- **Passive seismic event monitoring.** The deformation induced by heating the salt will likely result in multiple scales and degrees of brittle failure of the alcove structure and surrounding formation. During initial heating, small-scale deformation might occur along cracks or fracture planes, either by crack growth or by slippage along pre-existing planes of weakness. These discrete events will result in very small microseismic or acoustic emissions. As heating progresses, large-scale fracturing can occur in the salt alcove walls, ceiling, and floor. Data from these events can be used to determine the location, development, and extent of the fractures, as well as the fracture mechanism itself. Performing the passive seismic monitoring will not require additional instrumentation; both passive and active types of thermally induced seismicity can be detected using the same seismometers or accelerometers that would be deployed for the active seismic experiments discussed above. Event location resolution is expected to be about 0.3 m, based on previous work. Further, with sufficient 3D coverage of receivers surrounding the microseismic sources, it would be possible to resolve the type of crack deformation being induced, for example, tensile vs. shear deformation. The microseismic data would provide an important measure of how thermal-induced strains are accommodated discretely in the salt body and how they lead to major structural events. A passive seismic monitoring system will provide insight into the presence and source of brittle phenomena. One might expect flexural tensile brittle processes and possible acoustic emission from proximal anhydrite, because of its stiff rheologic response.

Therefore, a carefully arrayed seismic network will be evaluated for deployment in the field experiment.

- **Active time-lapse seismic reflection imaging and monitoring of alcove interfaces.** Seismic/elastic reflection imaging (migration) techniques produce much higher resolution 3D images of subsurface material interfaces than transmission tomography, from which such interfaces are often invisible. Seismic reflectors are structural interfaces separating two materials with different seismic impedances. The primary interfaces of interest in this study are those between the solid salt alcove walls and the crushed salt backfill, plus the interface between the heater and its surroundings. Seismic reflection signals would be used to produce high-resolution 3D images of interfaces in the vicinity of the heater test (Fehler and Huang, 2002, Annu. Rev. Earth Planet. Sci., 30:259-284.).

- **Electrical resistivity measurements.** Measurement of electrical resistivity is a powerful technique for probing and monitoring geological systems, including rock and salt formations, because the technique is very sensitive to small changes in electrical properties. Repeated in situ measurements of salt resistivity would provide high resolution 3D time-lapse images of temporal changes related to fluid migration. A combination of field and laboratory measurements is proposed to apply electrical techniques to characterizing the moisture movement within the salt. In situ field measurements would be performed to obtain baseline measurements and to characterize electrical resistivity as the salt body warms. Several techniques would be used for imaging electrical resistivity, including electrical profiling (surveying) and transient electromagnetics (EM). Data from individual 2D electrical surveys and electromagnetic soundings can be combined into 3D data cubes. Because resistivity values of salt range from 10 to 1013 ohm-m under ambient conditions, the influence on resistivity of grain size, hydration, temperature, and possible clay content must be determined via laboratory measurements in order to interpret the field data. These measurements would allow for better interpretation of the range of resistivity values that would be observed, as well as for better discrimination among thermal compaction, water content and migration, and clay content. Although electrical resistivity methods are typically less well know by geophysicists, there is a large amount of experience, and many companies which specialize in electrical techniques (e.g., Zonge, www.zonge.com; geometrics, www.geometrics.com; sensors&software, sensoft.ca; fugro airborne services, www.fugroairborne.com, hydrogeophysics, www.hydrogeophysics.com; and Willowstick, www.willowstick.com).

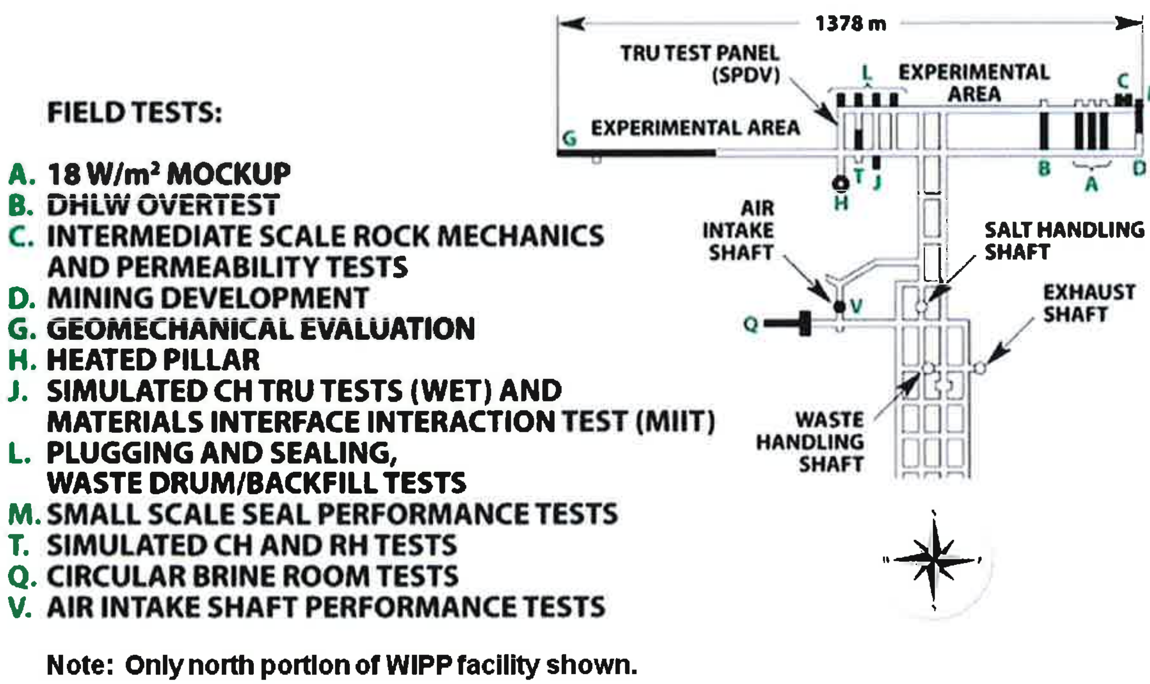
- **Joint Seismic and EM imaging.** Electrical and electromagnetic signals are more sensitive to brine and vapor movement than seismic measurements. On the other hand, the resolution of seismic imaging is much higher than EM imaging. Joint seismic and EM imaging could significantly enhance detection of brine and vapor movement. Joint seismic and EM imaging is proposed for monitoring brine and vapor movement in the salt formation during heating and cool-down processes.

### 3.5.5. Feasibility of Reentry into the North WIPP Experimental Area

Excavation for siting the SDI field test could potentially allow reentry to the north experimental area, which was abandoned over twenty years ago. The feasibility of this idea will be developed as the SDI work continues and is not currently planned, budgeted, or scheduled. The concept is put forward here because the proposal team recognizes a possible opportunity for forensic reconnaissance of previously heated rooms.

As illustrated in Figure 3-13, heated room experiments were conducted in A and B rooms in the north experimental area. The A room tests were heated at an equivalent of 18 W/m2 mockup. The B room was called the defense high-level waste (DHLW) overtest. These tests were abruptly terminated, and at least some heaters were abandoned in place. At least one heater was overcored and removed, but no examination was made of the reconsolidated salt attached to the heater, the nature of brine migration in the intact salt adjacent to the heater, or of possible corrosion on the heater itself. Other abandoned heaters and the proximal salt may be accessible for examination after more than 20 years in situ. The opportunity and practicality of reentry will be investigated.

**Figure 3-13: Location of Past Field Tests Located Within WIPP**



# 4. COST AND SCHEDULE

## 4.1. COST AND SCHEDULE

Table 4-1 lists the cost (in thousands of dollars) by element for each portion of the proposal by fiscal year. The budget estimates are constrained for the first two fiscal years. Table 4-2 shows a breakdown of the activities by funding organization, both DOE-EM or DOE-NE.

Figure 4-1 shows the expected duration for the test by element under the funding profile. Figure 4-2 shows an accelerated schedule with a heater test start in FY14 if additional funding were provided in the first two years of the test.

The Yucca Mountain Drift Scale Test took approximately 2.5 years (mid 1995 to Dec 1997) to construct and install at a cost of approximately $19 million (including mining, drilling, and engineering costs). The SDI thermal test is estimated to take approximately 3.5 years (Oct 2012 to mid 2015) at approximately $28 million (plus the in-kind costs of construction, drilling, and engineering work). Therefore, based on past experience and comparison with other large underground thermal tests, these cost and schedule estimates are reasonable.

## Table 4-1: Cost by Element (in thousands of dollars) - Budget Constraint on the First Two Fiscal Years

COSTS (estimated) BY FISCAL YEAR ($1,000K)

| SDI Proposal Element | Sect # | Task/Product | Comments | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Management, Quality Assurance, and Safety | 2.1 - 2.3 | Management, Quality Assurance, and Safety | | $450 | $1,000 | $900 | $900 | $600 | $600 | $600 | $600 | $700 | $600 | $6,950 |
| | | Proj Mgmt, QA Support, Performance and Safety Analysis/Approvals | * Includes F&OR document development in FY11 (Section 3.1) | $450 | $600 | $900 | $900 | $600 | $600 | $600 | $600 | $600 | $800 | $6,650 |
| | | Detailed Test Plan Development | * Development of detailed test plan in FY13 | | $400 | | | | | | | | | $400 |
| International Collaboration | 2.4 | International Collaboration | | $0 | $200 | $200 | $200 | $250 | $250 | $250 | $200 | $200 | $200 | $1.950 |
| Lab Thermal and Mechanical Studies | 3.2 | Bound Salt Thermomechanical Response | *Test Plan development and early lab testing in FY11 | $250 | $400 | $600 | $300 | $300 | $300 | $300 | $300 | $400 | $300 | $3,450 |
| Laboratory Hydrologic, Chemical, and Material Studies | 3.3 | Laboratory Tests in Support of Modeling, PA, and the Field Test | | $0 | $210 | $700 | $500 | $500 | $300 | $300 | $300 | $400 | $300 | $3,510 |
| Coupled Process Modeling | 3.4 | Coupled Process Modeling | | $0 | $300 | $700 | $500 | $200 | $200 | $200 | $200 | $300 | $300 | $2,900 |
| | | Thermomechanical-Hydrological Benchmark Modeling | | | $250 | | | | | | | | | $250 |
| | | Process Coupling and Validation | | | $50 | $500 | $300 | $100 | $100 | $100 | $100 | $100 | $200 | $1,550 |
| | | Chemical | | | | $200 | $200 | $100 | $100 | $100 | $100 | $100 | $200 | $1,100 |
| Field Test Installation and Operations | 3.5 | Install and Conduct Field Test Proof of Principle | * Heating start FY15 - Accelerated cool down by FY19 | $0 | $2,300 | $2,400 | $8,900 | $2,500 | $2,100 | $2,100 | $2,100 | $2,850 | $3,350 | $28,600 |
| | | ***Instrumentation, Data Collection, and Testing*** | | | | | | | | | | | | |
| | | Alcove Instrumentation Development and Procurement | * 7 Alcove arrays and one redundant set | | $200 | $200 | $1,900 | | | | | | | $2,300 |
| | | Canister Heaters and Controllers Procurement | | | | | $750 | | | | | | | $750 |
| | | Data Acquisition System Procurement, Shakedown, and Calibration | | | | | $350 | | | | | | | $350 |
| | | Fiber Optic System Procurement and Shakedown for Data Transfer | | | | | $250 | | | | | | | $250 |
| | | Underground Camera System Procurement and Shakedown | | | | | $200 | | | | | | | $200 |
| | | Geophysical Assessment and Monitoring (e.g., vapor movement) | | | $100 | $200 | $400 | $100 | $100 | $100 | $100 | $300 | $200 | $1,600 |
| | | Instrumentation Shakedown, Calibration, and Installation | | | | | $1,850 | | | | | | | $1,850 |
| | | Underground Testing Personnel (e.g. data collection, active measurements) | | | | | | $1,300 | $1,100 | $1,100 | $1,100 | $1,100 | $600 | $6,300 |
| | | Post-test Sample Collection Personnel | | | | | | | | | | $450 | $250 | $700 |
| | | Investigate Salt Properties of Test Bed Location | * Test bed specific investigations at WIPP | | | | $200 | $200 | | | | | | |
| | | Field Test Scientific Management (e.g. PIs) | | | | | | $300 | $300 | $300 | $300 | $300 | $300 | $1,800 |
| | | ***Construction and Ops Support*** | | | | | | | | | | | | |
| | | Mining - Access Drifts, Test Bed | * Preservation of mining and hoist crew | | $1,500 | $1,500 | | | | | | | | $3,000 |
| | | Coring - Core Rig Purchase + Instrument Coring | * Purchase or lease of new core rig | | | | $1,700 | | | | | | | $1,700 |
| | | Ventilation Control | | | $250 | $250 | $50 | | | | | | | $550 |
| | | Dedicated Power Installation | * New line to test bed area | | $200 | $200 | $600 | | | | | | | $1,000 |
| | | Safety Case and Work Control | | | $50 | $50 | $50 | | | | | | | $150 |
| | | Ops Support (e.g. access, utilities, heater installation) | * Over 50% infrastructure costs saved at WIPP | | | | $600 | $600 | $600 | $600 | $600 | $700 | $500 | $4,200 |
| | | Test Forensics, Mine Back, Coring | | | | | | | | | | | $1,500 | $1,500 |

| | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TOTAL SDI BUDGET (*new budget*) NEEDED BY YEAR | $700 | $2,910 | $4,000 | $11,300 | $4,350 | $3,750 | $3,750 | $3,700 | $4,850 | $3,550 | $42,860 |
| TOTAL DISCRETE COST BY YEAR (*including existing WIPP resources*) | $700 | $4,410 | $5,500 | $11,300 | $4,350 | $3,750 | $3,750 | $3,700 | $4,850 | $5,050 | $47,360 |
| DOE-NE BUDGET (*new budget*) FOR THE TEST | $700 | $910 | $2,000 | | | | | | | | |
| DOE-EM BUDGET (*new budget*) FOR THE TEST | $0 | $2,000 | $2,000 | | | | | | | | |
| TOTAL DOE-EM COST (*including existing WIPP resources*) FOR THE TEST | $0 | $3,500 | $3,500 | | | | | | | | |

*** Shared EM-NE costs from FY14 to Completion***

**DOE-NE provided funding:** (red)
**DOE-EM provided funding:** (blue)
**Covered with Existing WIPP Labor/Infrastructure:** (green)

### Table 4-2: Cost by DOE Organization in FY12/FY13 (in thousands of dollars)

| SDI Sect # | Task/Product | FY11 | FY12 | FY13 |
|---|---|---|---|---|
| **DOE-NE Provided Funding** | | | | |
| 2.1 - 2.3 | Management, Quality Assurance, and Safety | $450 | | |
| 3.2 | Bound Salt Thermomechanical Response | $250 | $400 | $600 |
| 3.3 | Laboratory Tests in Support of Modeling, PA, and the Field Test | | $210 | $700 |
| 3.4 | Coupled Process Modeling | | | |
| | Thermomechanical-Hydrological Benchmark Modeling | | $250 | |
| | Process Coupling and Validation | | $50 | $500 |
| | Chemical | | | $200 |
| | **DOE-NE BUDGET (*new budget*) FOR THE TEST** | $700 | $910 | $2,000 |
| **DOE-EM Provided Funding** | | | | |
| 2.1 - 2.3 | Management, Quality Assurance, and Safety | | | |
| | Project Mgmt, QA Support, Performance and Safety Analysis/Approvals | | $600 | $900 |
| | Detailed Test Plan Development | | $400 | |
| 2.4 | International Collaboration | | $200 | $200 |
| 3.5 | Install and Conduct Field Test Proof of Principle | | | |
| | *Instrumentation, Data Collection, and Testing* | | | |
| | Alcove Instrumentation Development and Procurement | | $200 | $200 |
| | Geophysical Assessment and Monitoring (e.g., vapor movement) | | $100 | $200 |
| | *Construction and Ops Support* | | | |
| | Mining - Access Drifts, Test Bed | | $1,500 | $1,500 |
| | Ventilation Control | | $250 | $250 |
| | Dedicated Power Installation | | $200 | $200 |
| | Safety Case and Work Control | | $50 | $50 |
| | **DOE-EM BUDGET (*new budget*) FOR THE TEST** | $0 | $2,000 | $2,000 |
| | **TOTAL DOE-EM COST (*including existing WIPP resources*) FOR THE TEST** | $0 | $3,500 | $3,500 |
| | **TOTAL SDI BUDGET (*new budget*) NEEDED BY YEAR** | $700 | $2,910 | $4,000 |
| | **TOTAL DISCRETE COST BY YEAR (*including existing WIPP resources*)** | $700 | $4,410 | $5,500 |

**: DOE-NE provided funding** (red)
**: DOE-EM provided funding** (blue)
**: Resources Covered with Existing WIPP Labor/Infrastructure** (green)

**Figure 4-1: Estimated Schedule for Test Program Duration (Constrained FY12/FY13 Scenario)**

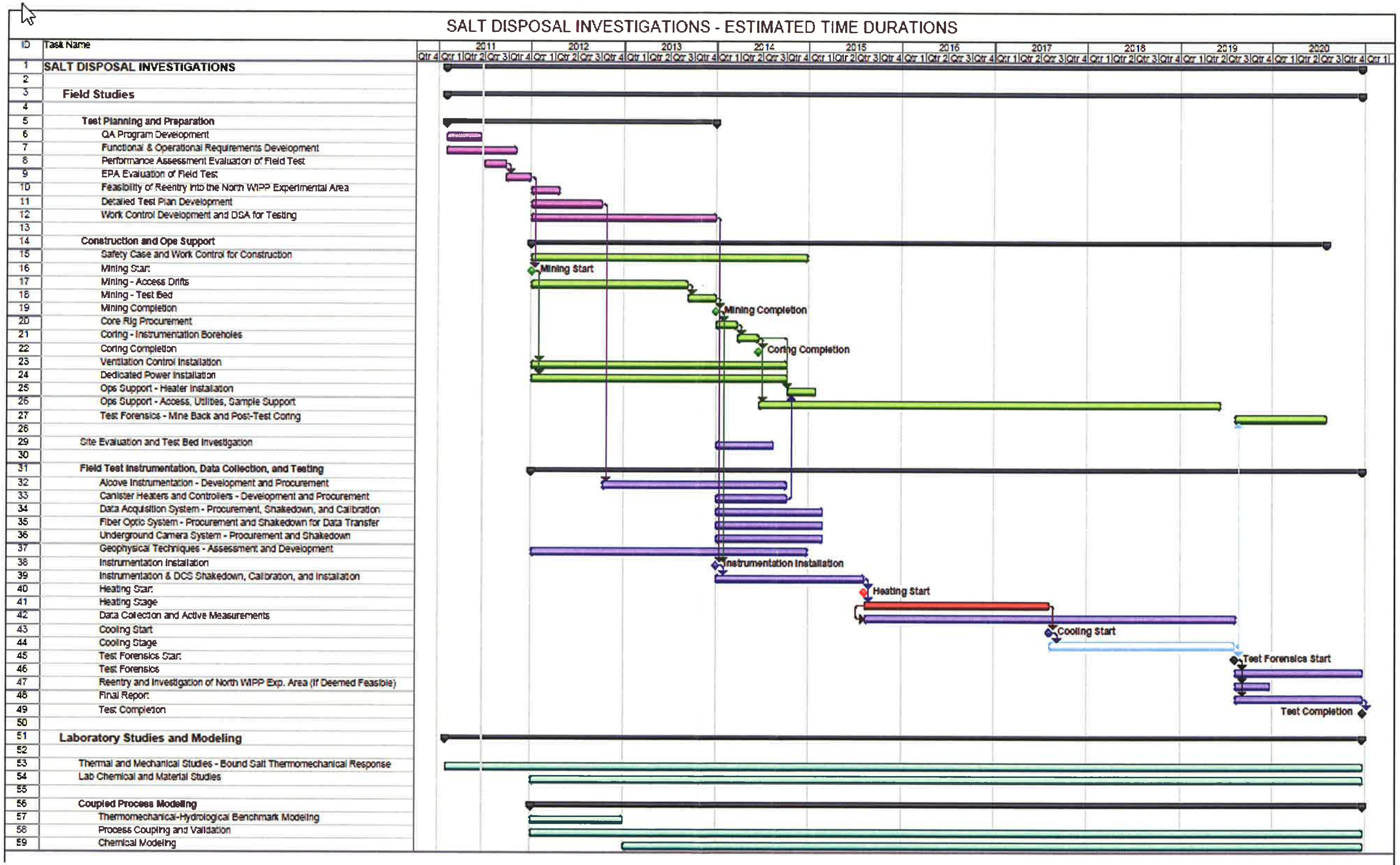
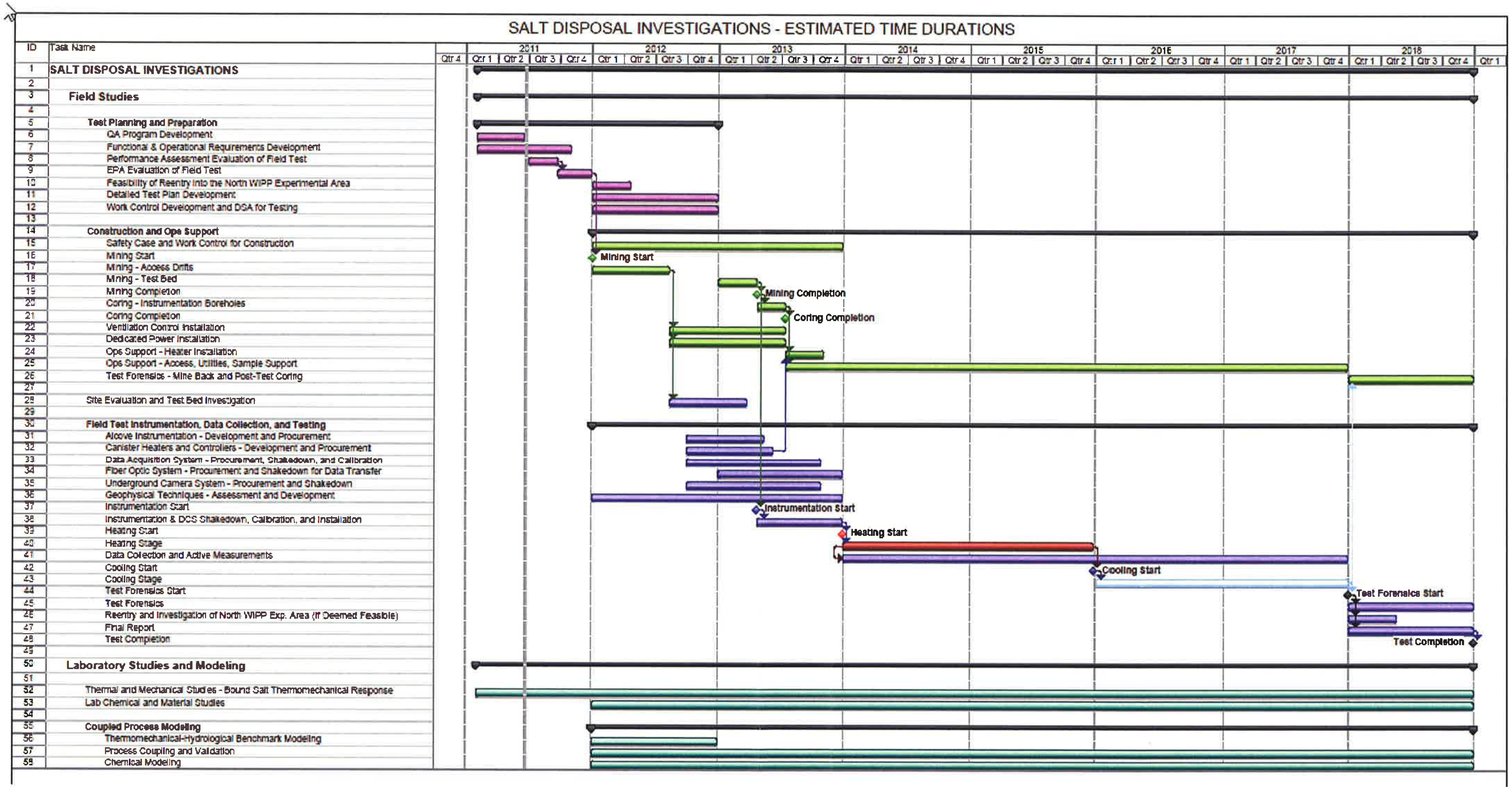


**Figure 4-2: Estimated Schedule for Test Program Duration (Accelerated Scenario)**



## 4.2. MAJOR ACTIVITIES AND ACTIONS

**Primary actions and test planning (FY11):**

- Complete the SDI Management Proposal
- Complete a Test Plan for laboratory testing for crushed salt in the laboratory to measure thermomechanical behavior across a variety of temperature, stress, and porosities
- Initiate laboratory tests on crushed salt
- Develop an NQA-1-compliant Quality Assurance Program Document and associated procedures
- Complete the F&OR document for the field test

**Test planning, initial mining and laboratory studies (FY12):**

- Begin elevated temperature tests on intact salt in the laboratory to measure thermomechanical behavior across a variety of temperatures and stresses
- Continue the laboratory tests on crushed salt
- Develop and review the detailed field test plan with equipment lists, instrumentation and borehole layouts, data quality objectives, etc.
- Comprehensively evaluate existing and available information from past thermal experiments
- Develop the criteria for the underground test design and layout
- Begin mining the underground access drifts to the test bed location
- Begin installing ventilation control and power distribution
- Write a test plan for laboratory studies of water liberation and brine migration in salt
- Begin measuring the thermodynamic properties of brines and minerals at elevated temperatures in the laboratory
- Develop a test plan and begin measuring the effect of temperature on radionuclide solubility in the laboratory
- Develop a test plan and begin studying repository interactions with waste container and constituent materials in the laboratory
- Evaluate and use coupled multiphysics modeling capability for field test configuration and analysis

**Initial studies (FY13):**

- Continue development of fully coupled TM(H) code and model for field test analysis.
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Develop test plan for intact core testing in the laboratory
- Procure test equipment and instrumentation for the field test
- Develop work control and safety basis for the field test
- Complete mining of the underground access drifts
- Develop the documented safety analysis for the field test
- Mine the field test bed

**Field test implementation (FY14):**

- Core instrumentation boreholes
- Implement the field test equipment, including data collection equipment and fiber optic communication equipment
- Investigate salt properties of test bed location
- Preparedness assessment for field test start and baseline measurements
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Continued development of fully coupled TM(H) code and model for field test analysis

**Conduct the proof-of-principle field test (FY15 - 20)**

- Heating start on field test – FY 15
- Investigate thermal effects on intact salt in situ
- Develop a full-scale response for dry crushed salt
- Observe and document fracture healing in situ
- Track moisture movement and vapor phase transport in situ
- Complete laboratory thermomechanical testing and chemistry experiments
- Complete laboratory studies of water liberation and brine migration
- Cool down of field test by FY 19
- Post-test forensics, mine-back and post-test coring in FY 19 and FY 20
- Complete the final test and data reports
- Develop calibrated, coupled TM(H) model

# 5. REFERENCES


1. Beauheim, R. L., and R. M. Roberts, 2002. "Hydrology and hydraulic properties of a bedded evaporite formation," *J. Hydrol.*, 259, 66-88.

2. Blue Ribbon Commission on America's Nuclear Future. June 1, 2011. *DRAFT – Disposal Subcommittee Report to the Full Commission*

3. Brodsky, N.S., F. D. Hansen, and T. W. Pfeifle. 1998. *Properties of Dynamically Compacted WIPP Salt.* Fourth Conference on the Mechanical Behavior of Salt

4. Carter, N. L., and F. D. Hansen, 1983. "Creep of Rocksalt," Technophysics, 92, 275-333.

5. Carter, J.T., F.D. Hansen, R. Kehrman, and T.A. Hayes. 2011. *A Generic Salt Repository for Disposal of Waste from a Spent Nuclear Fuel Recycle Facility.* SRNL-RP-2011-00149. Savannah River: Savannah River National Laboratory.

6. Clayton, D. J., and C. W. Gable, 2009. *3-D Thermal Analyses of High-Level Waste Emplaced in a Generic Salt Repository*, U.S. DOE Office of Nuclear Fuel Recycling Report AFCI-WAST-PMO-DV-2009-000002.

7. DOE, 2010. "Blue Ribbon Commission on America's Nuclear Future: Advisory Committee Charter."

8. DOE, 2011. "Memorandum of Understanding Between The Department of Energy Office of Environmental Management and The Department of Energy Office of Nuclear Energy for Used Nuclear Fuel and Radioactive Waste Management and Processing Research and Development," April 29, 2011.

9. DOE, 2011. *Salt Disposal Investigations Quality Assurance Program Document.* DOE/CBFO-11-3465. U.S. DOE Carlsbad Field Office.

10. Fehler, M. C., and L. Huang, 2002. "Modern imaging using seismic reflection data", *Annu. Rev. Earth Planet. Sci.*, 30, 259–84.

11. Gable, C. W., D. J. Clayton, and Z. Lu, 2009. *Inverse Modeling to Determine Thermal Properties of Salt due to Heating From High Level Waste Emplaced in a Generic Salt Repository*, U.S. DOE Office of Nuclear Fuel Recycling Report AFCI-WAST-PMO-DV-2009-000001.

12. Geo. Cosmo. Acta., V73, pp 6544-6564.

13. Hansen, F.D., and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste.* SAND2011-0161. Albuquerque: Sandia National Laboratories.

14. Hansen, F.D., K. D. Mellegard, and P.E.Senseny. 1980. *Elasticity and Strength of Then Natural Rock Salts.* Proceedings of the First Conference on the Mechanical Behavior of Salt.

15. IAEA, 2001. "The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste," IAEA Technical Document IAEA-TECDOC-1243.

16. Jenks, G. H. and H. C. Claiborne, 1981. "Brine migration in salt and its implications in the geologic disposal of nuclear waste," Oak Ridge National Laboratory Report ORNL-5818.

17. Karlsruhe Institute of Technology. 2010. *Proceedings.*

18. Knauth, L. P., and M. B. Kumar, 1981. "Trace Water Content of Salt in Louisiana Salt Domes," *Science*, 213, 1005-1007.

19. Knauth, L. P., M. B. Kumar, and J. D. Martinez, 1980. "Isotope Geochemistry of Water in Gulf Coast Salt Domes," *J. Geophys. Res.*, 85, B9, 4863-4871.

20. Koster van Groos, A. F. and S. Guggenheim. *Dehydration of K-exchanged Montmorillonite at Elevated Temperatures and Pressures*, Clays Clay Miner. 34, 281-286 (1986).

21. Letter, Marcinowski to Triay. *EPA Approval for Experiments within WIPP.* March 11, 2003.

22. Letter, Swift to McMahon, Stroud, and Hansen. *New Direction for the Organization of the Salt Disposal Investigations Activities.* March 24, 2011.

23. Lundqvist, B., 2001. "The Swedish Program for Spent-Fuel Management," in P.A. Witherspoon and G. S. Bodvarsson, eds., *Geologic Challenges in Radioactive Waste Isolation*, Lawrence Berkeley National Laboratory report LBNL-49767, pp. 259-268.

24. Matalucci, R.V. 1987. *In Situ Testing at the Waste Isolation Pilot Plant.* SAND87-2382. Albuquerque: Sandia National Laboratories.

25. McKinley, I., P. Zuidema, S. Vomvoris, and P. Marschall, 2001. "Swiss Geological Studies to Support Implementation of Repository Project: Status 2001 and Outlook," in P.A. Witherspoon and G. S. Bodvarsson, eds., *Geologic Challenges in Radioactive Waste Isolation*, Lawrence Berkeley National Laboratory report LBNL-49767, pp. 269-276.

26. Meunier, A., Velde, B., and Griffault, L. (1998) *The Reactivity of Bentonites: A Review. An Application to Clay Barrier Stability for Nuclear Waste Storage. Clay Min.*, V33, pp 187-196.

27. MIT, 2011. The Future of the Nuclear Fuel Cycle, ISBN 978-0-9828008-4-3.

28. Mosser-Ruck, R., Cathelineau, M., Guillaume, D., Charpentier, D., Rousset, D., Barres, O., and Michau, N. (2010) *Effects of Temperature, pH, and Iron/Clay and Liquid/Clay Ratios on Experimental Conversion of Dioctahedral Smectite to Berthierine, Chlorite, Vermiculite, or Saponite. Clay and Clay Min.*, V58, # 2, pp 280-291.

29. National Academy of Sciences – National Research Council. *The Disposal of Radioactive Waste on Land.* Washington, D.C. September, 1957.

30. National Academy of Sciences – National Research Council. *One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*. 2003.

31. National Academy of Sciences – National Research Council. *Waste Forms Technology and Performance: Final Report*, Committee on Waste Forms Technology and Performance; National Research Council, ISBN: 0-309-18734-6, 2011.

32. Pfeifle, T. W., and L. D. Hurtado, 1998. "Permeability of natural rock salt from the Waste Isolation Pilot Plant (WIPP) during damage evolution and healing," *Int. J. Rock. Mech. Mining Sci. Geomech.*, 35, 4, 637-638.

33. Rempe, N.T. 1998. "Negligible Environmental Consequences of Confined Underground Nuclear Detonations as Positive, Beyond-Worst-Case Analogues for Deep Geological Waste Isolation." *International Conference on Radioactive Waste Disposal. DisTec'98*. Hamburg, Germany. ISBN 3-98066415-0-3.

34. Roedder, E., 1984. "The fluids in salt," *American Mineralogist*, 69, 413-439.

35. Roedder, E., and H. E. Belkin, 1979a. "Application of studies of fluid inclusions in Permian Salado salt, New Mexico, to problems of siting the Waste Isolation Pilot Plant", in McCarthy, ed., Scientific Basis for Nuclear Waste Management, Vol. 1, pp. 313-321.

36. Roedder, Edwin and Belkin, H.E. (1979) *Fluid Inclusion Study on Core Samples of Salt from the Rayburn and Vacherie Domes, Louisiana. United States Geological Survey Open-File Report* 79-1675, 25 p.

37. Roedder, Edwin and Belkin, H.E. (1980) *Thermal Gradient Migration of Fluid Inclusions in Single Crystals of Salt from the Waste Isolation Pilot Plant Site (WIPP).* In C.J.M. Northrup, Ed. Scientific Basis for Nuclear Waste Management, Vol. 2, p. 453-464. New York, Plenum Press.

*38.* Sandia National Laboratories. 2010. US/German workshop. *http://www.sandia.gov/SALT/SALT_Home.html*

39. Schuster, G., 1996. "Resolution Limits for Crosswell Migration and Traveltime Tomography", *Geophys. J. Int.*, 127, 427-440.

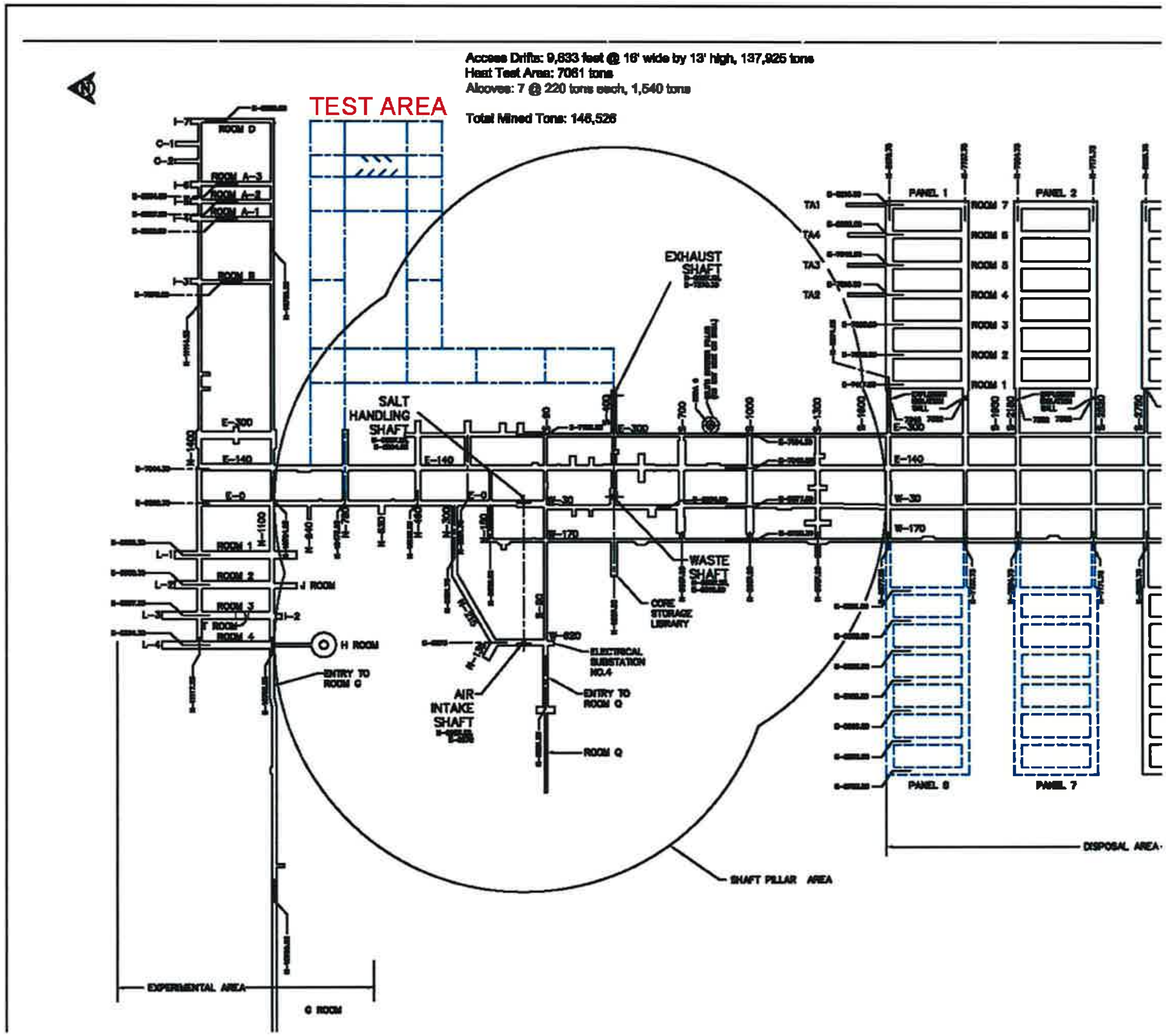
40. Stone, C.M., J.F. Holland, J.E. Bean, and J.G. Arguello. 2010. *Coupled Thermal-Mechanical Analyses of a Generic Salt Repository for High Level Waste*. Salt Lake City: American Rock Mechanics Association

41. U.S. NRC, 10CFR Part 51, V. 75, No. 246, Dec. 23, 2010. "*Consideration of Environmental Impacts of Temporary Storage of Spent Fuel After Cessation of Reactor Operation".*

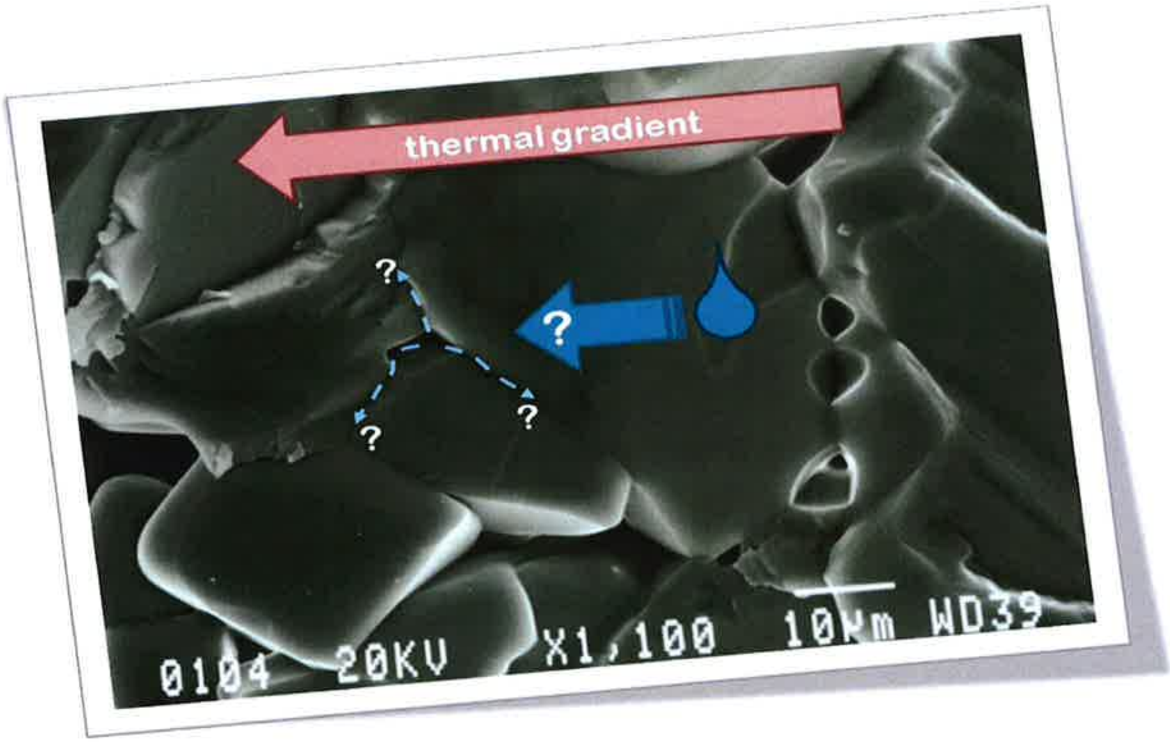
42. Vidal, O., and Dubacq, B. 2009. *Thermodynamic Modeling of Clay Dehydration, Stability and Compositional Evolution with Temperature, Pressure and H2O Activity*.

43. Wu, T.C., Bassett, W.A., Huang, W.L., Guggenheim, S., and Koster van Groos, A.F. (1997). *Montmorillonite Under High H2O Pressure; Stability of Hydrate Phases, Rehydration Hysteresis, and the Effect of Interlayer Cations. Am Min*, V82, pp 69-78.

## APPENDIX A - PROPOSED AREA WITHIN WIPP FOR THE SDI HE



## APPENDIX B – THE NEED FOR SALT DISPOSAL INVESTIGATIONS AND FIELD TESTS (developed June 29, 2010)




### Introduction

> **A science-based research program that will enable DOE to guide America's rational decision on future nuclear waste disposal options**

This brief memorandum recaps some of the reasons that salt research is timely and of national interest. The proposal submitted to the DOE Office of Nuclear Energy (NE) and Office of Environmental Management (EM) senior management in February 2010 outlines a clear process of advancing salt repository science beyond the work done in the 1960s through the 1980s. The United States has not advanced the notion of defense high-level waste (DHLW) disposal in salt since these programs were abandoned more than 20 years ago. Given the current environment in the U.S. regarding future repositories, this missive evaluates historical information, describes the gaps in our knowledge and then advances an argument describing the need for a science-based research program that will enable DOE to guide America's rational decision on future nuclear waste disposal options.

The administration's intent to reevaluate long-lived radioactive waste disposal in America, as evidenced by the recently appointed Blue Ribbon Commission on America's Nuclear Future, has motivated DOE to research geologic disposal solutions that do not directly link spent fuel retrievable storage with the permanent disposal of HLW. Isolation in salt clearly remains a robust geologic solution. Future considerations by DOE on decay and disposal of commercial high-level waste fractions from recycling will benefit from research proposed to resolve the few remaining key questions about thermally hot radioactive waste isolation in salt. These investigations will necessarily leverage earlier work and build on an existing considerable knowledge base about HLW storage and disposal in salt.

**Why This Research Is Needed**

Public understanding and confidence in permanent isolation of radioactive waste in salt have improved as a result of a decade of successful disposal operations at WIPP. Directed research and collaboration with international salt repository programs can help reduce identified uncertainties regarding thermally-driven processes involved with radioactive decay and disposal in salt and therefore further increase technical understanding for these potential missions. The proposed work will build upon a foundation of excellence in salt repository applications that began with the 1957 National Academies of Science recommendation to use salt for permanent isolation of radioactive waste from the biosphere.

| Year | Project | Location | Description |
|---|---|---|---|
| 1965-1969 | Lyons mine, Project Salt Vault | Lyons, Kansas | Irradiated fuel & electric heaters |
| 1968 | Asse salt and potash mine | Germany | Electric heaters |
| 1979-1982 | Avery Island | Louisiana | Brine migration |
| 1983-1985 | Asse (U.S./German cooperative) | Germany | Brine migration under heat & radiation |
| 1984-1994 | WIPP | Carlsbad, New Mexico | 1. DHLW Mockup<br>2. DHLW Over-test<br>3. Heated axisymmetric pillar test |

**Table B-1. Summary of in situ salt thermal tests**

Table B-1 summarizes the history of in situ salt thermal tests both in the U.S. and internationally over the past 50 years. A more detailed description of each program can be found at the end of this paper. Despite this foundation, there are a number of important gaps in scientific understanding of the thermo-mechanical and hydrologic-chemical behavior of radioactive and thermally hot waste in a salt medium.

Consider the recent interview with a current member of the Blue Ribbon Commission on America's Nuclear Future, on the subject of waste disposal in salt by Scientific American (August 2009, "*What Now for Nuclear Waste*?", Matthew Wald, pp. 46-53):

> *Salt is nice, in some senses, from a geologic perspective. But if the salt is heated, the watery inclusions mobilize and flow toward the heat, so burying spent fuel there would require waiting until the hot waste products cool down a bit—somewhere around the second half of this century.*

This demonstrates one of many misperceptions about disposal in salt. The interviewee states fluid inclusions migrate toward the heat source under a thermal gradient as a fact, yet there remains great uncertainty in brine and vapor transport.

Previous in situ salt tests related to repository issues and operations were sufficient to advance design for safe disposal of non-thermal TRU waste in salt; WIPP licensing and 10 years of operations have confirmed operational and performance expectations. Field heater tests as outlined in Table B-1 have provided significant benefit to our knowledge of salt behavior, however there are gaps that exist in the past experimental data that need to be addressed. Advanced computer modeling and data gathering techniques used today are vastly superior to the tools available 25 years ago. Regulatory and technical rigor is expected and necessary to form defensible conclusions about the efficacy of salt as an efficient and effective disposal media for thermally hot radioactive waste.

**Things We Don't Know or Understand**

Clearly, laboratory and field studies of the interaction of heat with salt have received attention in the past. However, the upper temperature limit for the thermo-mechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests have been predominantly conducted at room temperature. These past studies have been more than adequate to demonstrate that disposal of TRU waste and moderate areal thermal densities of DHLW in salt are safe and efficient. However, they do not provide the experimental data necessary to form a defensible basis for policy, engineering, and performance assessment of salt outside our experience with TRU waste.

Considering all of the existing experimental data from previous U.S. and German salt investigations, a recent (May 2010) U.S./German Workshop on Salt Repository Research, Design, and Operation began collaborations aimed toward identifying the current state of salt repository sciences. From this workshop, several critical, unresolved issues with regard to salt repositories were identified that should be addressed. The following issues and others will be summarized in the workshop proceedings:

1. Brine migration — Brine inclusions may preferentially migrate up the thermal gradient and corrode waste packages, but the transport process is unclear when inclusions reach inter-grain boundaries, as well as what happens when (if?) vapor phase transport dominates;
2. Buoyancy — Thermally hot waste containers have been postulated to "melt downward," and the entire disposal horizon has been postulated to float upward due to buoyancy;
3. Heat associated with HLW disposal in salt — Heat-generating waste has been characterized in 10 CFR 51 as exacerbating a process by which salt can rapidly deform, which could cause problems for keeping drifts stable and open during the operating period of a repository;
4. Solubility and transport — Radionuclide solubility in high ionic strength brines over wide temperature ranges is much more complex than in unsaturated water, and research is needed to describe leaching and transporting radionuclides;
5. Radiolysis — Further data are needed on the effect of radiolysis and temperature on the speciation of waste constituents, brine chemistry, waste materials, waste packages, and the salt.

A second US/German workshop on geochemistry and radiochemistry in salt repositories will be held in Carlsbad in late summer aimed toward furthering international cooperation and identifying the current state of knowledge and understanding of the chemistry in salt repositories. The product of the two collaborative workshops will guide and support the Salt Disposal Investigations (SDI) direction and focus.

## The Salt Disposal Investigations Proposal

The main reason to immediately conduct salt investigations leading up to and including a full scale in situ heater test is that they will provide critical information on the efficacy and flexibility of salt for the deep geologic disposal of thermally hot radioactive waste, building on the momentum of the success of WIPP. As enumerated in detail in the SDI proposal, the specific investigations will:

- Track moisture movement and vapor phase transport in situ.
- Observe and document fracture healing in situ.
- Measure the salt thermomechanical response.
- Investigate thermal effects on intact salt in situ.
- Study repository interactions with waste container and constituent materials.
- Develop full-scale response for dry, crushed salt.
- Demonstrate a proof-of-principle disposal in salt concept.
- Apply laboratory research to intact and crushed salt.
- Measure the thermodynamic properties of brines and minerals at elevated temperatures.
- Measure the effect of temperature on radionuclide solubility.

## Summary

Underlying the in situ testing and supporting laboratory research is the hypothesis that heat-generating waste can actually be advantageous to permanent disposal in salt. The ~300-year thermal pulse introduced by spent fuel or high-level waste may dry out a moisture halo around emplaced waste and thereafter accelerate entombment and salt healing by thermally activating the creep processes. At the same time, any very long-lived isotopes also present will be permanently encapsulated in a geologic formation that has demonstrably been hydrologically inactive for hundreds of millions of years, thereby potentially precluding the need for engineered barriers, including vitrification for disposal.

Directed research will inform, guide, and ultimately define requisite capabilities for the next generation of coupled multiphysics modeling, which in turn will be instrumental for development of performance assessment methodology. Building on the impressive performance and knowledge base developed for defense TRU waste disposal at WIPP, this research will identify specific requirements for a potentially viable long-term decay storage and deep geologic disposal concept for HLW in salt. These key elements will translate into parameters and phenomena to be measured in a proof-of-principle field test, which crowns the proposed effort. The proposed research, development, and demonstration of salt efficacy for the safe and efficient disposal of thermally hot waste will provide the basis for a repository that can readily isolate **vast** quantities of nuclear waste material, providing a key component of a safe and secure nuclear future for the nation.

**References to Appendix B:**

*US/German Workshop on Salt Repository Research, Design, and Operation*, Hosted by M. Horstemeyer Mississippi State University, A. Orrell Sandia National Labs, F. Hansen

Sandia National Labs, 2010, [http://www.sandia.gov/SALT/SALT_Home.html]

K. Kuhn, *Field Experiments in Salt Formations*, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 319, No. 1545, 1986

A. M. Starfield, *W. C. McClain, Project Salt Vault: A Case Study in Rock Mechanics*, International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, Vol. 10, 1073

R. V. Matalucci, *In Situ Testing at the U.S. Department of Energy's Waste Isolation Pilot Plant*, Tunnelling and Underground Space Technology, Vol. 5, No. 1/2, 1990

F. Hansen, *Assessing Engineered Systems in Geologic Repositories: WIPP, Presented at the Performance Assessment Community of Practice Workshop*, Salt Lake City, Utah, July 13-14, 2009 [http://www.cresp.org/PACOP/index.html]

F. Hansen, *Path Forward Investigations for Generic Salt Repository High-Level Waste Disposal Proof-of-Principle Concepts*, Sandia National Laboratories, Carlsbad, NM. ERMS 549032.

A. Hull and L. Williams, *Radioactive Waste Isolation in Salt; Geochemistry of Brine in Rock Salt in Temperature Gradients and Gamma-Radiation Fields – A Selective Annotated Bibliography*, Argonne National Laboratory, Argonne, IL., ANL/EES-TM-290, 1985

**History of Salt Disposal Research for Thermally Hot Waste**

Previous in situ salt tests related to repository issues and operations were sufficient to advance design for safe disposal of non-thermal TRU waste in salt; WIPP licensing and 10 years of operations have confirmed operational and performance expectations. However, disposal of heat-generating waste in salt gives rise to thermally driven processes that require investigation before a concept for disposal of such waste can be confidently developed. The need for additional, science-based testing to fortify the technical baseline supporting HLW disposal builds upon a considerable data base deriving from historical experiments. For example, field heater tests in salt were conducted in Project Salt Vault in Kansas in the 1960s and in WIPP in the 1980s. These field tests provide significant benefit to our knowledge of salt behavior; however, some gaps can be identified that have not been sufficiently resolved. The requisite studies in the SDI proposal derive from two main focus areas: one area comprises equivocal issues and technical gaps arising or remaining from the historical testing, while the other focus area takes advantage of the significant computational tools and capabilities available today that simply did not exist when the field tests were conducted a generation ago. Building upon past experiences and taking advantage of advanced technology allow the formulation of a solid, task-oriented, progressive proposal to address the remaining issues for HLW disposal in salt. The research, development, and in situ heater test demonstration will specifically provide the basis for decision making concerning long-term decay storage and deep geologic disposal of thermally hot radioactive waste in salt.

The following synopsis includes field experiments in salt formations that started as early as 1965 with Project Salt Vault near Lyons, Kansas, and nearly contemporaneous field testing and demonstration at the Asse salt mine in Germany. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits. The following is a brief history of heated in situ testing in salt:

**1957** The National Academy of Sciences/National Research Council (NAS/NRC) of the United States published a study on radioactive waste disposal on land, proposing for the first time the use of geological formations, especially rock salt.

**1965-69** The first integrated field experiment for the disposal of HLW was performed by Oak Ridge National Laboratory (ORNL) in bedded salt near Lyons, Kansas. This test, named Project Salt Vault (PSV), used irradiated fuel assemblies from the Engineering Test Reactor at Idaho Falls as a source of intense radioactivity, while electrical heaters were placed in boreholes in the floor to simulate decay heat generation of HLW. The tests simulated the heat flowing into the base of the pillar from a room filled with waste with the primary focus on rock mechanics of floor, ceiling, and pillar deformation. These pioneering tests with live spent fuel and simulated electrical heaters produced modest pillar temperatures of less than 50°C. The tests did concentrate on potential structural effects of radiation (there were none). Significant brine accumulation was observed after the electrical heaters were turned off, which initiated the lingering issues of moisture behavior in such a setting. Possible brine inclusion migration and vapor transport phenomena have not been completely resolved by field experiments.

**1968** A field experiment with electrical heaters was performed in the Asse salt mine to investigate the near-field consequences of emplaced HLW. These early experiments on the disposal of HLW at Asse evaluated thermomechanical properties of the Stassfurt Halite. Later on, operational options investigated included vertical borehole disposal of steel canisters and horizontal placement of steel casks surrounded with backfill crushed salt. The system was approved by the responsible mining authority. In all, three large-scale “heater” experiments were performed in the Asse mine, which yielded important data for the validation of material and computer models needed to assess the coupled long-term behavior of rock salt and crushed salt backfill in a salt repository. The Asse experiences provided important lessons and guidance for future testing which can be used in corroborating the lower temperature range of the SDI.

**1979** Also in Germany, the Gorleben salt dome has been investigated since 1979. In 1998, the German government expressed doubts with respect to the suitability of the Gorleben host rock. All exploration activities were halted by the end of 2000, and a moratorium was imposed. The moratorium ends in 2010, so German repository scientists are poised to restart salt repository investigations. Like the salt testing in the U.S., German research provides a wealth of information on salt disposal investigations, which has been and will be considered in collaboration efforts, as described in the SDI proposal.

**1979-82** Brine migration tests were performed by RE/SPEC for the Office of Nuclear Waste Isolation (ONWI) in the Avery Island salt mine in Louisiana. The migration of brine inclusions surrounding a heater borehole were studied on a macroscopic level by investigating gross influences of thermal and stress conditions in situ. Field tests were augmented in the laboratory by microscopic observations of fluid inclusion migration within an imposed thermal gradient. The maximum temperature reached in the field test was only 51°C. Moisture collection was minimal during heating, amounting to grams of water per day. When the heaters were shut off, cooling caused changes in tangential stress, which led to microcracking, opening of grain boundaries, and moisture release. Much of the moisture released was a result of cooling from turning off the heaters, which drastically reversed the thermal gradient; this would not occur in a HLW repository.

**1983-85** A bilateral U.S.-German cooperative Brine Migration Test in the Asse salt mine investigated the simultaneous effects of heat and radiation on salt. This field experiment used $^{60}Co$ sources with a total radioactivity of about 36,000 Ci. Test configuration included four identical heater arrays. The maximum temperature in the borehole was 200°C. Results of this test will be used to guide instrumentation selection and assessment of brine and vapor phase moisture movement in the proposed SDI field investigations. Contemporaneous German research is keenly interested in moisture movement, and they continue to analyze the specific brine and vapor migration experiments. These data and observations will be considered in test configuration, instrumentation, and methodology.

**1984-1990** Three separate simulated heater tests were performed at WIPP: 1) 18W/m$^2$ DHLW mockup; 2) DHLW over-test; and 3) the Heated Axisymmetric Pillar test. The 18W/m$^2$ DHLW mockup and DHLW over-test were designed to identify how the host rock and the storage room respond to the excavation itself and then to the heat generated from waste placed in vertical holes in the drift floor. These field tests imparted a relatively modest thermal load in a vertical borehole arrangement and did not use crushed-salt backfill or explore reconsolidation of salt. These tests were primarily focused on the mechanical response of the salt under modest heat load. Although the results can be used, for example, to validate the next-generation high-performance codes over a portion of the multiphysics functionalities, the SDI disposal concept would need to explore the interactions created by higher heat loads, a horizontal placement and crushed-salt backfill. The Heated Axisymmetric Pillar test involved an isolated, cylindrically-shaped salt pillar and provides an excellent opportunity to calibrate scale effects from the laboratory to the field, as well as a convenient configuration for computer model validation over a small part of the thermomechanical range of interest. These experiments provide a foundation for the low temperature range of SDI investigations, as described in the general proposal.

# APPENDIX C - KEY CONTRIBUTORS TO THE SDI PROPOSAL

## U.S. Department of Energy – Carlsbad Field Office

**Roger A. Nelson – Chief Scientist, Waste Isolation Pilot Plant**
Roger Nelson has almost 40 years of experience managing and conducting environmental programs for public and private sector projects. As Chief Scientist for WIPP over the past ten years, he serves as the project principal technical/scientific advisor. His focus is on identification and development of innovative and cost-effective waste handling, treatment, characterization, packaging, transportation, and disposal technologies. He promotes use of the unique underground environment at WIPP for use as a laboratory for basic science experiments requiring extremely low dose rate background radiation. He also champions WIPP in national and international waste management venues.

## Sandia National Laboratories

**Dr. Frank D. Hansen**
Dr. Hansen has over 30 years of experience in repository sciences and has contributed significant original research in rock mechanics, seal systems, materials, design, and analysis. He is a distinguished member of the technical staff at Sandia National Laboratories, a registered professional engineer, and an ASCE Fellow.

## Los Alamos National Laboratory

**Dr. Ned Z. Elkins**
Dr. Elkins has 35 years of experience in mining salt, potash, coal and metals, mine/refinery design and management, and nuclear waste geologic disposal programs in Nevada and Carlsbad, New Mexico. He managed the underground facility design of testing infrastructure and was responsible for implementation of the overall geotechnical field testing program for Yucca Mountain from 1989 to 1998, and he subsequently managed SNL's WIPP Program Group in Carlsbad from 1998 to 2000. Since 2000, Dr. Elkins has established and manages the Los Alamos Carlsbad Operations and Program Office in support of WIPP and the National Transuranic Waste Program.

**Timothy A. Hayes**
Tim Hayes has over 25 years of experience in actinide science with LANL. His career at LANL has given him experience performing and managing technical operations in a nuclear facility such as: actinide recovery and purification, advanced technology development for nuclear materials disposition and handling, manufacture of actinide-containing components, waste management, nuclear material shipping and transportation, nuclear facility safety basis, and nuclear material control and accountability. He has held management positions as Division Leader of Stockpile Manufacturing, Group Leader of Nuclear Material Security and Accountability, Deputy Group Leader of Radioactive Waste Management, and Team Leader of Actinide Processing and Challenging Waste Disposition.

**Dr. Bruce A. Robinson**
Dr. Bruce Robinson has served as the Program Manager of LANL's Yucca Mountain Project and as the Deputy Division Leader of the Earth and Environmental Sciences Division. In repository science, he was the lead author of the Yucca Mountain License Application section on Radionuclide Transport in the Unsaturated Zone. His personal research interests include: nuclear waste disposal; groundwater characterization and modeling; flow and transport in porous media; and optimization and inverse modeling. He is the author of 50 peer-reviewed journal publications.

**Clifford D. Stroud**
Cliff Stroud has 25 years of experience in nuclear waste geologic disposal programs and management. This has included work abroad, throughout the United States, with the Congress in Washington, D.C., and with each Energy Secretary. He has played a key management role with LANL in decayed storage or permanent isolation of radioactive waste in salt resulting in more than a decade of successful disposal operations at the WIPP.

**Douglas J. Weaver**
Doug Weaver is a mechanical engineer at LANL with nearly 20 years of experience conducting and managing large scale testing programs. He served as the project engineer for a series of thermal tests at Yucca Mountain that included a large block heated test, an underground single heater test, and the largest underground thermal test in the world, the YMP Drift Scale Test. Doug later managed the Yucca Mountain Project Test Coordination Office responsible for all surface-based and underground testing on the Project, including large geotechnical drilling programs and performance confirmation monitoring.

## Washington TRU Solutions

**Dr. Stanley J. Patchet**
Dr. Patchet is a Professional Engineer and Manager of Mine Engineering for Washington TRU Solutions at the WIPP.

## RESPEC

RESPEC Consulting & Services are world experts in the areas of salt mechanics, rock salt testing, and field services. RESPEC's materials testing laboratory is the largest and one of the best equipped laboratories in the world for studying rock salt. Among many notable tests, RESPEC performed the geotechnical engineering characterization for the Deep Underground Science and Engineering Laboratory (DUSEL) in the former Homestake Mine located in Lead, South Dakota. Laboratory tests described in this proposal will likely be conducted in RESPEC laboratories and as such, RESPEC staff provided input and review of the laboratory thermal and mechanical studies section of this proposal.