Review and Evaluation of Salt R&D Data for Disposal of Nuclear Waste in Salt

Fuel Cycle Research & Development

Prepared for
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SUMMARY

This report details the development and interim results of the design, construction, and population of a bibliographic database that catalogs work performed regarding the disposal of nuclear waste in geologic salt. The database contains reference information and abstracts to over 10,000 technical reports, and PDF copies of most reports.

After the construction and population of the database, reports were reviewed and ranked by their applicability to the current and future research into heat-generating radioactive waste disposal in salt. The main portion of the report text is a historical summary of regulations, repository siting in salt, and salt scientific programs in the US and Germany. Section 6 summarizes historical research performed by test type. Appendices detail the development of SITED, the data sources used to populate SITED, and the procedure used to review reports.

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ACRONYMS

AEC	US Atomic Energy Commission (predecessor of ERDA & DOE)
BAMBUS	Backfill And Material Behavior in Underground Salt (Asse test)
BfS	German Federal Office for Radiation Protection
bgs	below ground surface
BMWI	German Federal Ministry of Economics and Technology
CGI	Common Gateway Interface (standard for dynamic HTML generation)
CH	Contact Handled TRU waste
DHLW	Defense High-Level Waste
DOE	US Department of Energy (successor of AEC and ERDA)
DRZ	Disturbed Rock Zone (called EDZ in Europe)
ECD	DOE Energy Citations Database
EDZ	Excavation Disturbed Zone (called DRZ in US)
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Agency (successor to AEC)
ERMS	Electronic Records Management System (SNL WIPP Records Center ID)
HLW	High-Level Waste
HTML	Hypertext Markup Language (text format for web pages)
HTTP	Hypertext Transport Protocol (distribution protocol for web pages)
LAMP	Linux, Apache, MySQL & PHP (software “bundle” used to serve SITED)
LANL	Los Alamos National Laboratory
LWA	WIPP Land Withdrawal Act
MCC	Mississippi Chemical Company (operator of a Carlsbad potash mine)
MIIT	WIPP Materials Interface Interactions Test
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NRC	US Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act of 1982
ONWI	Office of Nuclear Waste Isolation (successor of OWI)
ORNL	Oak Ridge National Laboratory
OSTI	DOE Office of Scientific and Technical Information
OWI	Office of Waste Isolation (predecessor of ONWI)
PDF	Portable Document Format (Adobe Systems file format)
PI	Principal Investigator (project technical lead)
PSP	Plugging and Sealing Program (WIPP in situ test)
QA	Quality Assurance
RCRA	Resource Conservation and Recovery Act
RH	Remote Handled TRU waste
SITED	Salt Investigations Technical Expansive Database

SNL	Sandia National Laboratories
SPDV	WIPP Site Preliminary Design Validation
SQL	Standard Query Language (programming language for databases)
SRDI	Salt Research and Development Investigation
TRU	Transuranic waste (containing elements with atomic number >92)
TSDE	Thermal Simulation of Drift Emplacement (Asse in situ test)
TSI	Thermal/Structural Interactions (WIPP in situ test)
USGS	US Geological Survey
WPP	Waste Package Performance (WIPP in situ test)
WIPP	Waste Isolation Pilot Plant

REVIEW AND EVALUATION OF SALT R&D DATA FOR DISPOSAL OF NUCLEAR WASTE IN SALT

1 Introduction

The Salt Research and Development Investigation (SRDI) is a study funded in May 2012 by the US Department of Energy (DOE) office of Nuclear Energy, related to salt disposal of heat-generating waste. The SRDI project is being performed collaboratively by Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL), including both Carlsbad, NM and primary (Albuquerque, NM & Los Alamos, NM) offices. There are six primary activities involved in the SRDI project:

1. Existing Salt Data Compilation and Assessment,
2. Test Planning for Re-Entry into the North Experimental Area of WIPP,
3. Laboratory Studies,
4. Modeling Studies Related to Salt,
5. International Collaboration, and
6. Salt Instrumentation Development and Test Methodologies.

This report details the development and interim results of SRDI Activity 1, directed primarily by the SNL Carlsbad Programs Group, with support provided by the LANL Carlsbad Office. The SRDI is executing a plan to understand the history and prepare for a future where salt is a disposal medium for heat-generating radioactive waste. SRDI activity 1 involved the design, construction, and population of a bibliographic database for cataloging work that has already been done on the subject. The database is built on a MySQL database using an open-source PHP distribution called Refbase. The database contains reference information and abstracts to over 10,000 technical reports, and PDF copies of most reports. After additional work in fiscal year 2013, the database will also contain electronic versions of data from laboratory and in situ salt experiments relevant to SRDI.

The relevant material included in SITED covers various aspects of research into geologic salt as a host medium for disposal of heat-generating radioactive waste. The research includes laboratory tests, in situ tests, and modeling of the relevant physical processes in salt, including: thermal, geomechanical, hydrological, geological, metallurgical, and geochemical behaviors. Each of these processes is also potentially coupled with other processes, producing combination behaviors (e.g., thermomechanics or poroelasticity).

References are listed at the end of each section in an abbreviated format. When a report has an identifying number (e.g., SAND, ORNL, or OSTI number), then other reference information is not listed in the citation (e.g., conference or journal information). Reports can be found with full bibliographic information in SITED, searching on the identifying report number. All citations given in this report can be downloaded in PDF form from SITED.

The database has been designed, constructed, and populated with references and electronic documents from various DOE-sponsored library sources. The review of the US- and German-based salt research literature in the database is mostly complete. In fiscal year 2013 we will finish the task related to the discovery, acquisition, and reading of electronic data for the tests described in this report.

2 Bibliographic Database Developed for Activity 1

Activity 1 included the design, selection, implementation, and population of an online bibliographic database. This database was initially populated from several DOE sources, and was supplemented during the review process from several external sources. Electronic (PDF) copies of reports are attached to entries whenever available. The records in the database were reviewed and ranked by their potential relevance to the current SRDI project.

The Salt Investigations Technical Expansive Database (SITED) collectively refers to the database software, the web-based interface, and the server used to deliver both the web pages and attached files. The open-source web reference database (Refbase – www.refbase.net) was chosen because it has a simple, intuitive, and powerful interface and best satisfies the design criteria, given the project time and budget constraints.

The database design had several key requirements that led to the selection of the Refbase database software. The requirements for the database and its interface included the ability to:

- access the interface from outside SNL via the public internet;
- allow creation or editing of database records by authorized personnel;
- allow searching/querying existing records by authorized personnel (potentially a different group than those allowed write access);
- allow bulk record import from primary sources;
- allow attachment of multiple files (e.g., PDF, ASCII text, or data) to each record; and
- limit read/write access to authorized personnel.

Several commercial and free open-source alternatives were considered. Refbase was chosen because it fulfilled the above requirements and was freely available as PHP source code for customization to our specific needs when necessary. The database is hosted and the web interface is served from an SNL webserver (https://sited.sandia.gov/sited), which is accessible both inside the SNL intranet, and from any computer with a modern web browser and internet access.

The appendices detail the implementation of SITED (see Appendix B), the data sources used to populate the database (see Appendix C), and the procedure used to review reports (see Appendix D). The next two sections introduce the detailed project descriptions through narrative descriptions of the regulations and siting process history in the US.

3 US Regulatory History for Salt Radioactive Waste Repositories

The Manhattan Engineering District formed in 1941 to develop a nuclear weapon. Actions relating to this and other weapon activities and subsequent nuclear energy research created radioactive materials, some of which were considered unwanted waste. Since only small amounts of waste materials were generated during the early years, not much emphasis was given to practical or consistent disposal methods. Waste products were disposed in trenches, boreholes, pits and canyons. The Atomic Energy Act of 1946 made the government responsible for control and ownership of all radioactive materials, therefore it became the government's responsibility to control disposal of waste materials (US Congress, 1946). The Atomic Energy Act of 1954 later superseded the 1946 act (US Congress, 1954).

In 1955, the government was looking into other disposal methods besides shallow land disposal, when the National Academy of Sciences (NAS) was tasked with analyzing radioactive waste disposal methods. Most waste was liquid, generated from defense programs with some nuclear energy reactor research wastes. It was believed uranium ore was quite limited in availability, which led the government to require all commercial spent fuel to be reprocessed, leading to more liquid waste similar to defense-generated waste. The 1957 NAS report recommended disposal of this liquid waste in salt formations (NAS, 1957). This was reaffirmed in subsequent NAS reports (NAS, 1961 & 1970). Radioactive waste disposal did not get much attention until 1966 when the NAS published a report critical of the government's lack of progress in radioactive waste disposal (NAS, 1966). At that time, the Atomic Energy Commission (AEC) and Oak Ridge National Laboratory (ORNL) were investigating disposal concepts in Kansas that culminated in Project Salt Vault. This project analyzed the behavior of salt and its potential use as a disposal medium (mostly radiation and heat effects). In situ experiments were performed at an abandoned salt mine in Lyons, Kansas between 1963 and 1967, including demonstration of radioactive waste disposal (Bradshaw & McClain, 1971).

However, due to political concerns over the Lyons, Kansas site being used as a "pilot project" and uncertainty with site characterization information related to oil and gas boreholes and solution mining, the site was abandoned in 1972. AEC, ORNL, and the US Geological Survey (USGS) turned their attention to other salt formations as potential locations for further study. In part due to local support to use existing potash mines for radioactive waste disposal, the Delaware Basin was chosen in 1973 for further study. In 1974, two exploratory boreholes were drilled to investigate a site east of Carlsbad.

In 1970 the AEC decided to stop certain waste disposal actions and limit waste types that could continue to be disposed. It was decided to retrievably store waste containing more than 10 nCi/g (nanocuries per gram) of ^{235}U, its daughter products, Pu, and transplutonium radionuclides, until a more suitable disposal option was available (Zerwekh, 1979). Transplutonium radioactive waste is now referred to as transuranic or simply TRU.

In 1975, AEC was split into the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Agency (ERDA) (US Congress 1974a) to separate the regulatory and research branches of the AEC. In 1977 the Department of Energy Act consolidated ERDA with the Federal Energy Administration to create the cabinet-level DOE.

In the 1960's and early 1970's the AEC was responsible for self-regulated management and disposal of radioactive waste. The National Environmental Policy Act (NEPA) of 1969 mandated Environmental Impact Statements (EIS), which also applied to federal disposal facilities (US Congress, 1969). It was not until 1975 that the Environmental Protection Agency (EPA) was tasked to write a generic radioactive waste disposal standard that would be applicable to the government's disposal of spent fuel, high-level waste (HLW), and TRU waste. This standard was not promulgated until 1985 (EPA, 1985).

In 1976 ERDA changed and enlarged its program for management and disposal of HLWs. The National Waste Terminal Storage program was created and run by ORNL, through their Office of Waste Isolation (OWI) (Lomenick, §5.1.3). In 1978, the National Waste Terminal Storage program shifted to the Office of Nuclear Waste Isolation (ONWI), managed by Battelle Memorial Institute, in Columbus, OH.

In 1980, President Carter declared that the safe disposal of radioactive waste generated by defense and commercial activities was a national responsibility. The subsequent EIS specified that DOE would pursue the mined geologic disposal alternative.

In 1980 Congress authorized the Waste Isolation Pilot Plant (WIPP) as a research and development site to demonstrate the safe disposal of radioactive waste generated from US defense activities, exempted from regulation by the NRC (US Congress, 1979). At that time, waste classifications or categories were not well developed. The Atomic Energy Act of 1954 classified radioactive materials as source, special nuclear, or by-product materials (US Congress, 1954). The by-product material was categorized as defense or commercial with respect to its origin and as either high-, intermediate-, or low-level waste with respect to its radioactive characteristics. The government originally intended to dispose of all of these wastes at a "pilot" disposal site, however the 1980 Congressional Act limited the WIPP disposal site to only defense-generated waste (US Congress, 1979). Another part of the 1980 Congressional Act required the government to enter into an agreement with the State of New Mexico to allow for better communication between the parties and to include the state in certain site actions. The first Consultation and Cooperation Agreement was established in 1981 (State of New Mexico, 1981).

DOE published the final WIPP EIS in 1980 (DOE, 1980) and the record of decision was issued in 1981 (DOE, 1981). Construction of the first WIPP shaft was started shortly thereafter.

The Nuclear Waste Policy Act of 1982 (NWPA) was promulgated to develop a disposal facility for HLW and spent fuel (US Congress, 1982). This standard set the responsibilities of the NRC and the EPA for a high-level disposal facility and exempted facilities that were solely used to dispose of defense wastes. The NWPA required analysis and siting activities for disposal in different types of geologic materials. In 1982, DOE chose nine potential HLW disposal sites, seven of which were in salt. By 1986, the list of potentially acceptable repository sites narrowed to three: Deaf Smith County, Texas (bedded salt); Hanford, Washington (basalt); and Yucca Mountain, Nevada (welded tuff). Congress amended the NWPA in 1987, directing DOE to characterize only Yucca Mountain as a potential location, and created the Nuclear Waste Technical Review Board (US Congress, 1987). Another important element of the NWPA was the definitions of high-level, low-level and spent nuclear fuel.

Another important Act to radioactive waste disposal was the Low-Level Waste Policy Amendments Act of 1985 (US Congress, 1985), which defined the responsibilities of the government, the states, the regulator, and disposer, and defined (through reference to NRC regulation) low-level waste. The NWPA and the Low-Level Waste Policy Amendments Act helped define radioactive waste classifications, identified parties responsible for their disposal, and the organizations responsible for regulating their disposal.

The most important WIPP-relevant regulations were the Land Withdrawal Act (LWA; US Congress, 1996) in 1992 and the first promulgation of the EPA's radioactive waste disposal standard (EPA, 1985). The Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level, and Transuranic Radioactive Wastes was published in 1985 and later remanded due to a lawsuit. The LWA reinstated the disposal standard with the exception of the parts applicable to the lawsuit and required EPA to re-promulgate the remanded sections and to develop specific criteria to demonstrate compliance with the disposal standard applicable to WIPP (EPA, 1996). The main intent of the LWA was to withdraw land for the WIPP, task EPA as the regulator, and list tasks the DOE would need to complete before the WIPP could start disposal operations. The LWA limited the WIPP to dispose of only defense TRU waste, set other repository waste limits, and further defined TRU waste. The earlier AEC's definition for TRU waste had radionuclide concentrations greater than 10 nCi/g while the LWA set the limit to greater than 100 nCi/g of alpha-emitting transuranic isotopes, with half-lives greater than 20 years. The LWA also defined contact and remote handled waste types based on the outer waste container's dose rate. Specific curie limits were placed on Remote Handled (RH) waste and the total quantity of transuranic waste that could be emplaced at WIPP was defined as 6.2 million ft^3 (the Consultation and Cooperation Agreement had previously set the RH limit to 250,000 ft^3). The EPA disposal standard outlined the necessary level of protection a disposal system would need to protect the environment, the public, and workers (EPA, 1993). The standard included containment requirements, assurance requirements, and individual protection requirements for a disposal system.

In addition to the radioactive waste regulations, hazardous waste regulations applicable to WIPP waste. The 1976 Resource Conservation and Recovery Act (RCRA) is a Federal regulation applicable to management and disposal of solid waste including hazardous materials (US Congress, 1976; 40 CFR 260-270). The EPA was given authority to implement RCRA and individual states may be granted authority to regulate their state's management and disposal programs. The State of New Mexico has this authority. Hazardous waste is defined by its characteristics, which include ignitability, corrosivity, reactivity, or toxicity. Originally, the DOE argued that the EPA did not have jurisdiction to regulate DOE "byproduct" waste, however after further deliberations conceded that "mixed" defense waste disposal falls under RCRA. Mixed waste has both radioactive and hazardous materials. The WIPP demonstrated compliance with the State of New Mexico's hazardous waste disposal requirements through a permit application that was submitted in 1995 and approved by the New Mexico Environment Department in 1999. With respect to mixed waste, the LWA stated the WIPP waste was exempt from land disposal treatment standards of the Solid Waste Disposal Act (SWDA; US Congress, 1965).

One important element of the LWA required the DOE to comply with other environmental laws and regulations. These laws and regulations included the Clean Air Act and Amendments (US Congress, 1990), the Safe Drinking Water Act, (with exemption) title XIV of the Public Health Services Act (U.S Congress, 1974b), the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (US Congress, 1980), and other applicable Federal laws pertaining to public health and safety or the environment. The DOE was also required to biennially submit documentation of continued compliance with the laws, regulations, and permit requirements described above to the EPA and with the SDWA to the State of New Mexico. The WIPP demonstrates compliance with this requirement in the WIPP Biennial Environmental Compliance Reports (e.g., DOE, 2006).

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Note: US Congress references (i.e., public laws), and EPA and NRC Federal Register references in the regulatory history section are not in SITED, but can be downloaded elsewhere (e.g., the US Library of Congress thomas.loc.gov and the US National Archives Office of the Federal Register archives.gov/federal-register).

4 US Salt Repository Siting Studies

Pierce & Rich (1958 & 1962) presented a summary of late 1950's USGS regional salt characterization work, producing reports that included an inventory of US salt deposits. These studies identified four regions as potentially suitable for a salt-based nuclear waste repository. The salt regions of interest were (see Figure 1 for locations):

- Salina Group bedded salt of the Michigan and Appalachian basins;
- Gulf Coast domal salt;
- Permian Basin bedded salt of southwestern Kansas, western Oklahoma, western Texas, and southeastern New Mexico; and
- The Paradox Basin, primarily in southeastern Utah and southwestern Colorado.

This study was later confirmed by further more detailed studies of salt deposits (Johnson & Gonzales, 1978) and anhydrite deposits (Dean & Johnson, 1989). Strong public objection and lack of state cooperation prevented any significant characterization or research efforts related to radioactive waste disposal in the Michigan and Appalachian Basins of the northeastern US (Lomenick, 1996: §D.2).

Project Salt Vault was a solid waste disposal demonstration in bedded salt performed by ORNL in Lyons, Kansas. The AEC intended to convert the project into a pilot plant for storage of HLW, having prepared an "Environmental Statement" for the site (AEC, 1971). Despite these intentions, the Lyons site was abandoned due to nearby solution mining and questionably plugged oil and gas boreholes. With help from the USGS, ORNL began looking in the Permian basin for a different disposal site in Texas or New Mexico. A location northeast of the current WIPP site was chosen for further study. ORNL cored two exploratory boreholes through the Permian salt at this location (AEC-7 and AEC-8). A major site characterization effort was undertaken by SNL for the Los Medaños area (Powers, et al., 1978). After early geologic complexities and pressurized brine were encountered in the ERDA-6 borehole, the site was moved southwest to its current location.

In the mid-1970's, OWI and later ONWI looked for a HLW Permian Basin salt site in Texas or Oklahoma, since no favorable location was available in Kansas, and the WIPP site in southeastern New Mexico was already planned to be limited to defense-generated waste. After screening studies into several Permian sub-basins, the Palo Duro Basin was selected because it contains salt deposits of adequate thickness and a minimal amount of oil and gas activity (Lomenick, 1996: §K.1).

From 1978 to 1981 several ONWI HLW characterization efforts cored boreholes in different domes and features of the Paradox Basin of western Colorado and eastern Utah (Lomenick, 1996: §D.3). From 1978 through 1985, over 100 Gulf Coast salt domes in east Texas, northern Louisiana, and Mississippi were characterized for consideration as HLW disposal sites, out of the more than 500 known and inferred salt domes (Lomenick, 1996: §G.1.1). More detailed studies considered seven domal salt sites, but by 1985 consideration had focused on Richton and Cypress Creek Domes in Mississippi, Vacherie Dome in northern Louisiana, and Oakwood Dome in east Texas. Richton Dome was finally considered the most favored domal site (Lomenick, 1996: §D.1).

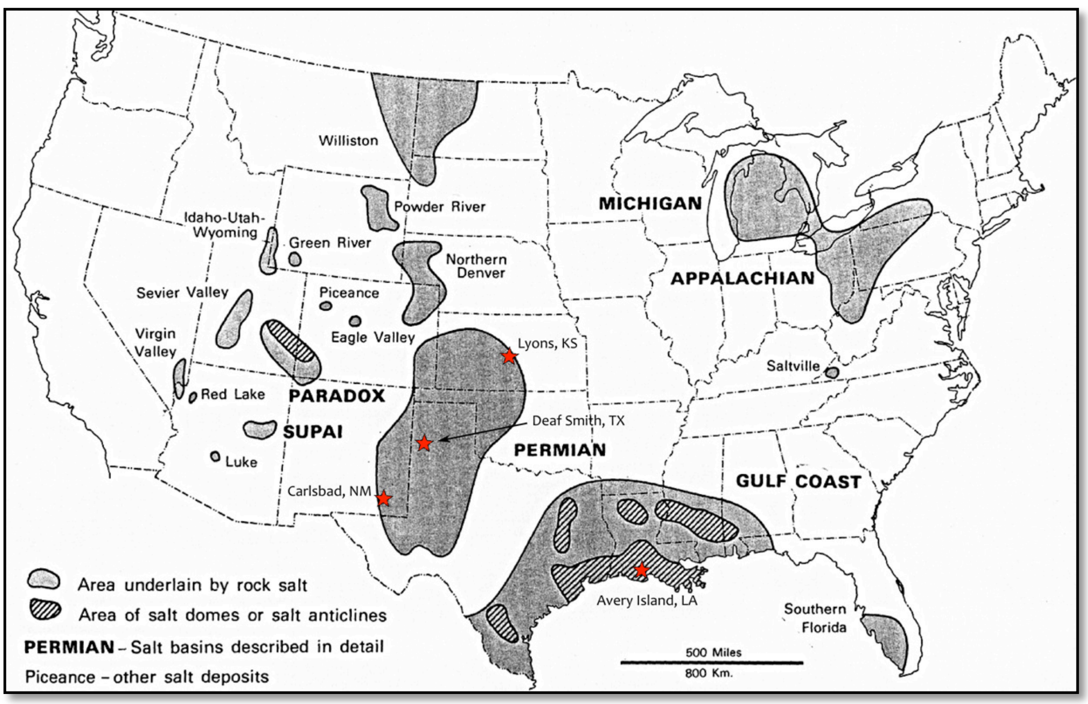

Figure 1. Rock salt deposits in the United States (Johnson & Gonzales, 1978)

In February 1983, the US Department of Energy selected nine potentially acceptable HLW disposal sites (Lomenick, 1996: Appendix G). These nine sites included two non-salt sites (Hanford and Yucca Mountain), and seven domal or bedded salt sites. Of the seven salt sites, two were southeastern Utah locations in the Gibson Dome of the Paradox Basin (Davis Canyon and Lavender Canyon), two were locations in the Palo Duro Basin of northern Texas (Deaf Smith and Swisher), and three were Gulf Coast domal salt sites. The domal salt sites were Vacherie Dome in northern Louisiana and Richton and Cypress Creek Domes in southern Mississippi.

In 1986 DOE reduced the list of nine potentially acceptable HLW sites down to three sites for characterization (Lomenick, 1996: §6.7). The two non-salt sites (Hanford and Yucca Mountain) were chosen, along with the Deaf Smith site in the Palo Duro Basin (US DOE, 1986). In 1987, the Nuclear Waste Policy Act Amendments called for the phase-out of all site-specific HLW activities at all candidate sites other than Yucca Mountain. Defense high-level waste (DHLW) was also comingled with commercial spent fuel and other HLW now destined for Yucca Mountain, and was no longer considered for disposal at the defense-only waste WIPP site.

Salt Repository Siting References

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5 Repository Salt Research Projects

This section begins with a historical summary describing the major salt research projects, followed by short project descriptions with key references in each section. Section 6 groups salt tests of relevance to the SRDI project by type giving pointers back to individual project descriptions in this section.

5.1 Salt Research Historical Summary

Project Salt Vault was the first significant in situ salt research performed in the United States. This was both a research project and a demonstration of solid HLW disposal. In the 1960’s Salt Vault was carried out by ORNL for the AEC in abandoned salt mines in Kansas. Once the Lyons site was rejected as a repository location, focus shifted to the Los Medaños area of New Mexico.

Early heated salt tests were conducted in 1968 at the Asse facility in Germany, while low- and intermediate-level wastes were actively being disposed elsewhere in the abandoned potash and salt mine.

In 1975, SNL became the lead laboratory on the southeastern New Mexico disposal project started by ORNL. SNL continued laboratory salt creep testing, begun by ORNL on salt cores collected from the AEC-7 and AEC-8 boreholes (Mora, 1999). Since limited salt was available for testing from these boreholes, larger samples and tests were sought from the nearby Mississippi Chemical Company (MCC) potash mine. Instrumentation was installed to monitor creep closure of the potash mine workings, and in situ tests were planned. Laboratory tests began immediately on larger salt samples collected from the MCC potash mine to investigate brine migration and the thermal properties of salt (e.g., Salt Block I & II).

In 1978 in situ heated salt tests began at Avery Island for investigation of commercial HLW disposal in salt domes. Laboratory creep and thermal testing of salt samples continued using core from WIPP, Avery Island, and several candidate HLW repository sites. The first underground excavations at the WIPP site were completed in 1981, Site Preliminary Design Validation (SPDV) work by Bechtel continued through 1983, included the first WIPP closure measurements and detailed site geology. SNL's work on the WIPP site included contributing to the site design with Bechtel and the development of a significant in situ salt testing program.

In situ tests at the Avery Island and the MCC continued through 1984. These locations were not considered potential repository locations, but because of their immediate availability, they were used as testing locations to both refine underground testing techniques and compare the variability of salt properties across different sites.

The three main in situ research programs at WIPP were Thermal/Structural Interactions (TSI) program, the Waste Package Performance (WPP) program, and the Plugging & Sealing Program (PSP). The plans for these tests were well documented, numerically simulated beforehand using the best available models, and subject to a rigorous peer-review process. As the test designs were finalized, mining of the testing area began with Room D in 1984, and continued through 1986. While mining progressed elsewhere in WIPP, experimental rooms were instrumented and heaters were installed, with the first in situ heater tests (A and B rooms) turned on in 1985.

At the same time the WIPP experimental areas were being excavated, site characterization work was ongoing at the Deaf Smith site in Texas. Although only borehole cores were collected (no shafts were mined), laboratory creep tests were carried out by the ONWI. Heated brine inflow experiments with radioactive sources were also being carried out from 1983 to 1987 at the Asse facility in Germany.

After the 1987 amendment to the NWPA, the Deaf Smith site was abandoned and the only US salt research remaining related to heat-generating waste was DHLW research already ongoing at the WIPP (i.e., TSI tests and DHLW WPP tests) that were now ordered to wrap up as quickly as possible. Salt research related to the WIPP TRU waste mission continued, including the PSP studies (e.g., Room Q brine inflow).

Drift-scale heated salt tests were conducted at the Asse facility from 1990 to 1999. These tests were followed up by a significant laboratory testing program (BAMBUS II), dedicated to the post-mortem analysis of the instrumentation and crushed salt around the heated disposal casks.

Hansen & Leigh (2011) give a recent high-level summary of salt work completed to date around the world. They include a vision for future heat-generating nuclear waste disposal in salt, drawing from SNL's role as lead laboratory on the WIPP, Yucca Mountain, and Strategic Petroleum Reserve projects.

Salt Repository References

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5.2 Project Salt Vault, Kansas

Project Salt Vault was a disposal demonstration of high-level solidified radioactive waste in an abandoned Carey Salt Company mine 300 m below ground surface (bgs) in Lyons, Kansas (operational from 1890-1948). The project was started in the early 1960's by ORNL and was funded by the AEC Division of Reactor Development and Technology. The disposal demonstration included the transportation of irradiated fuel from the Engineering Test Reactor at the Idaho Plant (now Idaho National Laboratory) and the development of waste handling processes and disposal infrastructure at the bedded salt mine.

Early ORNL in situ experiments (1961-1962) were performed in a different Carey Salt Company mine in Hutchinson, Kansas. In June 1962, a 2.4 m × 2.9 m room, 0.6 m high, was excavated into a large salt pillar and closure monitored for 214 days. The excavation was subsequently heated to 170° C (initially heated with 11-kW heaters, the power level dropping after the first 40 days when the salt heated up), and monitored another 511 days for room closure (Bradshaw & McClain, 1971: §4.1.1). Additional experiments showed disposing liquid HLWs directly in salt would be impractical due to concerns regarding volatilization and containment (Bradshaw et al., 1964). This set of experiments in part led to the realization that liquid HLWs must be solidified before disposal. The NAS panel had considered disposal of liquid wastes directly in salt to be the most promising option, with solidification of waste a secondary option (Lomenick, 1996: §2.1.2).

Experiments in the Lyons Carey mine were designed to determine the structural, chemical, radiological, and thermal waste impacts in a bedded salt environment. The bedded salt in the Carey mine had significant quantities of non-salt components, including shale layers. Laboratory tests in Project Salt Vault included experiments on:

- lab-scale (40 cm diameter) heated compression of model salt pillars;
- temperature and radiological impacts on salt material properties;
- corrosion studies on thermocouples, heaters and canisters;
- measurements of salt brine content; and
- temperature-induced brine inclusion migration.

Results from laboratory tests were reported in the rock mechanics literature (Lomenick & Bradshaw, 1969a & 1969b; Bradshaw & Sanchez, 1969) and in the main ORNL Salt Vault report (Bradshaw & McClain, 1971).

In situ tests included arrays of seven waste canisters in vertical boreholes drilled into the mine floor, which operated from November 1965 to October 1967. Six canisters were placed in a hexagonal pattern around a central heater (see Figure 2). There were two in situ experimental arrays, one with actual waste (canisters surrounded by supplemental heaters) and another array of canisters that only contained heaters. Each 7-heater array had a total power of 10.5 kW, and salt temperatures over 200° C were observed at the borehole-canister interface (Bradshaw & McClain, 1971: §14.11.3). Fuel assemblies were moved between identical sets of boreholes (rooms 1 and 5) to allow them to be changed out twice and to allow the boreholes to be inspected as the heat of the assemblies decayed.

Another in situ test included a rib pillar (between rooms 2 and 3) heated by an array of 22 1.5-kW heaters on the floor around its base for approximately a year (Bradshaw & McClain, 1971: p. 347), to gain information about creep and plastic flow of salt at elevated temperatures. In situ thermal and structural monitoring was conducted in adjacent pillars and the mine floor. Off-gas and condensate systems were monitored during the experiments. Two of the heaters in the rib pillar experiment were operated at a higher power level (3 kW each) for a period of 4 months before the start of the main rib pillar test in October 1966 (Bradshaw & McClain, 1971: §10.5.4.1). These two canisters were made from carbon and stainless steel; the stainless steel heater container failed structurally during the test.

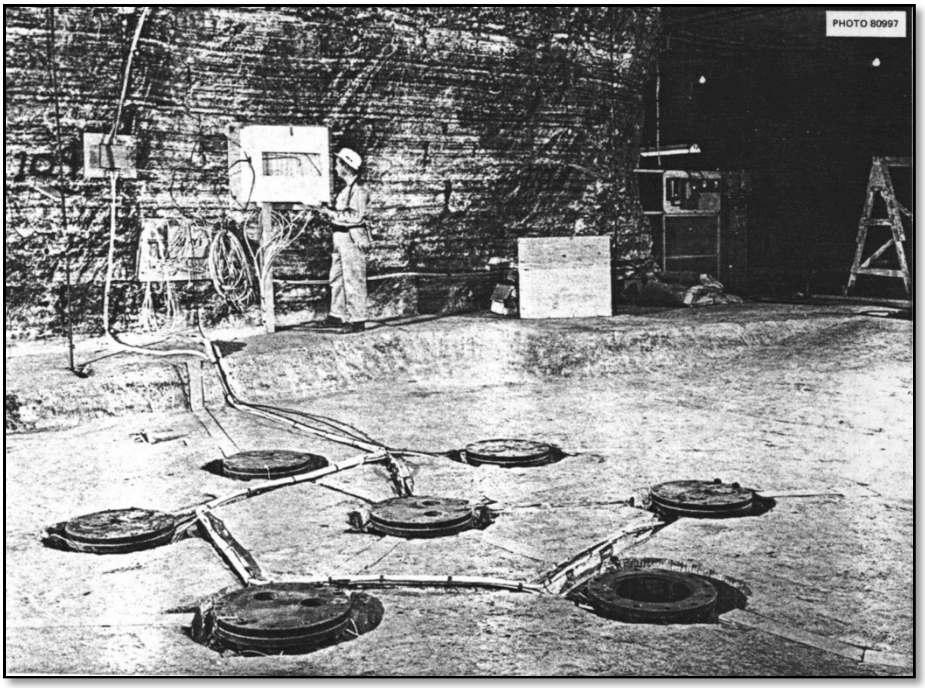

Figure 2. Project Salt Vault heater array (Bradshaw & McClain, 1971)

The Simulated Waste Container Test was a corrosion heater test experiment that was added after encountering corrosion problems with stainless steel canisters in the Modified Pillar Test. Six 4.3-kW heaters were placed into holes in the floor and backfilled with crushed salt. The test was short-lived; the two stainless steel canisters failed within two months, another canister failed within five months. During the operational period, salt temperatures reached as high as 300° C (Bradshaw & McClain, 1971: §10.5.4.2).

Laboratory brine migration studies were performed (Bradshaw & Sanchez, 1969) and off-gas condensate was collected from heated boreholes (Bradshaw & McClain, 1971: §11.2). The large amount of brine collected (35 liters of water in room 5, which had significant shale stringers in the salt) and the increase in brine inflow following shutdown of the heaters were observed but were unexpected (see Figure 3).

Most Salt Vault in situ tests were initiated in November of 1965 and were terminated in October of 1967. Fuel assemblies were returned to Idaho. The demonstration showed the feasibility of high-level radioactive waste disposal in bedded salt.

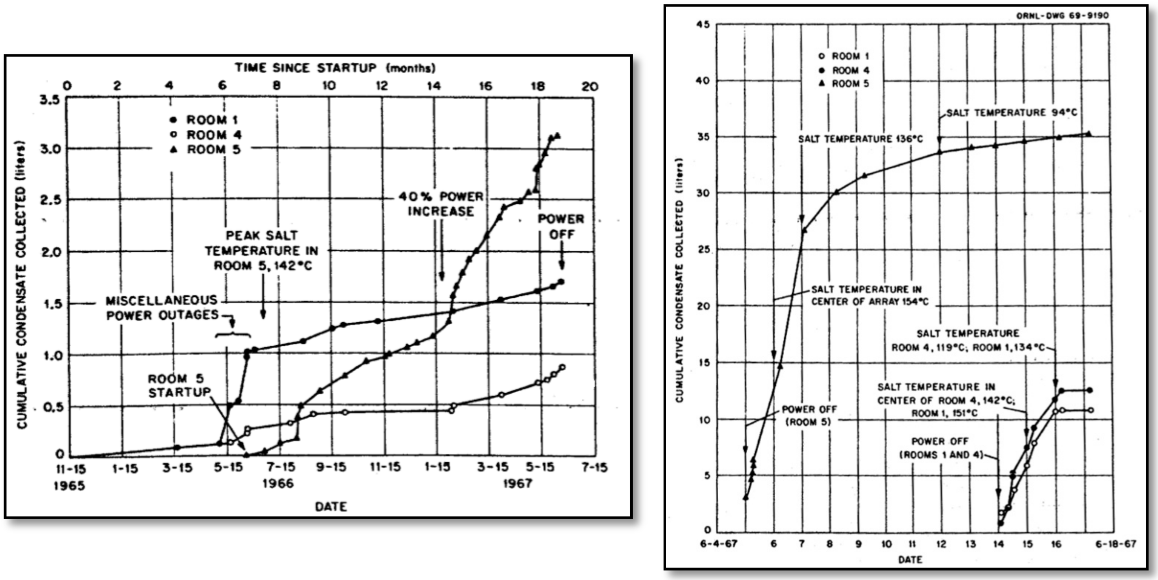

Figure 3. Salt Vault brine condensate results (Bradshaw & McClain, 1971: §11.2)

Salt Vault References

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5.3 Avery Island Salt Dome, Louisiana

Beginning in 1977, The Avery Island salt mine, operated by the International Salt Company in new New Iberia, Louisiana served as the location for a suite of in-situ tests led by OWI and later ONWI (managed by RE/SPEC). The tests provided information regarding the behavior and suitability of salt rock as a disposal medium for high-level civilian radioactive waste. Many laboratory tests were also conducted on Avery Island salt cores (Hansen & Mellegard, 1980; Mellegard et al., 1983; Pfeifle et al., 1983; Senseny et al., 1983). The in situ tests were performed in the uppermost level of the salt mine (169 m bgs). These tests represented a comprehensive testing program that provided:

- a field database for validation of numerical models,
- data to develop an understanding of the response of domal salt to imposed heat and load, and
- instrumentation and testing techniques specifically for use in salt.

The primary in situ studies included heater tests, brine migration studies, corejacking tests, gas permeability studies, and observations of salt creep. These tests were mostly concluded by 1983, with a few providing data for a short time thereafter. The Avery Island tests provided useful information in the development and validation of numerical tools and measurement techniques used later in WIPP in situ tests (see Section 5.6).

5.3.1 Avery Island In Situ Heater Tests

Three simulated waste canister heater tests (Sites A, B & C) were conducted in the Avery Island salt mine, beginning in June 1978. The test measured temperature and displacement (Llewellyn, 1977; Just, 1981; Van Sambeek et al., 1983). Site A was used to estimate domal salt thermal conductivity, having three heat flux meters installed (Wagner, 1982). Sites B and C operated approximately at the heat load expected from HLW spent fuel canisters. Site B used a 3-kW heater, while Site C used a central 4-kW heater and eight peripheral heaters totaling 5.6 kW (see Figure 4) to re-create a regional temperature field due to emplacement of an array of HLW canisters (a total power of 9.6 kW – Waldman & Stickney, 1984). Sites A and B heaters used no backfill next to the heaters (sand below the heaters and rock wool insulation at the hole top), and Site C heater was placed in crushed-salt backfill. All three heater tests operated continuously for over three years without any major equipment malfunctions or interruptions; Site C operated for five years (1858 days). A large quantity of temperature distribution, heat flux, displacement, and stress data were produced by the tests (Van Sambeek et al., 1983; Waldman & Stickney, 1984).

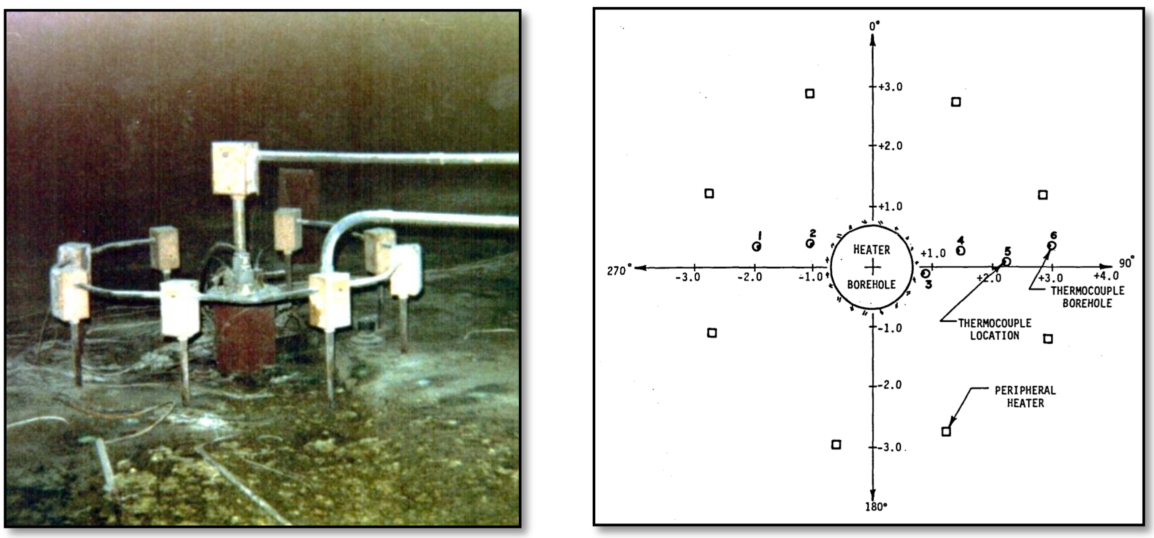

Figure 4. Avery Island in situ heater test at Site C (Van Sambeek et al. 1983)

5.3.2 Avery Island Brine Migration Studies

Dome salt contains between one and two orders of magnitude less water than bedded salt (Shefelbine, 1982). These in situ experiments interrelated field, laboratory, and analytical results for the purpose of determining the rate and amount of brine movement in heated dome salt (Krause & Gnirk, 1982). Three sets of experimental conditions were tested by Krause (1983):

- AB – Natural brine movement under ambient temperatures,
- NB – Natural brine movement under elevated temperatures, and
- SB – Synthetic brine movement under elevated temperatures.

The NB and SB tests used 1-kW resistive heaters similar to the peripheral heaters used at Heater Test Site C. The brine movement was detected by collecting moisture via a nitrogen purging and desiccant extraction system. Results from this series of tests are summarized in Figure 5.

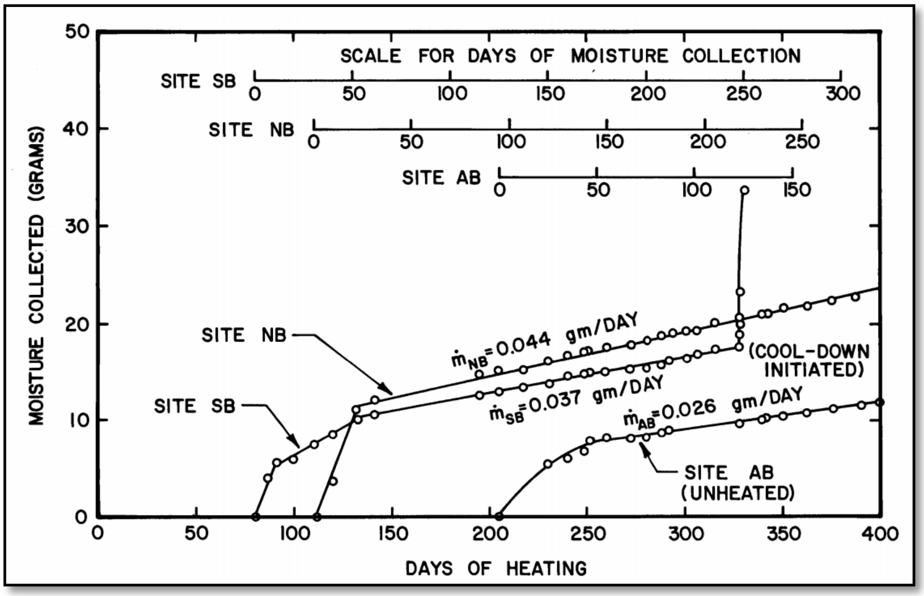

Figure 5. Avery Island brine inflow results (Krause, 1983)

In another set of Avery Island brine inflow tests by SNL (Ewing, 1981) the heating was provided over 138 days by 2-kW electric quartz lamps in a borehole. In these tests 6 grams of brine accumulated in the heater during heating, at an average rate of 0.02 grams/day, with an additional 2 grams flowing into the borehole after shutting down the heaters (Shefelbine, 1982).

5.3.3 Avery Island Accelerated Borehole Closure Tests

The accelerated borehole closure (corejacking) tests measured the time-dependent change in the internal diameter of a hollow cylinder of rock salt subjected to constant pressurization and constant temperature on its external surface (Van Sambeek, 1984; Van Sambeek & Stickney, 1984). External loading of the hollow cylinder was accomplished using two overlapping sets of curved metal flatjacks (corejacks); see Figure 6.The suite of tests consisted of a matrix of ambient and heated conditions (1-kW heaters attached to the corejacks brought the salt to 60° C), combined with ambient, ~11 MPa, and ~15 MPa pressure loads. Tests were performed for various lengths of time, from a few to 328 days. These experimental results were helpful in guiding models refinements (Stickney, 1987).

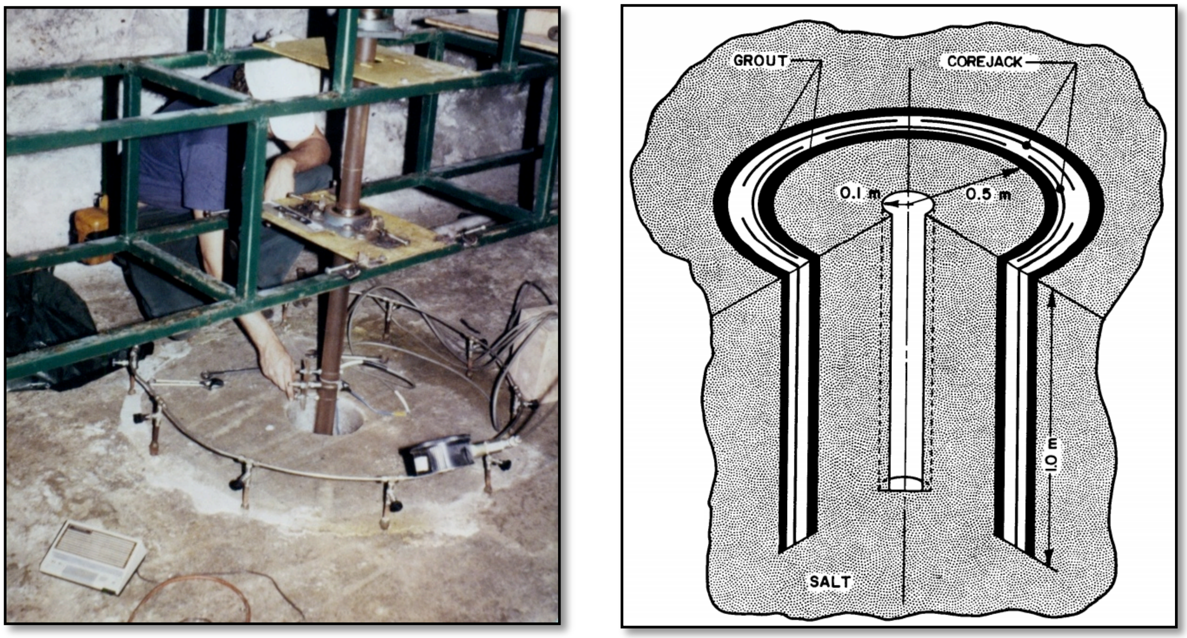

Figure 6. Avery Island corejacking experiment (Stickney, 1987)

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5.4 Mississippi Chemical Company Potash Mine, New Mexico

Prior to the availability of underground access at the WIPP site, in situ heater, brine inflow, and salt deformation experiments were performed in the nearby MCC potash mine (Sattler & Hunter, 1979; Ewing, 1981; Molecke, 1984). The MCC mine is in the McNutt Potash Zone of the same Permian salt formation that WIPP is located in, at a depth of 350 m bgs.

The general objectives of these experiments were similar to those at Avery Island and included:

- evaluation of the thermochemical and mechanical response of bedded salt to heat sources;
- testing package material/salt interactions; and
- evaluation of instrumentation and experiment designs.

5.4.1 MCC Large-Scale Deformation Test

Before 1978 two large-scale instrumented pillar deformation tests were fielded in the MCC Mine (Sattler & Christensen, 1980). These tests not only measured the high rate, large deformation (~1 cm/day closure) of pillars during high extraction (90%) retreat mining, but also served as the test bed for development of geomechanical instrumentation. Newly developed borehole stress meters were first field evaluated in these tests (Cook & Ames, 1979). This field test was SNL's first experience with thermal-structural measurements in the underground environment under mining conditions, and was a valuable training situation for future underground tests.

5.4.2 MCC Heated Brine Inflow Test

A MCC in situ brine-inflow experiment was conducted, using the same equipment as the SNL Avery Island tests, in the same stratum from which Salt Block I and II samples were taken (Ewing, 1981; Shefelbine, 1982). Small water inflow rates were measured to the unheated boreholes up to three months. The heated experiment ran for 113 days, during which 188 grams of water flowed to a 2-kW heater. A relatively large amount of water was collected (87 grams in 16 days), at a rate of 0.4 grams/day observed during the longest uninterrupted operational period. Brine inflow pulses were observed when the heater power was cutoff, increased, or decreased. A power interruption, followed by an episode of overheating around 35 days (observed salt temperatures of 270° C, assumed to be beyond the salt decrepitation point) caused a large spike in water inflow over a short period of time, which overflowed the brine collection system (Ewing, 1981).

Quantities of salt encrustations in the boreholes measured during post-test investigations were consistent with the assumption that all the collected water evaporated from inflowing brine, and inconsistent with the vapor-phase model for brine inflow. Observations about the salt encrustations were generally consistent with both stress-gradient and fluid-inclusion-motion models (Shefelbine, 1982).

5.4.3 MCC Material Interaction Tests

A six-part Waste Package Materials Field Tests (Molecke, 1984) was conducted in the MCC potash mine in 1981 through 1983 (see Figure 7). This series of tests, which exposed metal samples to brine, crushed salt, 1.5-kW heaters, and borehole creep closure, was a direct precursor and practice-bed for the WIPP simulated DHLW experiments in Rooms A1 and B (see Section 5.6.4.1). These tests allowed SNL to develop applicable test emplacement, measurement, and sampling techniques. Thermal conductivity data for backfill materials (including crushed WIPP salt) were also determined from in situ data (Molecke & Torres, 1983).

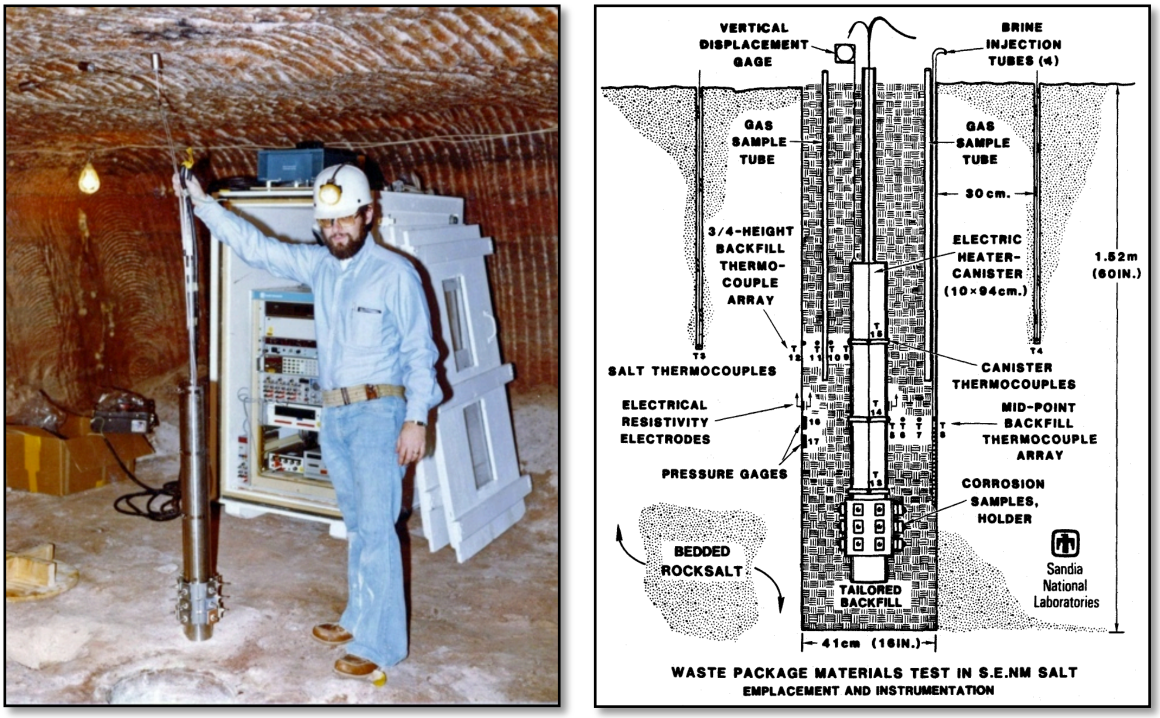

Figure 7. Heater and package corrosion test in the MCC potash mine (Molecke, 1984)

MCC references

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5.5 Deaf Smith Site, Texas

The Deaf Smith, Texas site was a potential civilian HLW site located at in Permian bedded evaporite deposits of the Palo Duro Basin in northern Texas. The site was the one of the potential high-level radioactive waste disposal sites that DOE was analyzing as directed by Congress (DOE, 1986). The goal was to derive site characterization information and develop a conceptual repository design such that an EIS could be developed. Some laboratory creep tests were performed on core collected from boreholes (Pfeifle et al., 1983a & 1983b), but most of the historical information relating to this site consists of planning documents, due to the timing of this investigation. A Congressional act in 1987 removed this site from the list for further consideration. The following describes the planned characterization activities in the site's planning documents. Lomenick (1996) summarizes the early characterization efforts and regulatory milestones associated with the Deaf Smith in his Appendix K.

A draft Deaf Smith site characterization plan (SCP) was completed in January 1988 (DOE, 1988: Volumes 1-10), but no EIS or significant site-specific characterization work was actually completed. The basic purpose of the SCP was to:

- Describe the site, conceptual repository designs, an appropriate waste package, and the waste-emplacement environment in detail.
- Identify uncertainties and limitations identified during site screening, for resolution during site characterization.
- Describe general work plans, including performance confirmation needed to resolve issues, reduce data uncertainties, and make site-suitability findings.

Develop information needed for an EIS and licensing documents suitable for submission to the NRC. Part A (Volumes 1-3) of the Deaf Smith SCP included discussion of the following topics:

- geologic characteristics of the site and the surrounding region;
- geomechanical and thermomechanical properties of the proposed host and rock and its environment;
- hydrologic and hydrogeologic features of the site and surrounding region;
- geochemical, mineralogical, petrological, and hydro-chemical site analyses;
- present and past meteorological and climate data and site analyses;
- models and analyses used in previous and current site investigation activities; and
- preliminary conceptual repository and waste package designs appropriate for existing site knowledge.

Volumes 1 through 3 of the Deaf Smith SCP constituted Part A, which was presented in sufficient detail to prepare the reader for the discussion of proposed site characterization activities in Part B (Volumes 4 through 10).

Volumes 4 through 10 of the Deaf Smith SCP included the detailed site investigation program (Part B). These plans were quite detailed and contained data from other salt disposal programs such as the Asse mine in Germany, the Waste Isolation Pilot Plant, and Avery Island for comparison with the planned Deaf Smith site experimental results.

Deaf Smith References

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5.6 Waste Isolation Pilot Plant Site, New Mexico

The WIPP is located 659 m bgs in Permian salt deposits east of Carlsbad, New Mexico. WIPP is currently an operating repository for TRU waste. It was an active research location for in situ testing of both TRU and defense high-level (DHLW) wastes until 1987, when the mission of WIPP was limited to TRU waste. A large-scale underground testing program resulted in a great deal of data and reports, leading to a new understanding regarding the behavior of bedded salt under repository conditions. The results that may be relevant to the SRDI mission are summarized in this section.

There are several historical accounts of the events and science associated with WIPP. Rechard (2000) gives a brief timeline of WIPP developments and regulatory milestones. Mora (1999) is a longer documentary of WIPP history up to licensing and opening (1974-1999). The National Research Council (1996) has prepared a book that described the research used in WIPP to a wider audience. Matalucci (1988) is a color pamphlet with photos describing the larger WIPP in situ tests, while SNL (1987) is a pamphlet about WIPP science activities prepared for a stakeholder audience.

A large number of in situ salt experiments were conducted in the underground at WIPP from 1983-1995 (Matalucci et al., 1982; SNL, 1987; Munson et al., 1997). Some of these tests were conducted to provide information immediately relevant to the TRU waste WIPP design (e.g., plugging and sealing), while other tests were only relevant to DHLW, and were conducted in WIPP because of the site's availability. Summaries of underground in situ WIPP testing can be found in Matalucci (1988), Tyler et al. (1988), and Munson et al. (1997).Figure 8 shows the WIPP underground facility, locating major experimental locations.

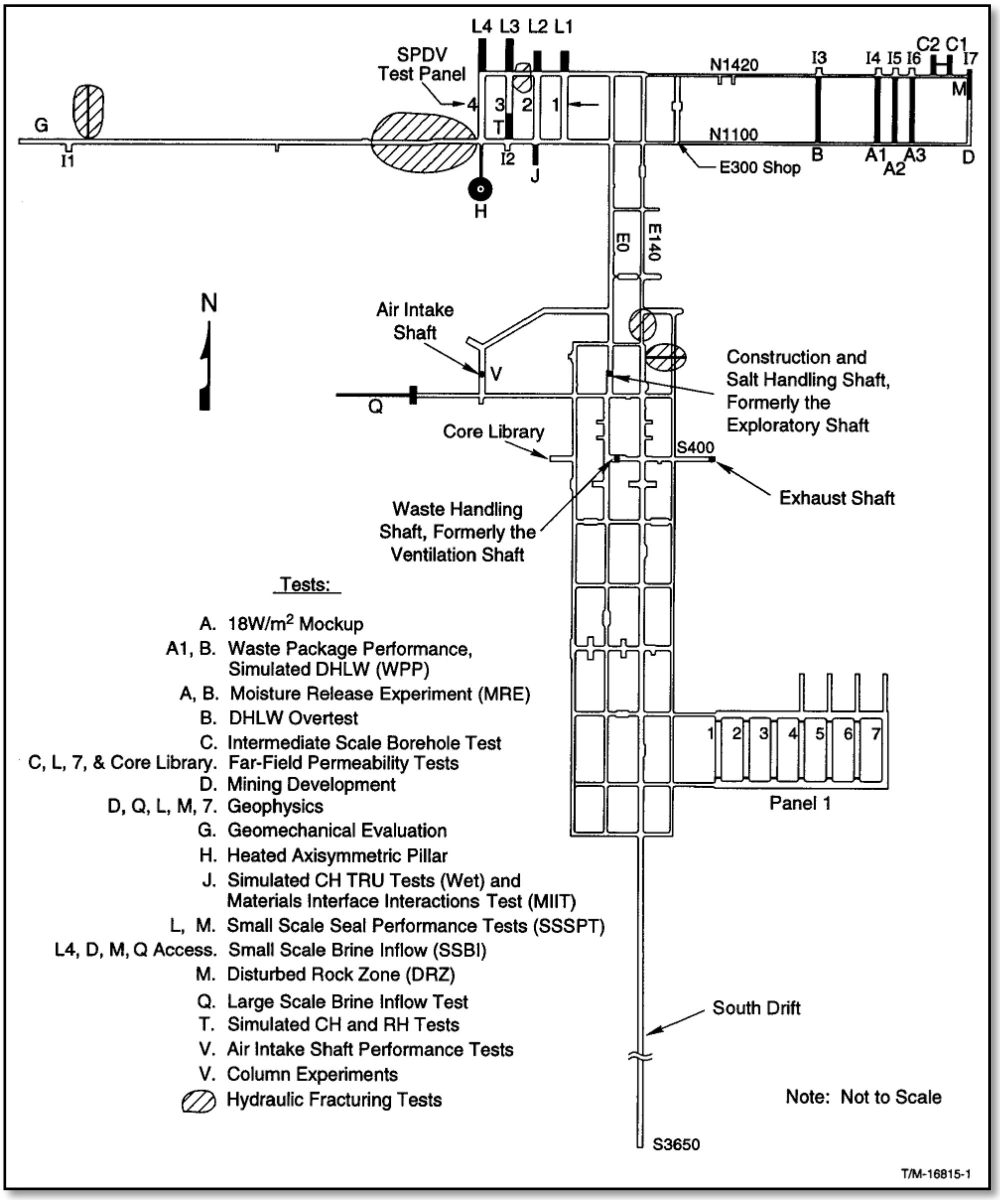

Figure 8. WIPP underground test and experimental areas (Munson et al., 1997)

5.6.1 Quality Assurance/Quality Control for WIPP In Situ Tests

The primary WIPP in situ testing plan was Matalucci et al. (1982), with preliminary testing direction laid out in detail in the Sandia National Laboratories FY79 plan (SNL, 1979). All significant experiments had their own individual test plans, which referenced the main Matalucci et al (1982) report. The quality assurance (QA) program for the group performing the in situ tests was governed by a high-level WIPP QA Program Plan (Romero, 1988). These test planning documents and QA guidelines applied to the laboratory testing, the in situ testing, and modeling exercises done at WIPP.

Summary WIPP References

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5.6.2 WIPP Laboratory Heated Salt Tests

Several laboratory investigations related to heated salt and brine migration were performed, in addition to the creep testing discussed in Section 5.6.3.1. These tests, along with some early in situ tests at Avery Island and the MCC potash mine, are summarized in Shefelbine (1982). In general, domal salt has less water than bedded salt, and non-salt layers can be a large source of water in bedded salt. Laboratory experiments in the late 1970's and early 1980's were conducted with relatively pure salt, and predicted somewhat low brine inflow rates. WIPP brine inflow rates in the PSP (Rooms A1, B, D, and Q, see Section 5.6.5) experienced higher inflow rates than these laboratory tests predicted, in some cases due to geologic heterogeneity and other times attributed to damage-induced heterogeneity. Despite the apparent underestimation of these tests compared to some WIPP in situ tests, their results still clearly explain the macroscopic flow processes in salt. It was previously hypothesized that significant brine migration occurred due to migration of fluid inclusions under a thermal gradient (e.g., Jenks, 1979; Olander et al., 1980), but these tests showed in most cases this was a secondary effect.

5.6.2.1 1-kg Experiment

Hohlfelder (1979) used a salt sample testing apparatus to compare measurements of moisture release from heated salt between three different measurement approaches. The three methods were:

1) weighing the samples before and after heating, equating the change to water loss;
2) purging the sample environment with very dry nitrogen, then measuring the water in the nitrogen outflow using dew-point gages;
3) performing the same purging with nitrogen, but passing the gas through desiccant canisters to compute moisture release, weighing the canisters before and after exposure.

The results of the three approaches agreed to within 10%, validating the approaches used in WIPP and Avery Island in situ moisture release tests.

5.6.2.2 Salt Block I and II Tests

Two meter-sized samples of rock salt were collected from the MCC potash mine. The samples were used in the Salt Block I (Duffey, 1980) and Salt Block II (Hohlfelder, 1980) larger-than-core-scale laboratory tests.

Both tests involved a 1.5 kW central heater in a 1-m cylindrical block of salt. The Salt Block I test was performed to test instrumentation, and verify the isotropy of salt thermal conductivity. Some post-test analyses of brine content were made on samples taken from the large block of salt. The Salt Block II test involved much more thermal, deformation, and brine-release monitoring during the test (see Figure 9), and the block was also destructively analyzed after the test. Brine inclusions within 15-20 cm of the heater were distorted, but inclusions were not the primary source of produced water from the salt (Lambert, 1979).

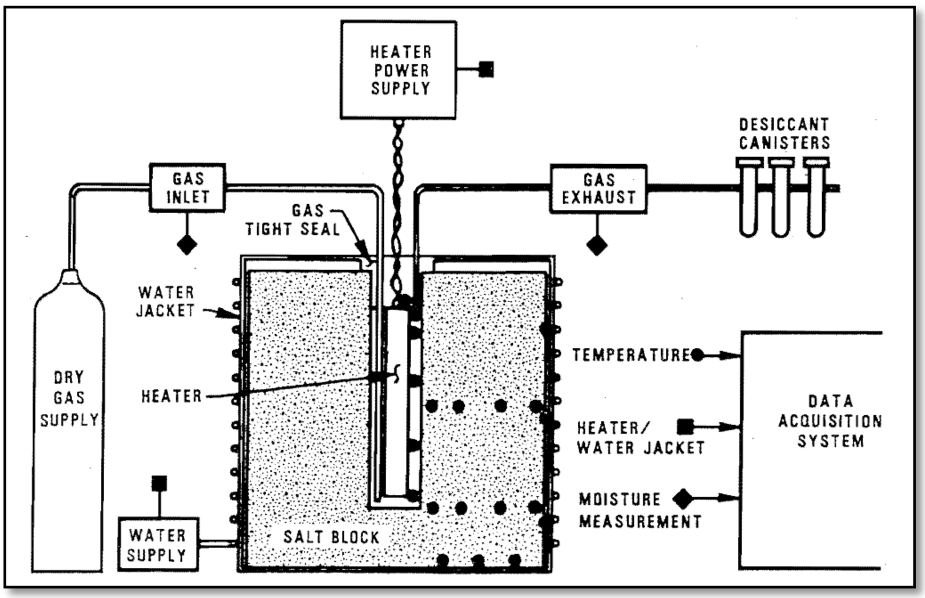

Figure 9. Salt Block II experiment setup (Hohlfelder, 1980)

The results of these two tests also illustrated that the extensive laboratory creep testing with small-scale borehole core samples (e.g., AEC-7, AEC-8, and ERDA-9, discussed in Section 5.6.3.1) were representative of larger scale samples.

5.6.2.3 Salt Decrepitation Experiment

Hohlfelder et al. (1982) recorded water loss and acoustic emissions over 3 days from heating two 1.6-kg cores of rock salt to 200° C. There were increases in brine loss rate at temperature increases and decreases, and there was a large acoustic emission associated with decrepitation (i.e., cracking) of the salt as the water turned to steam. Another increase in brine loss rate occurred as the salt sample cooled, which was accompanied by more acoustic emissions, but acoustic emissions were not as strong as during initial decrepitation. Acoustic emission monitoring was proposed in an unperformed WIPP TSI Room G experiment (the wedge pillar).

5.6.2.4 Thermal Gradient Tests in Smaller Samples

Krause (1981) carried out an experiment on a series of one hundred 5-cm salt blocks. They were exposed to a matrix of different temperatures (125-250° C), thermal gradients, and test lengths (168-528 hours), monitoring the distance brine inclusions traveled and the amount of water released by the sample. The results indicate that more water was given off from the samples than could be explained by brine inclusion migration alone.

Another experiment by Krause (1981) applied a thermal gradient across a thin cylindrical disk of salt, monitoring brine release on both the hotter and colder ends. An equal amount of water was given off on both ends, which is at variance with the hypothesis that brine migrates up-gradient, toward the heat source.

Laboratory Salt Test References

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5.6.3 WIPP Thermal/Structural Interactions Tests

The TSI program consisted primarily of the Rooms A, B, G, and H tests (see Figure 8 for locations), which addressed two main concerns (Munson & Matalucci, 1986). The first concern was stability of excavated rooms during waste emplacement and possible retrieval, while the second concern was long-term disposal room deformation to encapsulate the waste. Stability is a typical mining operation concern, although the storage-room design emphasizes stability instead of mineral resource extraction and is inherently more stable. TSI tests also investigated the effects of heat generated from DHLW. Heat accelerates salt creep and speeds up room closure. The second issue focuses on the creep behavior of salt, its ability to flow under the effects of stress and heat. The TSI tests were designed to provide information about long-term deformation in excavated rooms and overlying rock, which encapsulates the emplaced wastes.

Both thermal and structural interactions play key roles in the performance of an underground disposal site. The TSI tests were designed to validate constitutive models, computer codes, and theoretical predictions. TSI tests were implemented and fielded largely as planned (Munson et al., 1997a). Carrying such large-scale tests out successfully in the field required a range of supporting activities and project management (Matalucci & Munson, 1984; Munson & Matalucci, 1984; Munson et al., 1984). Important construction, testing, and heater-related dates are given in Table 1.

Table 1. WIPP TSI Mining Dates – from Munson et al. (1997a: Table 5.3.1)

Room/Test	Begin Mining	End Mining	Begin Heat	End Heat
Construction and Salt Handling Shafts	7/1981	10/1981		
SPDV South Drift	11/1982	3/1983		
SPDV TRU Test Panel	3/1983	4/1983		
Room G Access Drift Hydraulic Fracture Test #1	12/1983			
Room D	3/1984	4/1984		
Room B	5/1984	6/1984	4/1985	1/1989*
Room A2	6/1984	7/1984	10/1985	6/1990*
Room A1	9/1984	10/1984	10/1985	7/1990*
Room A3	10/1984	11/1984	10/1985	8/1990*
Room G Phase I	11/1984	1/1985		
Room H	1/1985	2/1985	2/1986	7/1995†
Room G Cross Drift Hydraulic Fracture Test #2	2/1986			
Air intake shaft pilot bore	12/1987	2/1988		
Air intake shaft up-reaming	5/1988	8/1988		
Room Q	7/1989	8/1989		
Room C Intermediate-scale pilot and final boreholes	11/1989	12/1989		

* ERMS-308061

† ERMS-410145

The need to benchmark and verify the predictive modeling capability required the generation of a very accurate database from in situ tests. The WIPP in situ tests were developed specifically to address the relevant issues, endorsed through extensive peer review, implemented with rigorous quality assurance practices (Munson, et al., 1989a), and fielded with careful attention to detail. Details regarding instrumentation can be found in Munson et al. (1997b), and details of the data acquisition and management system are described in McIlmoyle et al. (1987), Ball & Shepard (1987), and Ball (1992). Since performance assessment extrapolations are made forward in time thousands of years based upon models verified against in situ data obtained over only a few years, it was clear that the quality and accuracy of the TSI database needed to be the highest that can possibly be obtained from the underground. The critical nature of the database obtained from in situ tests governed the effort to gather good data (Tyler et al., 1988: Chap. 2).

References for the following TSI section are consolidated to the end, in Section 5.6.3.9 on page 34.

5.6.3.1 WIPP TSI Salt Creep Laboratory Testing and Modeling

A principal component of the TSI Program was the laboratory testing effort (Tyler et al., 1988: §2.3). Laboratory tests were the basis for constitutive models and material parameters. Material response data encompassed physical properties (e.g., density or thermal conductivity) and mechanical properties (e.g., creep or quasi-static strength).

The creep of heated salt is a plastic non-linear process; it has been the focus of a large amount of research at WIPP. Laboratory testing of cores was done pre-WIPP from early boreholes, including AEC-7, AEC-8, and ERDA-9 (Hansen, 1976). A comprehensive summary and database of salt laboratory testing is provided in Mellegard & Munson (1996), while a similar database is given by Pfeifle & Hansen (1998) for anhydrite samples. Built upon an early deformation-mechanism map for halite (Munson, 1979; Munson & Dawson, 1979), a large amount of later research went into more realistic constitutive models for the various deformation types. Competing constitutive models were proposed, developed, and refined to explain the different phases of creep under different confining pressures, temperatures, and time scales (Carter, 1983; Morgan & Krieg, 1987; Munson, 1993; Weatherby et al., 1993; Chan et al., 1996; Koteras & Munson, 1996).

In 1981, nine competing numerical models were used to simulate drift-scale closure under WIPP-like conditions. By this point the reference stratigraphy (Krieg, 1984) and conceptual model used for WIPP had incorporated significant non-linear complexity due to the plastic nature of hot salt creep and the inclusion of frictional slippage along clay seams. Two benchmarking exercises were carried out to validate several structural deformation codes against each other (Krieg et al., 1980; Wayland & Bertholf, 1980; Morgan et al., 1981; Callahan & DeVries, 1995), since no analytical solutions exist for benchmarking that can include the necessary complexities, and no WIPP field data yet existed for code benchmarking.

The more formal “parallel calculations” exercise of Munson & Morgan (1985) built upon the experience of Benchmark I and II exercises, and successfully showed the ability of SNL and its contractors to:

- define and transmit modeling test problems;
- assure control over the quality of the inputs to the calculations;
- assure complete independence of the calculations (blind participants); and
- provide a discrepancy resolution process.

The Germans subsequently used the parallel calculations approach in their modeling benchmark exercises (Morgan et al., 1987).

As a policy, physically justifiable parameters were always used (Munson et al., 1989b). Arbitrary adjustment of model parameters was discouraged, when the goal was simply to improve model fit to data. Drift response calculations used state-of-the-art models, often incorporating recent advances in constitutive models.

WIPP in situ experiments were modeled several times before and after data became available. A scoping calculation was the first simulation performed for each in situ test (e.g., Torres, 1986); many scoping calculations were only documented in internal memos (e.g., see references in Morgan & Stone (1985c)). Scoping calculations were used to arrive at experimental configurations. Once each experiment was defined, pretest parametric calculations were performed to assist detailed heater arrangements, instrument selection, instrument ranges, and other test aspects (e.g., Branstetter, 1983; Morgan & Stone, 1985a, 1985b & 1985c). Updated computational models were again used in these calculations. Thus, in the time period between excavation and experiment start-up, the thermal (if applicable) and structural responses of each in situ experiment were computed with the best computational models available. This timing for pretest calculations allowed the as built geometry of the tests to be modeled and also allowed the latest model refinements to be included. Data were analyzed after experiments were complete, using iteratively more refined and realistic (e.g., three-dimensional) models (Arguello, 1989; Munson et al., 1990a; Chan et al., 1996; Hoffman & Ehgartner, 1996).

5.6.3.2 WIPP Site Preliminary Design Validation

Both the planned and unplanned tests in the SPDV area contributed to the TSI database of thermal and structural rock behavior (DOE, 1983a & 1983b). The SPDV South Drift (see Figure 8) was planned as an exploratory drift to the southern extremity of the facility. It was soon realized that the drift was ideally two-dimensional, and it was instrumented for simple closure measurements. These data were the earliest WIPP in situ measurements. South Drift Closure measurements showed previous creep models under-predicted closure by a factor of three, which led to revision of the conceptual and numerical models as TSI tests were running (Munson et al., 1989c).

The SPDV Test Panel (seeFigure 8) was instrumented and data obtained from this test panel formed the basis for the SPDV. Pretest reference calculations were performed by the site architect/engineer (Bechtel) and SNL (Miller et al., 1982; Branstetter, 1983). Measurements were taken in the Construction and Salt Handling Shaft, which have also become a valuable data source for analysis of shaft closure.

5.6.3.3 WIPP Room D (Ventilation Drift)

Although Room D was not a planned TSI test, it was a ventilation drift mined before any of the TSI test rooms (Tyler et al., 1988: p. 91). As a consequence, many of the instrument installations and measurement procedures were developed and tested first in this room (Munson et al., 1992a; Munson et al., 1997a). Therefore, the first TSI measurements came from this room, and they have become part of the in situ test database (Munson et al., 1988). The Room D configuration is identical to an unheated Room B.

5.6.3.4 WIPP TSI Room A (DHLW Mockup)

The 18-W/m^2 DHLW Mockup heated test was developed to simulate reference repository conditions for DHLW. The test consists of three rooms (Al, A2, and A3 – see Figure 10) in a configuration where Room A2 (the center room – see Figure 11) closely simulated the mechanical and thermal stress field of a full repository setting (Munson, 1983a; Eaton, 1984; Morgan & Stone, 1985a). See Munson et al. (1992a & 1997a) for as-built room specifications and Munson et al. (1997b) for a detailed instrumentation description.

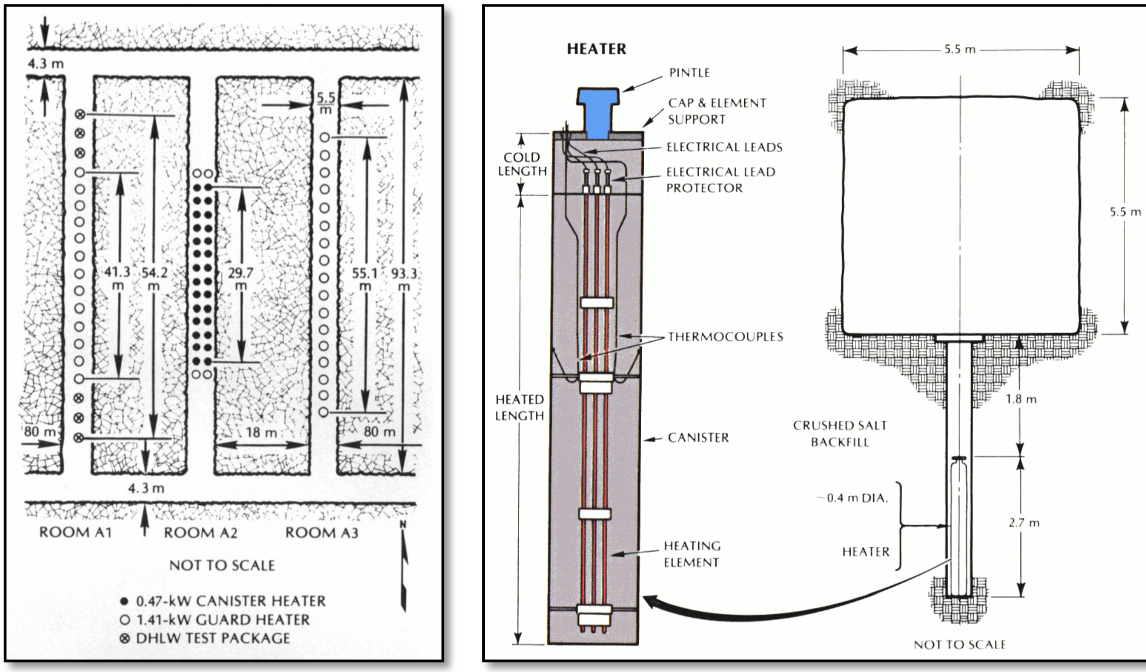

Figure 10. WIPP TSI Room A layout and heater orientation (Matalucci, 1987)

Heaters were installed in vertical boreholes, inside simulated DHLW canisters (see Figure 10). The DHLW Mockup test was the first full-scale prototype repository test in an underground salt environment. The data from this experiment are intended for safety case and repository design (Munson et al., 1991b & 1992c).

The Room A2 reference test configuration contained a double row of 28 0.47-kW reference heaters with four 1.41-kW guard heaters on the ends. Rooms A1 and A3 were guard rooms, used to create the equivalent effect in Room A2 due to a gallery of repository rooms. The thermal load in the guard rooms was created with a single row of 1.41-kW guard heaters. The thermal field produced by this arrangement was intended to closely match the repository thermal field around the central room at early times (about 10 years). All three of the rooms were 5.5×5.5 m in cross section by 93.3 m in length (see Figure 10). The three A rooms were separated by 18-m-wide salt pillars.

Across the three A rooms there were 34 0.47-kW reference heaters and 34 1.41-kW guard heaters, totaling approximately 64 kW of heaters.

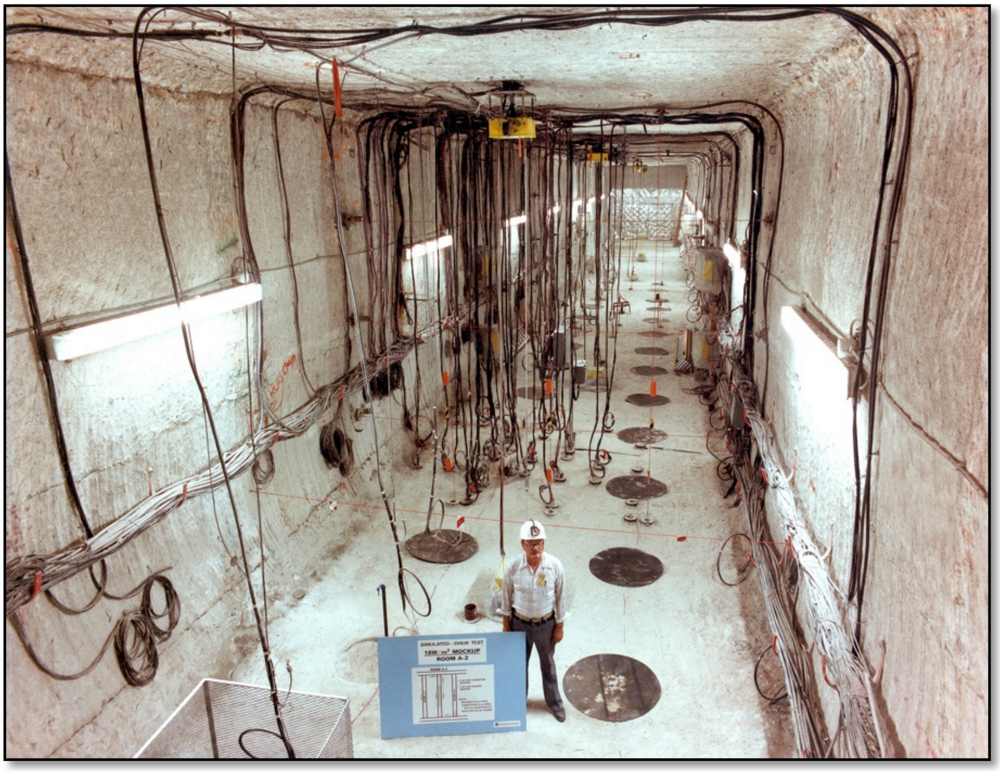

Figure 11. WIPP TSI Room A2

Following the test plan of Munson (1983a), instruments were installed to measure:

- vertical and horizontal room closure;
- temperatures in salt surrounding the rooms and canisters;
- differential deformations of the salt mass surrounding the rooms; and
- stresses (pressures) in the salt mass surrounding the rooms.

Geomechanical and thermal measurements were made from July 1984 until June 1990, when a roof fall occurred (see Figure 12). The in situ data reports of Munson et al. (1991b & 1992c) report the thermal and mechanical data collected.

In addition to the main objectives cited above, this test has also provided valuable data on the geomechanical effects of excavating adjacent rooms (a mine-by experiment). Room A2 was mined first and instrumented before excavations of the adjacent rooms (Munson et al., 1992a). These measurements allow comparison with computer simulations of excavation effects, including stress redistribution and changes in strain rates (Beraun & Molecke, 1987; Wawersik, 1988).

Figure 12. WIPP TSI Room A2 after 1990 roof collapse.

5.6.3.5 WIPP TSI Room B (Overtest)

The DHLW Overtest was an accelerated heater test of the full-scale reference mockup (Rooms A1-A3). The Overtest in Room B increased thermal loading and experienced accelerated room closure and rock-failure modes by increased deformation as the result of creep (Munson, 1983b; Morgan & Stone, 1985b; Beraun & Molecke, 1987). Seventeen 1.8-kW overtest heaters were located in a single row along the centerline of Room B (see Figure 13) with four 4-kW guard heaters at the ends. This arrangement produced a heat flux approximately three times that in Room A2. The canister/salt interface in Room B reached approximately 250°C (Tyler et al., 1988: p. 89).

The Room B configuration duplicated Room A2's cross-sectional dimensions of 5.5×5.5 m; the 17 test canister heaters were spaced at 1.5-m intervals along the axis of the room. Room B also housed 12 waste-package containers, including moisture-release tests, on each end of the central array. See WPP DHLW Experiments in Section 5.6.4.1 and moisture release experiments in Section 5.6.5.3.

In total, Room B contained 17 1.8-kW overtest heaters, four 4-kW guard heaters, and eight 1.5-kW DHLW waste package heaters, totaling 58.6 kW of heaters.

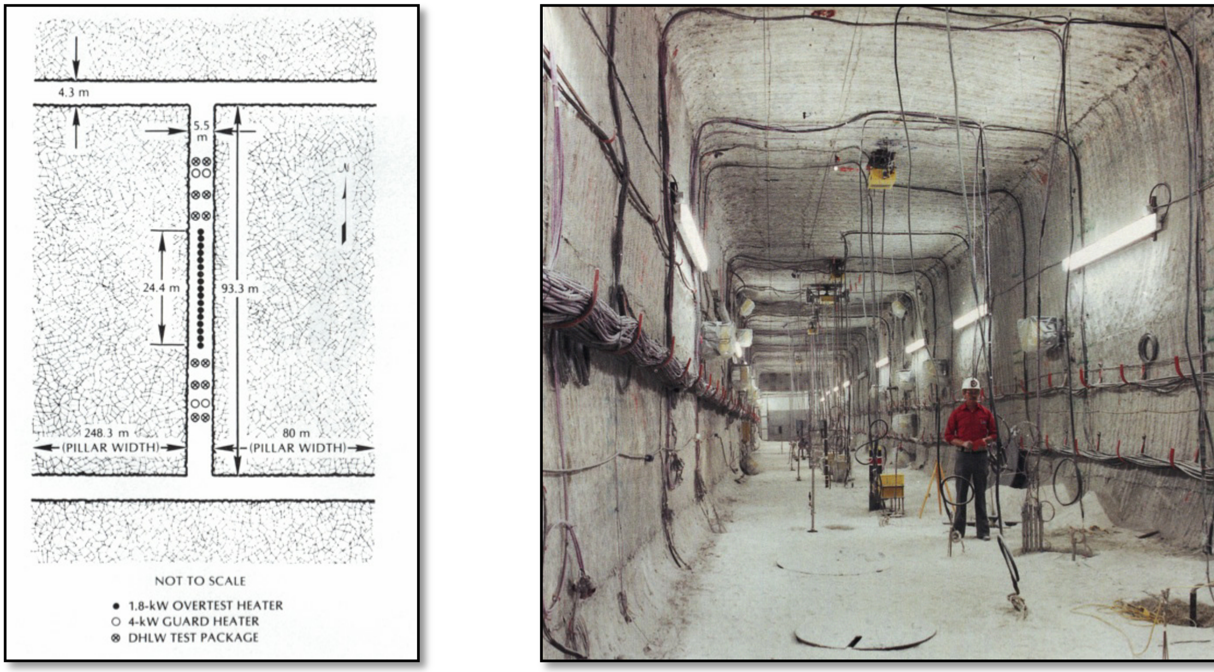

Figure 13. WIPP TSI Room B (Matalucci, 1987)

The canister heaters used in Rooms B and A were mild steel Schedule 80 pipe, selected for its resistance to brine and moisture corrosion. The canisters were cylinders closed on one end by a permanently welded end cap and on the other by a sealed but removable cap (see Figure 10). The removable cap supported the heater elements and internal thermocouples, containing the necessary electrical feeds for power and instrumentation.

Following the test plan of Munson (1983b), the same quantities were measured as in Rooms A1-A3. Measurements in Room B began in May 1984 during the excavation phase, and data were reported through February 1988 (Morgan et al., 1986; Krumhansl et al., 1990; Munson et al., 1990b). Instrumentation details are reported in Munson et al. (1997b).

DHLW test packages were over-cored and removed for materials corrosion testing. The unaffected heaters remained on, but the room was ventilated for worker safety from July 1988 through April 1989 (see Figure 14).

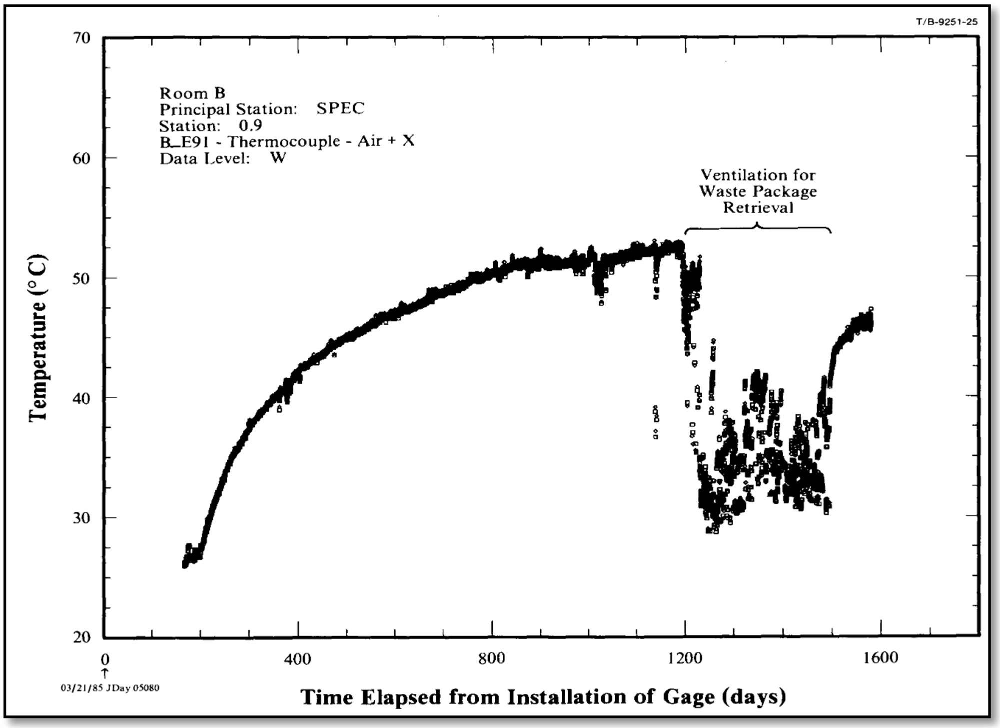

Figure 14. WIPP TSI Room B air temperature time series (Munson et al., 1990b)

5.6.3.6 WIPP TSI Room H (Axisymmetric Pillar)

The Heated Axisymmetric Pillar test was a cylindrically shaped salt pillar 11 m diameter × 3.05 m high (Torres, 1983). This axisymmetric pillar was located in the center of 11 m wide × 3.05 m high excavated annulus (see Figure 15). Room H's large-scale imitation of a laboratory test permitted comparison between calculations based on laboratory data and those based on field data with fewer modeling dimensionality errors (Morgan & Stone, 1985c). Designing the test to approximate the two-dimensional model also allowed the test to focus on rock physics. The test in Room H addressed scale effects in rock response. Satisfactory agreement between measured and predicted response confirmed that laboratory-generated constitutive parameters and models could be applied to large in situ rock masses.

Figure 15. WIPP TSI Room H axisymmetric pillar with and without blankets (Matalucci, 1987)

The test uniformly heated the vertical pillar surface using a blanket heater. The detailed stratigraphy of clay seams, argillaceous salt, anhydrite layers, and polyhalite contents was examined and documented before the test. The blanket heater increased the pillar temperature by about 40°C over 3 years, to about 67°C (Munson et al., 1987).

The blanket heater (see Figure 15) consisted of 3-m long resistive heater tapes with an insulated covering. The heater tapes were hung vertically against the pillar and were spaced evenly around its surface. During normal operation the insulated door to Room H was closed to minimize heat loss and lights were kept off to reduce extra heat sources.

Following the test plan of Torres (1983), installed instruments measured

- vertical and horizontal room closures,
- temperatures of salt surrounding the annulus and pillar,
- differential deformations of the salt mass bordering the room, and
- stresses (pressures) in the salt mass bordering the room.

Deformation and pillar fractures were monitored by displacement measurements and visual pillar surface observations at designated locations. Measurements were made from July 1984 through July 1995. As-built construction is given in Munson et al. (1992a & 1997a), instrumentation is reported in Munson et al. (1997b), and early data are reported in Munson et al. (1987).

5.6.3.7 WIPP TSI Room G (Geomechanical)

The Geomechanical Evaluation test was an unheated TSI test located in Room G. It was planned as a phased mining of a long constant cross-sectional drift (Phase 1), with several un-implemented phases (Phases 2-4) investigating clay seam shear, rooms of variable cross section, and a wedge pillar. Room G was located far enough away from other test rooms and mining operations to avoid being influenced by activities outside the test area (seeFigure 8).

Following the test plan of Munson (1983c), Room G had instrument stations consisting of:

- anchored bolts placed in the floor, ribs, and ceiling to obtain measurements of displacements of the salt and drift closure; and
- pressure cells that measured stress distribution.

The in situ stress test was designed to establish the magnitude of the state of stress in the WIPP salt horizon. This test confirmed the supposition that stress is hydrostatic (Munson et al., 1992b).

The stress-verification tests in Room G consisted of a series of hydraulic fracture tests performed at different depths, in long boreholes drilled horizontally along the axes of drifts, which were subsequently excavated. The first 10.2-cm-diameter borehole was drilled 125 m deep into the Room G access drift. Fluorescent dye was added to the hydraulic fluid to allow easy mapping of the fracture pattern with a black-light source after the drift was excavated (see Figure 16). Examination of the orientation of the major fractures mapped at the face of the excavation indicates the plane of the minor principal stress (Wawersik & Stone, 1984; 1985; Wawersik, 1988). A similar test was carried out as part of the PSP for the anhydrite marker beds below room C1 (see Section 5.6.5.6).

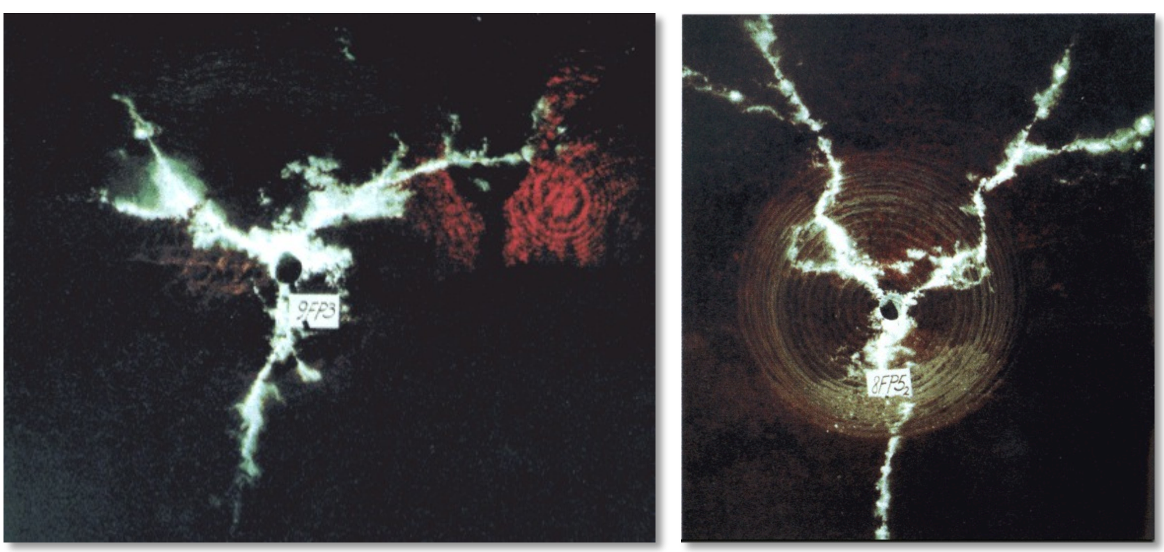

Figure 16. WIPP TSI Room G Fractures observed in hydraulic fracture tests (Matalucci, 1987)

5.6.3.8 WIPP Rooms V and C

Air Intake Shaft Performance Tests in the air intake shaft (Room V – Munson et al., 1991a) and the Intermediate-Scale Borehole Test between Rooms C1 and C2 (Munson et al., 1994) were additional tests added to the TSI program after initial test plans were developed (see Figure 8 for locations).

The Room V tests measured closure at six locations in the salt portions of the air intake shaft, and installed permanent gages at three locations. An apparatus was constructed to install measurement points behind the borehole up-reaming drill as soon as possible, while it was still reaming the pilot bore to its final 6.2-m diameter. The as-built construction of the air intake shaft test is discussed in Munson et al. (1997a), while the data are reported in Munson et al. (1995).

The intermediate-scale borehole test was performed to determine if the discrepancy between modeled and observed drift closure rates were a question of scale. In 1989, a 0.91-m diameter borehole was drilled through the 10-m pillar between Rooms C1 and C2. It was an opportunity to test three-dimensional codes and observe mining effects (Munson et al., 1992a). The as-built construction of the intermediate-scale borehole test is discussed in Munson et al. (1997a), while the data are reported in Munson et al. (1994).

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5.6.4 WIPP Waste Package Performance Tests

The WPP test program was designed to test the effects of the repository environment on containers for CH TRU waste, RH TRU waste, and DHLW (Molecke, 1984; Matalucci, 1984). The program consisted of four different experiments, which investigated the durability and reactions of various containers or container materials (including backfills) in the host rock.

During underground in situ testing, waste packages were an important component in WIPP research, because the container materials were to effectively isolate the wastes for years (5-year retrievability period for TRU wastes; up to 1000 years for DHLW). Although the RH TRU wastes were expected to generate on the average only 30W of heat per 3692-kg-mass container, the reference DHLW canister produced about 0.47 kW of heat from a 2100-kg mass. The waste retrieval requirement was later removed by the Land Withdrawal Act Amendment, which eliminated the test phase requirements for WIPP. Current WIPP performance assessment assumptions do not take credit for the containers' ability to reduce contaminant transport as an engineered barrier. Transportation regulations currently limit the heat load of CH waste to 40 W total for the TRUPAC-II shipping container (14 drums) (DOE, 2009) and RH waste to 0.3 kW total for the 72-B shipping container (3 drums) (DOE, 2010). Waste actually emplaced in WIPP is typically much cooler than this limit; an average RH container in WIPP has a power level of about a watt (DOE 1996: Appendix SCR).

The WPP program determined each container's resistance to corrosion, and how the container materials reacted in a host rock environment when heat, pressure, and local geochemical interactions all exerted their influence on the container. The program was also concerned with the effects of engineered backfill materials emplaced around containers to further restrict the migration of radionuclides to the environment in the event of a container breach.

All references for the WPP section are consolidated to the end in Section 5.6.4.5 on page 44.

5.6.4.1 WIPP WPP Simulated DHLW Experiment (Rooms A1 & B)

The primary purpose of the DHLW Technology Experiments was to evaluate the durability and containment integrity of waste package materials for HLW (Molecke, 1984; Molecke & Matalucci, 1984). In these experiments, 18 full-sized, simulated-DHLW packages were placed in vertical boreholes in both near-reference and overtest repository conditions. The only aspect not simulated in these tests was the radiation field.

The barrier materials evaluated included DHLW canisters and overpacks (304L stainless steel, mild steel, and TiCode-12), backfill barriers (crushed salt, low-density bentonite/sand mixture, and entrapped air), and simulated-DHLW glass waste forms. The assumed preferred method of containing radioactive waste products is to mix them in glass as they are poured into a DHLW container. The glass forms were emplaced in four of the accelerated test canisters.

Six test packages were located in Room A1 (see Figure 10). Each of these packages contained a 0.47-kW heater without DHLW borosilicate glass. Twelve other waste-package containers were emplaced in Room B (see Figure 13 and Figure 17). Eight of these 12 packages contained 1.5-kW heaters. Four packages were nonradioactive DHLW glass-filled canisters, provided by Savannah River Plant and Savannah River Laboratory. To accelerate the degradation processes, some of these 12 canisters were intentionally damaged with slots and holes. Controlled quantities of brine were also injected into the backfill surrounding the canisters to further accelerate degradation.

In addition, small samples of nonradioactive DHLW glass were emplaced in the backfill to assess corrosion of the glass in the WIPP environment. In Room A1, the glass was set next to the waste canisters; in Room B (see Figure 17), the glass was emplaced near the rock-salt/backfill interface.

Interactions between the barriers and the very near-field rock-salt environment (about 1 m) were evaluated. Materials changes included:

- corrosion and changes in the metallurgical properties of metals,
- changes in geochemistry and thermal-physical properties of the backfill material, and
- changes in the chemistry and physical properties for simulated-DHLW glass waste forms.

Figure 17. WIPP WPP Room B DHLW overtest

Several stress variables were considered in evaluating the material properties and changes. Variables included time, temperature, brine content, local geochemistry of the rock-salt environment, pressure, and the combined effects of all these factors.

Test results on materials were obtained during 1988-1989 over-coring and removal of the DHLW WPP packages from Room B and subsequent laboratory analyses (Molecke & Sorensen, 1989; Krumhansl et al., 1991; Molecke et al., 1993). The six waste packages in Room A1 were not removed, and currently remain in WIPP. In situ data were also collected by thermocouples and pressure gages and used in subsequent simulations (Molecke & Beraun, 1986; Beraun & Molecke, 1987a & 1987b).

5.6.4.2 WIPP WPP Materials Interface Interactions Test (Room J)

In the MIIT, a total of 1845 “pineapple-slice-shaped” samples of waste-package materials were placed on electric heaters and inserted into brine-filled boreholes (see Figure 18). MIIT was primarily a series of in situ waste-form leaching tests. The materials were retrieved and examined by surface and solution analyses after 6 months, 1 year, 2 years, and 5 years of exposure, to determine their long-term performance (Molecke & Wicks, 1986). The MIIT program was a joint effort between SNL and Savannah River Laboratory. It evaluated performance of waste glass forms produced in the US, Belgium, Canada, France, Germany, Japan, Sweden, and the United Kingdom.

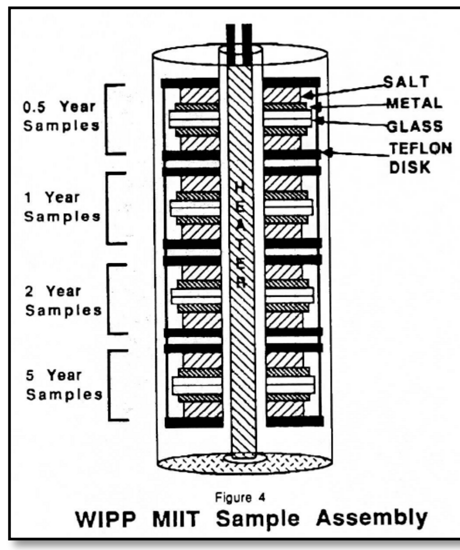


Figure 18. WIPP WPP MIIT test assemblies installed in Room J.

The waste-package materials used in the MIIT included 980 waste-form samples of 15 different compositions. Along with the waste forms, the test included 278 canister or overpack metals (some pre-stressed, others containing pits, and many containing welds) and 587 salt and backfill geologic specimens. The MIIT studied a glass ceramic form, an aluminosilicate form, and a TRU waste glass system as part of the waste-form samples.

The MIIT consisted of two major parts: MIIT-MI (Multiple Interactions) and MIIT-SS (Surface/Solution Analyses). The MIIT-MI assessed wasteform performance as a function of the proposed waste-package components (e.g., glass, metal, rock salt). The MIIT-SS represented the bulk of the test effort and was grouped into three types of experiments:

- simplified interaction between glass and salt;
- interaction between three components (glass, salt, metal); and
- an assembly of large glass cylinders.

The MIIT-SS were the first series of field tests involving nuclear waste glasses where in situ solution analyses was coupled with both bulk and surface analyses of leached waste forms.

The MIIT assemblies were emplaced in Room J on July 1986 into 50 8-cm diameter boreholes, each 1.2 or 2.1 m deep. All tests were kept at 90°C (±5°C), and most were placed in rock-salt equilibrated brine leachant, while four were placed in dry crushed salt. At after 5 years (1991), the remaining samples were removed for final analyses (Covington et al., 1991; Wicks et al., 1991; Molecke & Wicks, 1993; Molecke et al., 1993c; Wicks & Molecke, 1993).

5.6.4.3 WIPP WPP Simulated CH & RH TRU Experiments (Rooms J & T)

The simulated CH and RH TRU waste technology experiments evaluated the durability, corrosion behavior, and crushing of TRU waste containers. In these tests, Room J CH TRU drums were exposed to overtest conditions, while Room T waste packages were emplaced in a normal repository environment (Molecke, 1986; Tyler et al., 1988: § 4.1.1-4.1.2). The containers in both rooms were evaluated for metals durability, alterations, and degradation. Interactions were studied between the containers and several backfill materials.

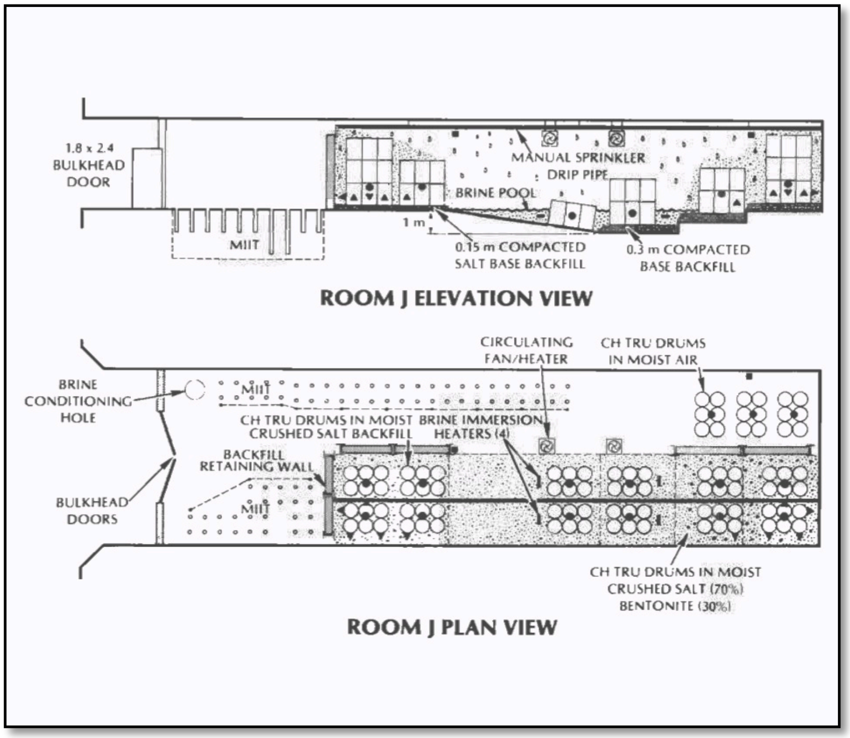
Both Rooms J and T housed separate experiments in addition to the drum evaluation (see Figure 19). Nuclide brine migration tests were performed in the brine pool in Room J, and drum deformation was evaluated in Room T. RH waste containers were only emplaced in the walls of Room T (Arguello et al., 1988; Molecke et al., 1993a).

Room J

Room J's overtest conditions included elevated temperature (40° C) and high humidity. A brine pool created humidity believed to correspond to worst-case accelerated conditions (see Figure 20). Through wicking action, the pool moistened crushed salt and bentonite backfills. A total of 174 CH TRU containers were emplaced in Room J: some were immersed in the brine pool, others were covered by one of two types of backfill (salt and salt/bentonite), and a third group was subject only to humid air.

All of these containers were evaluated for metals durability, alterations, and degradation, including:

- corrosion and metallurgical property changes for metals,
- anticorrosion effectiveness of waste container paint coatings,
- geochemical and thermomechanical changes of backfill materials, and
- interactions between the backfill and the near-field rock-salt environment.



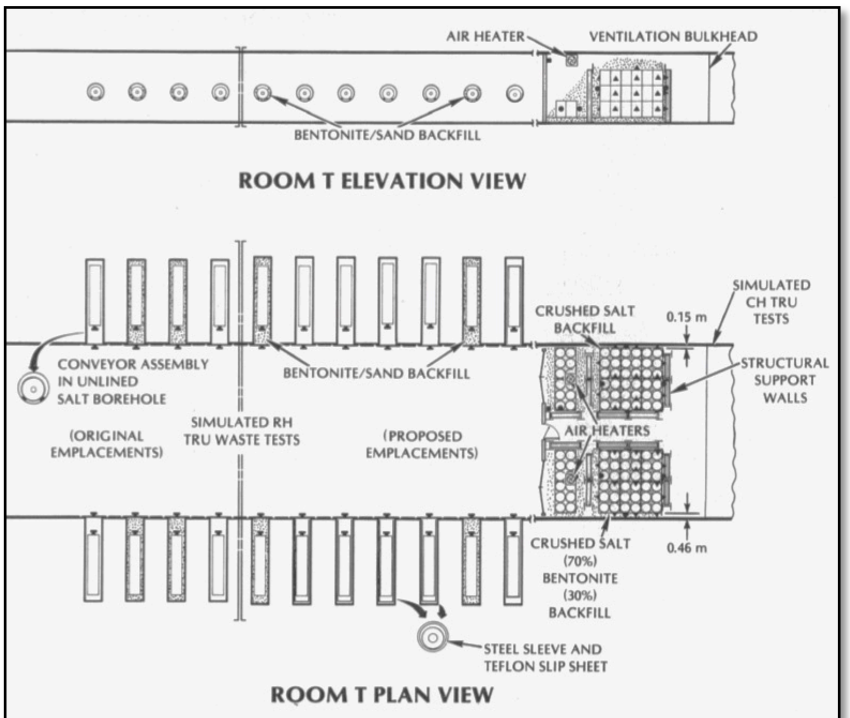


Figure 19. Rooms J and T plan and elevation views (Matalucci, 1988a)

Figure 20. Room J CH TRU CH drums and crushed salt in brine pool experiment

Data were collected through samples, (i.e., periodic backfill cores, TRU container removal, and brine pool sampling), subsequent lab analyses, and in situ instrumentation (Molecke, et al., 1993b).

In addition to container durability, Room J also provided data on near-field nuclide migration. Non-radioactive chemical tracers were used to simulate TRU radionuclides. Tracers were also used to monitor migration or seepage from the drums into the predominantly anhydrite marker bed, located about 0.3 m below the bottom of the brine pool (Tyler et al., 1988: §4.3.3.1.6; Molecke et al., 1993c).

Room T

The Room T reference environment was identical to the rest of the WIPP underground area, except for the hotter CH TRU area. Room T contained 8 RH TRU canisters (14 more were proposed but never installed) and 240 CH TRU drums. The RH TRU containers were emplaced in horizontal boreholes to represent the expected WIPP storage configuration. The CH drums were arranged in six-packs stacked three drums high.

All 8 RH canisters contained an adjustable 0.3-kW electric heater, used to simulate the thermal output of actual RH wastes. The RH canisters were on roller support assemblies in the unlined horizontal boreholes. This emplacement geometry allowed evaluation of effectiveness, ease of emplacement, retrieval techniques, and use of tailored backfills (VandeKraats, 1986). The test measured vertical borehole closure using convergence displacement gages installed between the waste canisters and borehole wall. Temperature measurements were made from installed thermocouples. Moisture-inflow measurements were made by sampling backfill in the boreholes (Molecke, 1992). The RH canisters currently remain emplaced in the WIPP underground.

Figure 21. WIPP WPP Room T backfilled CH canister experiment

The 240 CH TRU waste drums were evaluated for durability, alterations, and degradation similar to that done for the CH TRU drums in Room J. Most of the drums in Room T (and some in Room J) were filled with 150 kg with crushed WIPP salt (Tyler et al., 1988: §4.3.3.1.2). About half of Room T's waste drums were covered with either salt or salt/bentonite backfill (see Figure 21), which remain emplaced in the WIPP underground today. Backfill materials, including crushed salt and a bentonite/salt mixture, were emplaced to surround the drums. Because the reference repository conditions were expected to deform the drums (due to the design for the drum stack and the room geometry), the pressure exerted by room closure on the stacks was monitored using pressure transducers.

5.6.4.4 WIPP WPP Radioactive Source-Term Tests

Several tests involving radioactive sources were planned for WIPP, but none of them were ever realized, due to logistical and political problems obtaining and handling wastes in the WIPP underground. The first major planned radioactive test was a DHLW test in in “Room W.” Different versions of this test were discussed in Molecke & Matalucci (1984) and Matalucci (1988a). After the NWPA was amended in 1987, the test was re-imagined as a TRU waste test (Tyler et al., 1988: §4.1.5), before it was dropped completely.

The bin-scale and alcove tests were designed to investigate waste degradation, gas generation, and waste package interactions for TRU wastes under repository conditions (Molecke, 1990a & 1990b). These tests were planned, initialized, and revised (Lappin et al., 1990), but never executed underground at WIPP. Alcoves north of Panel 1 were mine and outfitted with instrumentation (see location inFigure 8), with some test bins installed (see Figure 22).

Figure 22. WIPP Bin-Scale Test instrumentation in alcove north of Panel 1

5.6.4.5 WIPP WPP Reference

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5.6.5 WIPP Plugging and Sealing Program Tests

The PSP included nine in situ tests and was responsible for developing materials and emplacement techniques for use in plugging shafts, drifts, and nearby boreholes to limit groundwater flow in both the short and long term. The PSP tests were grouped into two major technical areas: (1) characterizing the hydraulic properties of evaporite formations, and (2) developing seal materials and evaluating the seals.

In this report, we review brine inflow monitoring under ambient and heated conditions, a hydraulic fracturing test done in the anhydrite marker beds, and investigations into the reconsolidation of crushed salt. We have not reported the extensive PSP investigations into shaft seal performance, gas and brine permeability measurements, non-crushed salt sealing materials (e.g., salt-based cements, asphalts, and bentonite), and seal integrity testing. This material can be found summarized in Tyler et al. (1988: Chap. 3), Nowak et al. (1990b), and Krumhansl et al. (2000).

All the references for thePSP section are consolidated to the end in Section 5.6.5.7 on page 53.

5.6.5.1 WIPP PSP Crushed Salt Backfill

Prior to 1988, DHLW backfill development focused on assessing performance in the high temperature environments adjacent to canister-sized electric heaters used as surrogates for DHLW containers (Krumhansl et al., 2000: also see Section 5.6.4.1). The in situ tests placed 1.5 kW heaters (surface temperature up to 190° C) in vertical floor holes in the salt, surrounding them with various backfills. In some cases brine was added to the test emplacement to evaluate its impact on canister corrosion and backfill physical properties.

Post-test analyses of the crushed salt backfill from the WIPP DHLW tests were relatively easy. No chemical changes in the rock salt were anticipated and, even when brine was artificially introduced into the backfill, interactions with the mild steel were confined to a skin a few millimeters thick on the canister surface. The mechanical compaction of the crushed salt backfill was more significant. Creep deformation of the borehole walls compressed the backfill and encapsulated the heaters so tightly that it proved difficult to remove samples for post-test analysis. The resulting backfill had less than 1% porosity (Molecke & Sorensen, 1989) similar to undisturbed rock salt.

Early studies on crushed salt reconsolidation revealed that short-term dry compaction only increased density to about 80% of its theoretical maximum (Hansen, 1976; Stinebaugh, 1979; Holcomb & Hannum, 1982; Pfeifle, 1987). Later research demonstrated that adding less than 1% brine by weight accelerated compaction, even at pressures substantially below the 15 MPa lithostatic pressure (Shor et al., 1981). Permeabilities were obtained on the order of 1×10^{-17} m^2 for compacted salt-bentonite mixes (Pfeifle, 1991) and in the range $6\times10^{-18} – 3\times10^{-22}$ m^2 for crushed salt (Brodsky, 1994). Effective barriers were predicted to form in less than a year for crushed salt (Holcomb & Shields, 1987). Fully brine-saturated crushed salt compacts a factor of 10 slower, due to trapping of brine (Zeuch et al., 1991).

Constitutive models have been developed and tested (Sjaardem & Krieg, 1987; Callahan, et al., 1996 & 1998; Callahan & Hansen, 2000) for the consolidation of moistened crushed salt as produced by a continuous miner (Ran & Daemen, 1994). These were an improvement over previous simpler models (Yost & Aronson, 1987). There was a need to simulate the reconsolidation of crushed salt because of its use in repository seal design (Nowak & Stormont, 1987). Material parameters for the models were derived from hydrostatic consolidation tests performed in the laboratory on WIPP crushed salt samples (Holcomb & Shields, 1987; Holcomb & Zeuch, 1988).

5.6.5.2 Brine Release Conceptual Model Development

It was recognized during the 1960's Salt Vault tests that bedded salt is not completely dry (Bradshaw & McClain, 1971: §11.2; Shefelbine, 1982). Although bedded salt does not contain circulating groundwater, it may contain up to 4% water by weight (Roedder & Bassett, 1981). The total amount of water expected to reach buried canisters is small, but for performance and design calculations it is important to quantitatively estimate the amount of water likely to reach waste containers. Several mechanistic conceptual models were initially proposed and developed for long-term brine inflow toward heated excavations in relatively pure salt (Shefelbine, 1982). Pre-WIPP models for brine flow focused on thermally stimulated transport by mechanisms such as:

- motion of brine inclusions under a temperature gradient due to thermal effects on solubility (Jenks, 1979; Olander et al., 1980; Gnirk et al., 1981; McCauley & Raines, 1987);

- vapor phase transport through connected porosity due to the water vapor pressure over heated brine (Hadley, 1981; Hadley & Faris, 1981); and
- liquid transport along connected porosity driven by a salt stress gradient (Shefelbine, 1982).

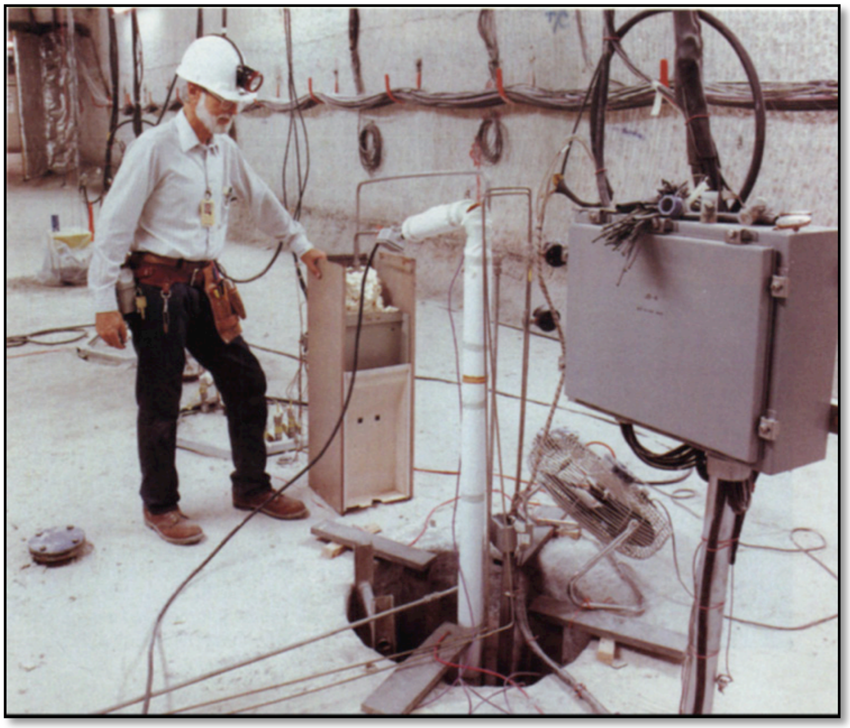
Isothermal darcy flow models for poroelastic media were subsequently developed using data from large-scale WIPP in situ experiments (Nowak & McTigue, 1987; McTigue & Nowak, 1987; Nowak et al., 1988, Hwang et al., 1989; Gelbard, 1992). The models were in good agreement with WIPP in situ brine inflow measurements when pre-excavation pore pressure (hydrostatic) and permeability values (1 to 10 nanodarcies) were used (Stormont et al., 1987; Peterson, 1987). Experimental results revealed nearly constant brine inflows to unheated test boreholes (e.g., Room D) and larger than expected inflows to heated boreholes (e.g., Rooms A1 and B).

With heating, additional darcy flow can be driven by differential thermal expansion of brine and salt. The isothermal model for brine transport was extended to take into account the thermoelastic behavior (McTigue, 1985) that drives flow heated boreholes. A conceptual model was developed and implemented (Nowak & McTigue, 1987; McTigue & Nowak, 1987; McTigue, 1989). A set of independently determined parameters (McTigue & Nowak, 1987) was then used with this model to successfully describe observed brine inflows to both unheated and heated WIPP test boreholes.

Laboratory tests were also conducted to quantify the effects brine flow has on salt creep (Brodsky & Munson, 1991), and some efforts were made to incorporate these observed effects into fully coupled numerical models.

5.6.5.3 WIPP PSP Moisture Transport and Release (Rooms A1 & B)

WIPP moisture release experiments (see Figure 23) were designed to quantify isothermal and heat-induced brine inflow to four large (30 to 36 inch diameter) boreholes (Nowak, 1985 & 1986; McTigue & Nowak, 1987; Nowak & McTigue, 1987). The moisture release experiments were integrated with waste package full-scale interactions tests (Molecke, 1985) that simulated near-reference repository conditions for DHLW in Rooms Al (0.47 kW/canister) and B (1.5 kW/canister). A flowing nitrogen system continuously swept the cumulative quantities of moisture by means of a condensation and desiccant apparatus, which was weighed periodically. Released water was measured both before and after heating began.



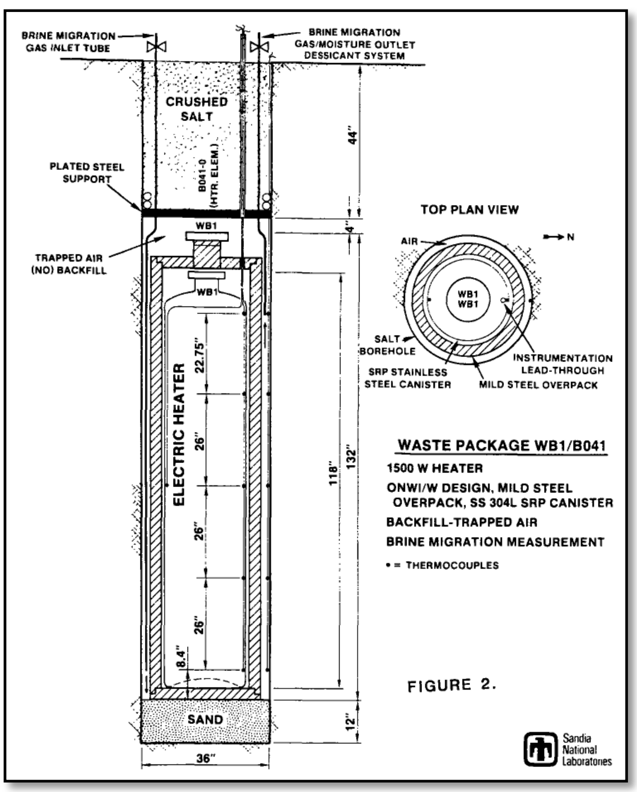


Figure 23. WIPP PSP moisture release experiment in Room B (Molecke, 1985)

Prior to the initiation of heating, water was collected from each of the four test boreholes at rates of 5 to 15 grams/day (Nowak, 1985 & 1986; Nowak & McTigue, 1987; McTigue & Nowak, 1987). The Brine Sampling and Evaluation Program (Deal et al., 1995) results from brine seeps around the WIPP underground are generally consistent with these rates.

After heating began, the water collection rate for each of the four boreholes rose to a peak and then decreased (McTigue & Nowak, 1987; Nowak & McTigue, 1987). The 0.47 kW boreholes in Room A1 yielded peak inflow of about 15 to 17 grams/day; the flow rates then declined to a nearly constant value of 10 grams/day after 100 days. Flow to the 1.5 kW boreholes in Room B continued to increase over a longer period, rising to maximum rates of about 80 to 90 grams/day after about 100 days; the flow rate then decreased slowly.

The inflow rates observed in Rooms A1 and B at WIPP are much larger than in situ brine rates observed at Avery Island (Section 5.3.2), the MCC potash mine (Section 5.4.2), or laboratory rates observed in heated salt samples (Section 5.6.2), but they are the same order of magnitude inflow observed in Project Salt Vault (Section 5.2). The high inflow rate was partially attributed to argillaceous clay layers that intersect the boreholes.

5.6.5.4 WIPP PSP Small-Scale Brine Inflow Tests (Rooms D, L4 & Q)

Seventeen brine inflow tests were monitored from September 1987 to 1991 in unheated boreholes drilled from three existing rooms at WIPP (Nowak, 1988; Nowak et al., 1990a). Experiments were carried out in Room D, Room L4, and the Q access drift (see Figure 8 for locations). Borehole relative humidity data were collected in Room D and Room L4 to check the integrity of borehole seals. Two of the boreholes in Room D yielded no brine over 3.5 years, while the 15 other boreholes produced between 2 and 90 kg of brine. Similar-sized boreholes in similar locations produced inflow rates that varied by as much as 2 orders of magnitude, but most observed inflow rates were of the same order of magnitude. Decreasing, increasing, and steady inflow rates were measured. Nine of the 15 brine-producing boreholes had similar behavior immediately after drilling. These 9 boreholes all exhibited a relatively high initial inflow rate followed by a fairly smooth decline with time (see Figure 24).

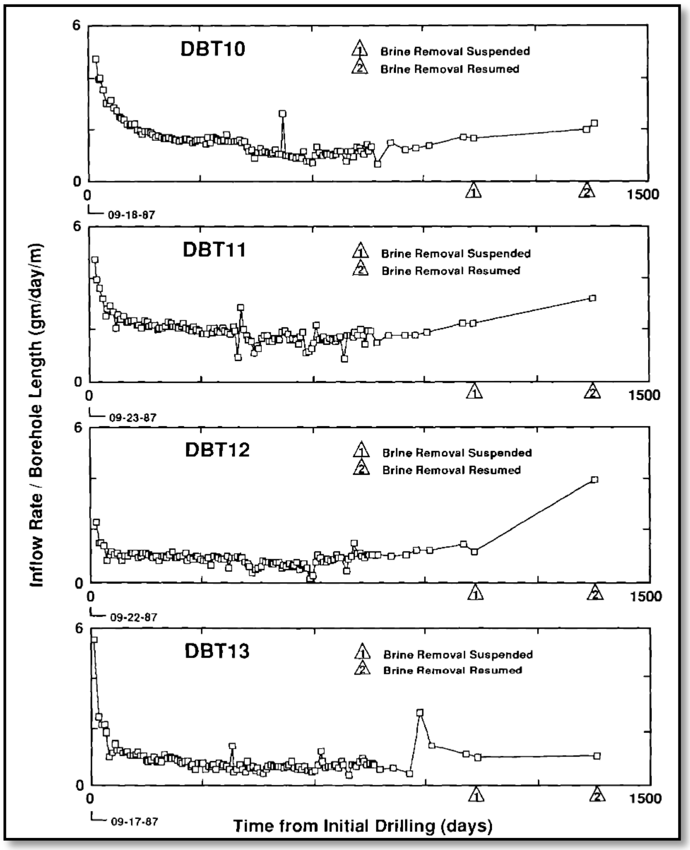


Figure 24. WIPP PSP Small-Scale Brine Inflow Tests results (Finley et al., 1992)

Borehole response differences can be explained through assumed formation heterogeneities. In most cases these heterogeneities are believed to be excavation-induced, rather than geological. Data suggest flow near excavations has been altered by rock deformation, including fracturing (Finley et al., 1992).

5.6.5.5 WIPP PSP Large-Scale Brine Inflow Test (Room Q)

Room Q was an unheated brine inflow test in an area that was well removed from the influence of the other WIPP excavations (see Figure 8). It was mined using a tunnel-boring machine (TBM) to create a 2.9-m-diameter cylindrical room 109 m long (Likar & Burrington, 1990). Excavation was completed in less than 1 month from July 12 through August 8, 1989 (Munson et al., 1997: §6.3.1). Room Q geometry and construction method were specifically selected to minimize the excavation impacts to the undisturbed salt. The circular-shaped opening was selected to reduce the stress-induced fracturing associated with a rectangular opening. A tunnel-boring machine was used to create the circular opening (as opposed to drill-and-blast or continuous mining methods) to minimize excavation-induced fracturing in the drift wall.

Experimental data collected in Room Q included brine inflow, pore pressure, permeability, disturbed rock zone (DRZ) properties, closure, humidity, and host rock salt composition (Nowak, 1989: §6.1.1). Brine inflow data were used to validate the brine inflow models for accuracy of scale-up from boreholes (see previous section) to room-size excavations. Seismic refraction, electrical conductivity, and room closure data were collected to characterize the excavation-induced DRZ. Room Q is shown in Figure 25.

Figure 25. WIPP PSP Room Q instrumentation

Room Q also included seals to minimize evaporation and moisture loss within the room. Two temporary seals were installed by early 1990. The permanent seal system was installed in March 1991 consisting of two seals set 2.4 m apart to form an air lock. Each seal was constructed from an aluminum bulkhead surrounded by an inflatable element to accommodate radial closure (Munson et al., 1997: §6.3.2).

Mining sequence closure points were installed during excavation at the face at the one-quarter, half, and three-quarter points along the length of the drift. Both horizontal and vertical closures were measured at each station. In April 1990 (several months after construction completion), permanent remote closure gages were installed (Nowak et al., 1990a). Example closure data are shown in Figure 26.

Before the room was mined, 15 boreholes were drilled and instrumented to allow pore pressure and permeability testing before and after the mining. The holes terminated in three lines, comprising five holes each, vertically above, vertically below, and horizontally north of the eventual centerline of the room. All of the boreholes terminated 22.9m along the length of the room in a plane normal to the axis of the room. In each of the three arrays, the boreholes were designed to terminate at distances of approximately 2.4, 3.3, 4.6, 7.6, and 13.7 m from the center- line of the room. The tests conducted in these holes before Room Q was mined provide the best representation of far-field properties of any permeability tests performed in WIPP (Beauheim & Roberts, 2002).

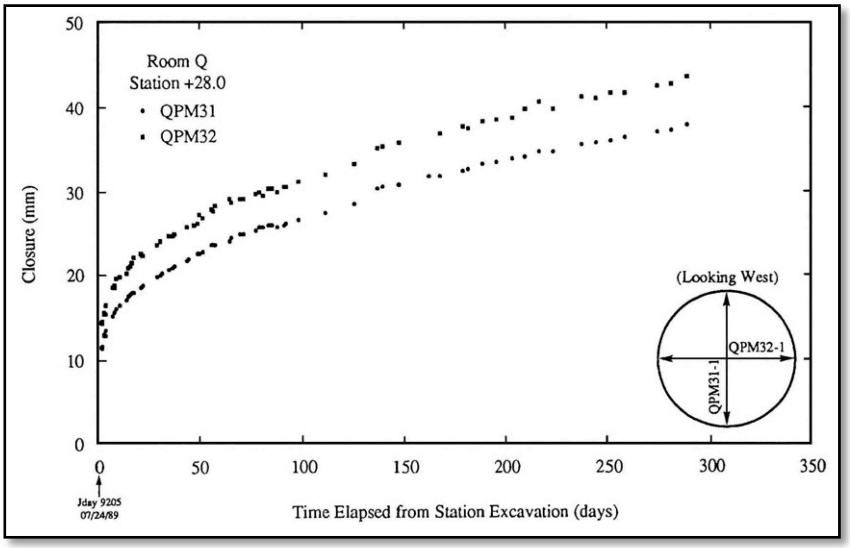


Figure 26. WIPP PSP Room Q closure data at station +28m (Munson et al., 1992)

Four anhydrite layers were isolated in the Room Q boreholes: MB138, MB139, anhydrites b and c, while twelve halite intervals were isolated. Pore pressures appeared to decrease with increasing proximity to Room Q. In some intervals, post-mining pore pressures appeared to continue to decrease with time. Pore pressures decreased by several MPa after mining at all boreholes. The changes in hydraulic properties and pore pressures that were observed can be attributed to one or a combination of three processes: stress reduction, changes in pore connectivity, and flow towards Room Q (Domski et al. 1996, Section 9).

Hansen (2003: §4.7) reports on DRZ estimation in both the access drift leading to Room Q and in the Room Q instrumentation alcove. Cross-hole and same-hole elastic wave velocity measurements in the access drift showed a well-developed DRZ extending at least 2 m into the drift wall. Sonic velocities were measured in the Room Q instrumentation alcove both horizontally and vertically across holes resulting in a about a 1-m DRZ. Typically, the DRZ was most developed at mid-height of the opening, with less damage along the floor, ceiling, and corners of the instrumentation alcove.

Early Room Q borehole data were summarized in Jensen et al. (1993). A hydrologic and structural modeling study was carried out to gain insight into six years of brine inflow data collected in Room Q (Freeze et al., 1997). Alternatively, flow predictions were also made using a mechanical “snow-plow” model for creep-induced brine inflow, with moderate success (Munson, et al., 1996). Beauheim & Roberts (2002) summarized the results of the Room Q hydrologic testing, especially related to observed and interpreted changes in static formation pressures and permeabilities due to mining.

5.6.5.6 WIPP PSP Marker Bed Hydraulic Fracturing (Room C1)

The marker bed (MB) hydraulic fracture experiment addressed the consequences of gas generation in disposal rooms in the Salado formation, and specifically, experimental evaluations of analyses concerning the gas pressurization of anhydrite interbeds such as MB139 (Davies, 1991; Wawersik & Beauheim, 1991; Wawersik et al., 1997). To accomplish this, complementary hydraulic fracturing and hydrologic tests were conducted in MB139 and MB140. Considerable variability was recorded in the measured formation (pore) pressures and permeabilities in MB139 one to two meters below the repository horizon, and to a lesser extent in MB140, 6 m below the floor of the experimental area in the WIPP. The observed variability suggested a strong influence of sub-horizontal networks of preexisting partially and fully healed fractures. It was proposed that MB139 is altered by the influence of nearby excavations (Stormont et al., 1987; Stormont, 1990a; Beauheim et al., 1998). MB140 served as a virgin analog of MB139 and other anhydrite interbeds in the vicinity of the repository horizon.

The maximum breakdown pressures observed in the deeper MB140 ranged from 22-13 MPa, while they were 19-12 MPa in MB139. Similar to the Room G hydraulic fracturing tests (see Section 5.6.3.7), it was found the vertical principal compressive stress component was smallest. Hydraulically induced fractures were found to propagate horizontally within the marker beds, and relatively large (0.2-0.4 mm) residual openings were created, which were confirmed by orders-of-magnitude increases in permeability.

5.6.5.7 PSP References

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5.7 German Salt Repository Sites

In Germany, radioactive waste is divided into heat-generating radioactive waste and non-heat generating waste. Heat-generating waste is comprised of spent fuel elements and liquid HLW from reprocessing. The liquid waste is concentrated and formed into vitrified glass blocks for disposal. Waste generating negligible heat is made up of other primary waste such as cleaning cloths, discarded tools, used filters, or residues from waste water treatment.

The Federal Office for Radiation Protection (BfS) is responsible for the task of erecting and operating facilities for the disposal of German radioactive waste. Under this task BfS is responsible for three German domal salt repositories and repository projects: the Asse heat-generating waste repository, the Morsleben low- and medium-level non-heat generating waste repository, and the Gorleben heat-generating waste exploratory mine. The Konrad repository is an additional repository site located in an abandoned iron ore mine that may be suitable for low- and medium-level waste (negligible heat generation). A decision is still pending on a repository site for heat-generating radioactive waste in Germany (BfS, 2012).

Research and development work was carried out at the Asse salt mine from 1965 to 1995 for the final disposal of radioactive waste in domal salt formations. Low- and medium-level waste (negligible heat generation) was emplaced in Asse until 1978. The focus of research at Asse has included investigating the salt/waste interaction and various emplacement technologies (BMWI 2008).

The Morsleben repository for radioactive waste (Endlager für radioaktive Abfälle Morsleben) was erected by the former East German Government and was used for the disposal of low-level and medium-level radioactive waste from 1971 to 1991 and 1994 to 1998. The emplacement operations were stopped after German reunification by a 1991 court order. In 2001 BfS declared the Morsleben site unsafe, stopped all disposal operations, and began the decommissioning process of backfilling and sealing the mine and shafts.

An October 2010 deadline for considering the Gorleben salt mine as a potential heat-generating waste repository has been extended. Future research will focus on the occurrence and safety of saline solutions and hydrocarbons in the salt strata, considering possible flow paths. Based on site characterization data and research, a preliminary safety analysis and its subsequent international peer review has proposed that the Gorleben salt mine can be converted into a repository.

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5.7.1 Gorleben Research Site

The German nuclear waste repository program evaluated salt structures throughout the country and in 1977 chose the Gorleben salt dome for further evaluation as a potential repository. Site exploration and testing activities occurred at Gorleben from 1979 until 2000, when a 10-year moratorium was placed on any further investigation or construction activities (BMWI, 2008). Exploration, characterization, and experimental activities up to the moratorium are comprehensively summarized in four German Federal Institute for Geosciences and Natural Resources (BGR) reports. Reports 1–3 describe the geological and hydrogeological characterization of the overburden, surrounding country rock, and the salt structure (Klinge et al., 2007; Köthe et al., 2007; Bornemann et al., 2008). Report 4 describes the in situ and laboratory geotechnical investigations at the site (Bräuer et al., 2011). Detailed measurements of the thermal, stress, permeability, pressure, and creep states of the salt dome were made and documented in this report. The results of all the exploration work up to the moratorium were favorable regarding the suitability of the salt dome to host a repository (BMWI, 2008).

The Gorleben salt dome is located near the town of Gorleben in Lower Saxony (see Figure 27). The dome is a northeast-southwest aligned structure approximately 14 km × 4 km. At its shallowest, the top of the salt is 250 m below the surface (bgs). The base of the salt structure is 3200-3400 m bgs (Bräuer et al., 2011). The salt dome intrudes and deforms Cretaceous–Quaternary strata. Tertiary–Quaternary sediments cover the dome to a maximum depth of 430 m, and have clearly been thinned due to salt tectonics. Uplift rates range from 0.08 mm/year during the Cretaceous to 0.02 mm/year during Tertiary and Quaternary time (Klinge et al., 2007; Köthe et al., 2007). Compositionally, the dome is predominantly halite, with lesser amounts of carnallite (hydrated K-Mg chloride), anhydrite, and claystone. In the target exploration zone for the repository (~840 m bgs), the formation is approximately 95% halite and 5% anhydrite. Due to salt diapirism (salt tectonics), both large and small scale folding has deformed (folded, fractured, boudinaged) anhydrite and claystone beds (Bornemann et al., 2008; Bräuer et al., 2011). These features are of interest in terms of brine and gas occurrence and movement and the geomechanical properties of the formations.

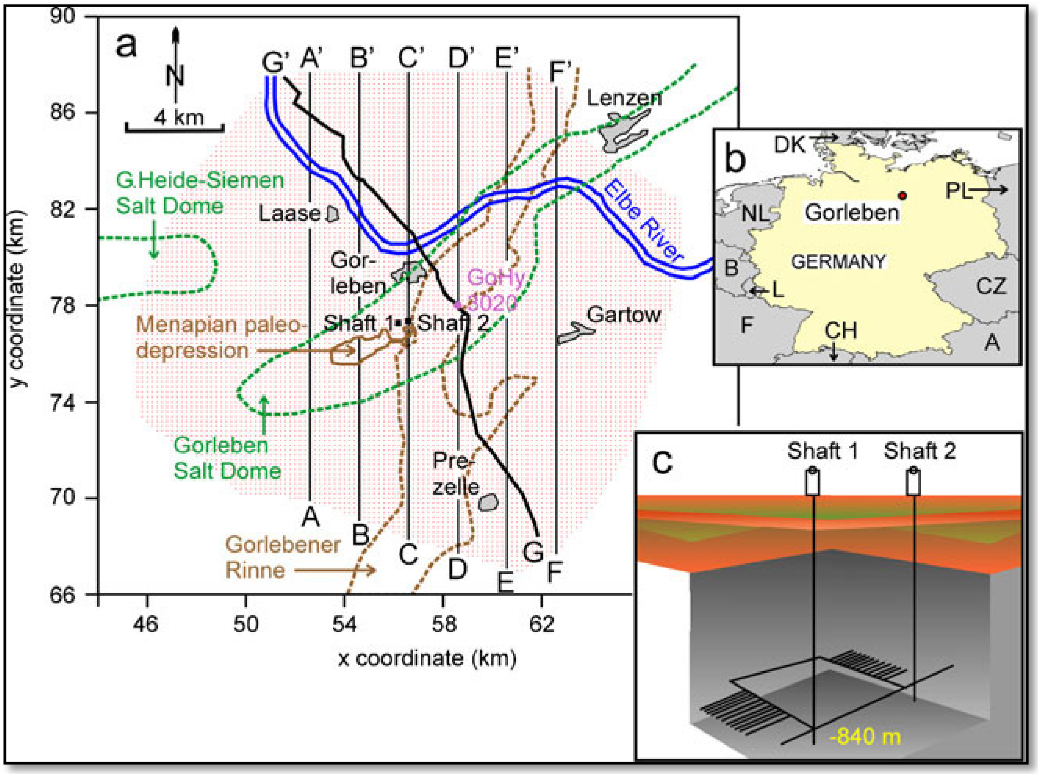

Figure 27. Gorleben exploratory mine (Biurrun et al., 2010)

Two cases of potential repository groundwater contamination have been simulated in the overlying siliciclastic aquifer using three-dimensional models (Schwartz, 2012). The simpler case considers single-phase liquid transport of radionuclides only (over 2 million years), while the more complex two-phase case includes gas generation (over 7,000 years).

The Gorleben site was explored for hydrocarbons from the 1930's through the 1950's using seismic and exploratory drilling. The salt dome had not been mined prior to the 1977 repository investigation activities. Current mine workings include 2 shafts connected by a drift at the 840 m level. Multiple cross-cut drifts, rooms and exploration areas have been constructed at this level for repository investigations. Mining and construction activities ceased along with investigations in 2000 due to the moratorium (BMWI, 2008).

Gorleben References

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5.7.2 Asse II Repository

Approximately 55 years of intensive salt mining shaped the Asse mine before its use as a research mine. From approximately 1909-1925, the site was an active potash mine for carnalite. In 1925 abandoned potash workings were backfilled with “moist” by-product salt from the potash refining process. From 1916-1964 the site was an active salt mine, with workings at the southern flank as close as 5 m to the country rock (see yellow “Rötanhydrit” [red anhydrite] and tan “Oberer Buntsandstein” [upper colorful sandstone] units left of mine workings in Figure 28). In 1965 the German Federal Government purchased the mine, and in 1967 began emplacing low- and intermediate-level waste as part of a “pilot” project, which ended in 1978. Mining has caused damage to the rock salt at the southwest flank of the mining operations, which has led to the current brine inflow problem. Research is currently focused on developing a safe sealing concept for the mine (BMWI 2008).

A US-German cooperative brine migration test was conducted from 1983-1987 in Asse to investigate simultaneous effects of heat and radiation on salt (Coyle et al., 1987). The four in situ experiments used ^{60}Co sources and 3-kW heaters, each surrounded by a ring of eight guard heaters. The test reached a maximum temperature of 210°C in the salt, and a maximum thermal gradient 3°C/cm. Results from the first 28 months of operation included:

- brine migration rates (see Figure 29);
- thermomechanical salt behavior (including room closure, stress, and thermal profiles);
- borehole gas pressures; and
- borehole gas analyses.

In addition to field data, laboratory analyses of pretest salt properties are also included.

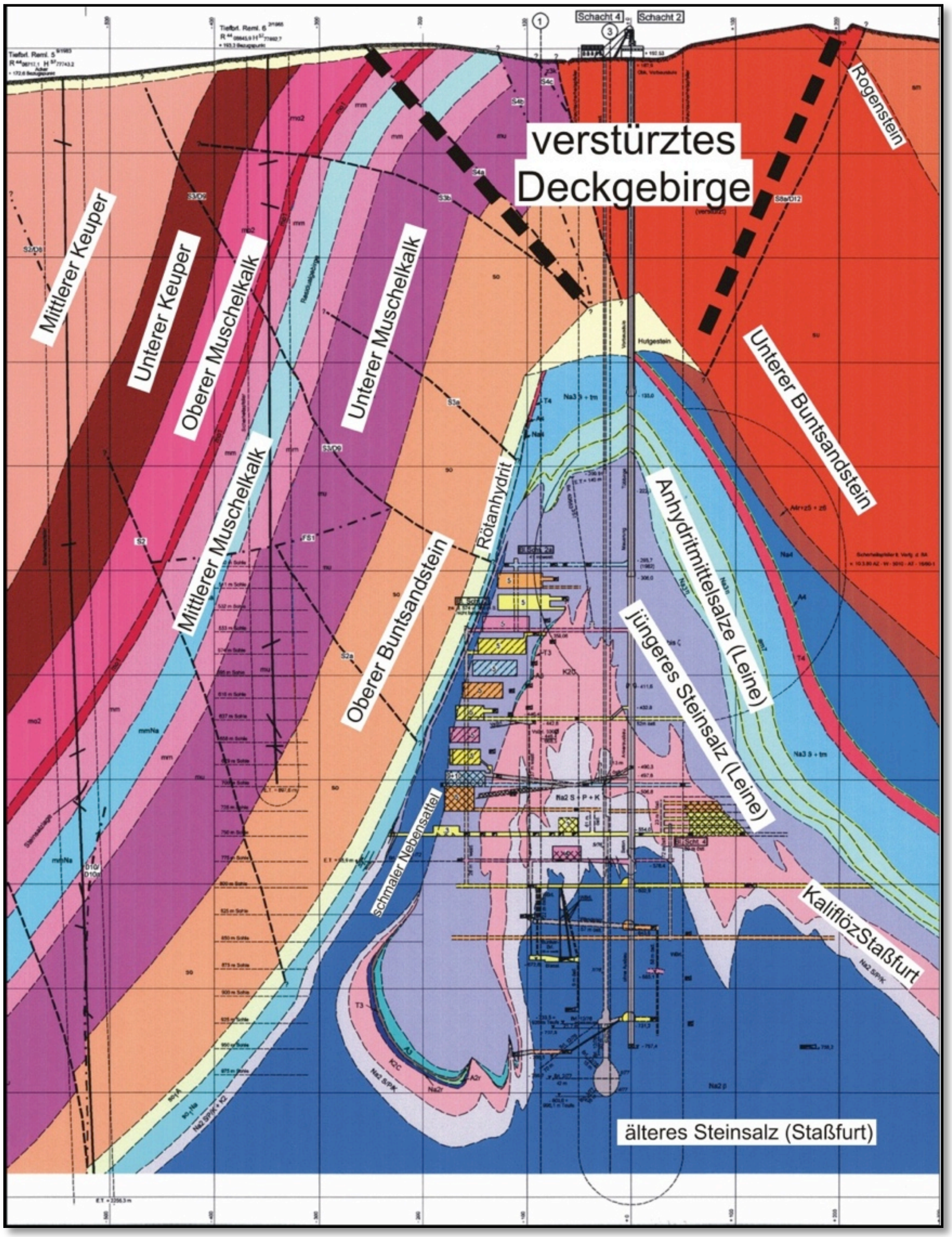

Figure 28. Asse Mine cross section; grid is 100 m spacing

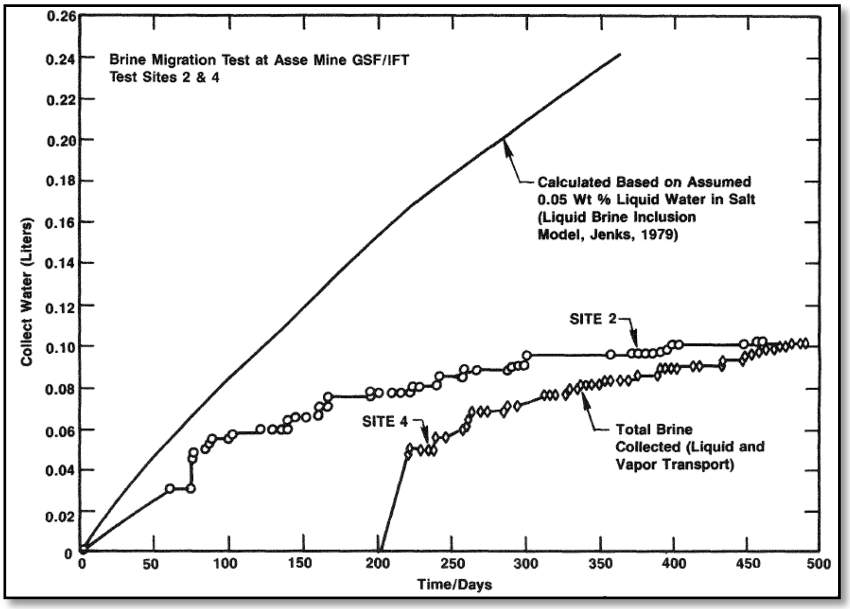

Figure 29. Asse heated brine inflow results (Coyle et al., 1987)

Gies et al. (1994) provide a summary of geological, mineralogical, geochemical, and petrophysical studies at Asse, to characterize the rock salt before the 1990 waste storage tests began. Data are summarized with their most important results made available for possible reuse or re-analysis.

In 1990 plans were developed for full-scale testing of a complete underground repository concept, including disposal of HLW in vertical salt boreholes. The HAW test program planned to use 38 radioactive sources emplaced in six boreholes located in two test galleries at the 800 m mine level for five years. The German Government decided in 1992 to immediately stop all test disposal preparation activities, due to licensing issues. Before stopping activities, a radioactive material emplacement system was installed and the responsible mining authority approved the system. In situ and laboratory test results were used to investigate thermal, radiolytic, and mechanical interactions between the salt, electrical heaters, and radiation sources. After the 1992 policy change there was a controlled shutdown of the heater tests in 1993 and a continuation of the laboratory activities until the end of 1994 (Kühn, 1986; Kühn & Rothfuchs, 1989; Muller & Rothfuchs, 1994; Rothfuchs et al., 1995; Brewitz and Rothfuchs 2007).

From 1990 to 1999, the Thermal Simulation of Drift Emplacement (TSDE) test had been conducted to simulate expected HLW repository conditions (Bollingerfehr, et al., 2004). Six 65-ton POLLUX® disposal casks (designed for transport and disposal of spent fuel) were electrically heated (6.4 kW per cask) and backfilled with crushed salt into two drifts (see top of Figure 30). During the 8-year test, temperatures at the salt-container interface reached 200°C. In situ thermomechanical data were collected in both the backfill and intact salt. Observations compared favorably with both two-dimensional and three-dimensional model predictions.

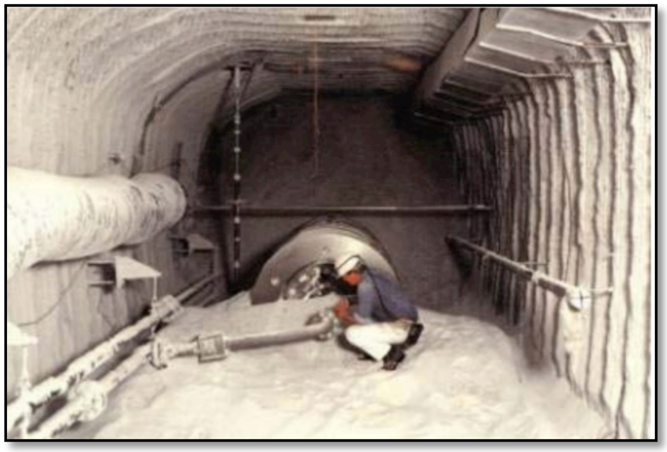

Figure 30. Asse TSDE in situ heater test in 1990 during installation (top) and 2000 during post-test excavation (bottom) (Bollingerfehr et al., 2004)

The Backfill And Material Behavior in Underground Salt (BAMBUS) project involved full-scale in situ experiments addressing backfill and intact salt behavior combined with laboratory modeling studies. Project results showed that the relevant thermal and geomechanical processes are sufficiently well understood and predictive models can be accurately extrapolated over wide ranges. Some difficulties existed in simulating room closure rates and details of backfill re-consolidation.

The follow-up international BAMBUS II project addressed the behavior of host rock and backfill under heated repository conditions (Bechthold & Hansen, 2003). In situ tests were used to confirm monitoring instrument performance, waste package corrosion under repository conditions, and waste package retrievability, in the light of the TSDE experiment. Project results were used to optimize repository design and construction and predict the long-term performance of the excavation disturbed zone (EDZ), backfill, and waste containers. One drift of the finished TSDE experiment was excavated to remove two of the heater casks and associated instrumentation in the drift and backfill (see bottom of Figure 30). Laboratory tests were performed on samples collected from the TSDE experiment to determine porosity and permeability of the backfill material and the EDZ. To investigate observed variability in the laboratory results of BAMBUS I, benchmarks were included with the desired test samples. The BAMBUS II effort also included improvements and advances to numerical models (Rothfuchs et al., 2003).

Kiensler et al. (2002) present experimental findings of full-scale leach tests performed on simulated cemented waste forms over more than 20 years in brines and water. Measurements include pH/Eh, density, leachate composition and releases of the radionuclides Cs, U, and Np. Observed radionuclide releases are compared to small-scale laboratory tests. Excellent agreement was obtained between model calculations and observations for U and Np concentrations.

Geochemical modeling (Metz et al., 2004) was performed on Asse with its total low- and intermediate-level radionuclide inventory of 3×10^{15} Bequerel (Bq). $MgCl_2$-rich brine is expected to enter the emplacement rooms and react with the cementitious waste products. Possible microbial degradation of organic waste components in $MgCl_2$-rich brine could produce significant quantities of CO_2, resulting in acidification of the brine and thereby an increase in radionuclide solubilities. The geochemical environment and solubilities of Am, Np, Pu, U, Th, Tc, Sr, Cs and I were modeled for each emplacement room. Laboratory experiments were undertaken to selectively verify the modeling predictions. The results are applicable for the selection of buffering backfill materials for mine closure. The modeling led to the conclusion that Portland cement and crushed salt can be used as backfill materials in different combinations.

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5.7.3 Morsleben Repository

The Morsleben site is located in the abandoned Bartensleben mine, which was chosen in 1970 as the then-East German location for low- and intermediate-level radioactive waste disposal. The Bartensleben shaft was completed in 1912 and was the site of potash mining until 1918 and rock salt mining until 1969. The first license for the waste disposal in Morsleben was issued in 1978. (Martens et al., 1995; Behlau & Mingerzahn 2001; Ranft & Wollrath 2002; Brewitz & Rothfuchs, 2007).

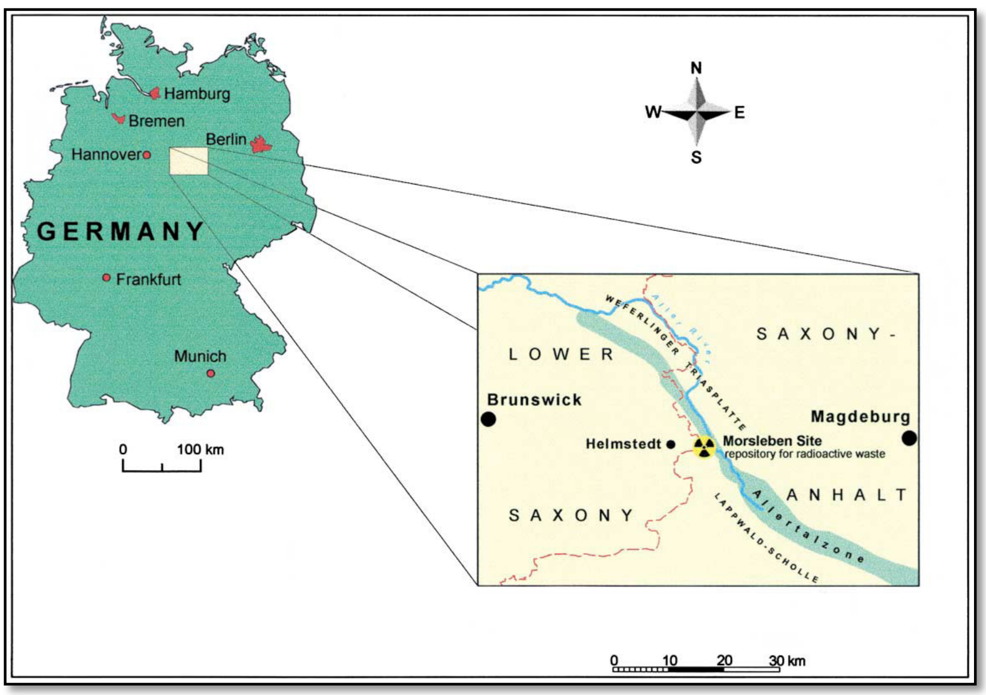

Figure 31. Location of the Morsleben repository (Behlau & Mingerzahn, 2001)

The repository is located in the upper Permian salt structure of the Aller valley zone. The salt formation consists of folded halite, potash, and anhydrite layers, overlain by a tight caprock (Ranft & Wollrath 2002). The overall thickness of the salt formation is between 350 m and 550 m.

Ebel & Storch (1990) and Ebel (1991) present brief historical overviews of the Morsleben repository creation, the results of research and development, and the plant construction. They describe the parties involved, licensing process, international cooperation, and important research and development results. They also outline the site's radioactive waste transportation system, disposal technologies, mine ventilation, radiation protection, and operational rules.

Pruess et al. (2002) estimated that negligible quantities of brine that invade the repository should be able to migrate to the biosphere during post closure. At the time of the study brine inflows into the mine were very low. About 10 m^3/year of Mg-rich salt solution flowed into the "Lager H" chamber. A location in the central part of the mine has a brine inflow rate of approximately 1 m^3/year, believed to be coming from the local groundwater system. Herrmann (1993) showed brines originate between the evaporative body and the overlying rocks for five mine seepage locations.

For the safety analysis of the post-operational phase of the Morsleben repository, radionuclide migration was computed with both one-dimensional and multi-dimensional transport codes (Heidenreich, 1992). Deviations between the low- and high-dimensional models are discussed and interpreted. Brine and radionuclide migration in the repository is simulated using a simplified shaft-gallery model. Eilers et al. (2003) describe the sealing of the Morsleben repository, while Resele et al. (2004) present a probabilistic safety assessment for the Morsleben repository using simplistic models with distributions of uncertain parameters.

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6 In Situ and Laboratory Tests by Topic

The following sections give lists of experiments (both in situ and laboratory based) which appear in Section 5, but are organized here by test type. References and summary text are given in the relevant portions of Section 5.

6.1 Heated Salt Tests

These tests involved observations of temperature and often geomechanical deformation accelerated by electric heaters. The tests often involved brine migration or waste package tests at the same location.

1. The Lyons, Kansas, Project Salt Vault site (see Section 5.2 on page 10) was a HLW disposal demonstration that had several heater tests (1965-1967).
    a. Two 10.5-kW heated salt tests (7 heaters in each test). One test used radioactive material and heaters. The test with radioactive materials moved twice between two locations as material was switched out.
    b. A 33-kW heated pillar test (22 heaters). Two of the heaters were started 4 months early at 3 kW, then reduced to 1.5 kW for the main test.
    c. A 25-kW waste container test (6 heaters) only ran 2 months before several stainless steel heaters failed from corrosion.
    d. A 11-kW room closure test was conducted by ORNL pre-Salt Vault in a Hutchinson, Kansas mine (1962-1965).
2. The Avery Island domal salt site (see Section 5.3 on page 12) was a HLW salt research site that had heater tests and other tests with heated components (1978-1983).
    a. Three canister heater tests (Sites A, B & C) ran for over 32 months
        i. Site A was installed in sand backfill, and was used to estimate salt thermal conductivity
        ii. Site B was a 3-kW heater in a borehole without backfill to simulate a HLW package
        iii. Site C was a 4-kW heater with 8 peripheral heaters, backfilled around the central heater with crushed salt (test ran for 5 years)
    b. Two of the three Krause (ONWI) brine migration studies (NB & SB) were heated with 1-kW heaters.
    c. The Ewing (SNL) brine migration study was heated with a 2-kW heater.
    d. Several of the accelerated borehole closure tests had 1-kW heaters incorporated with the corejacks, which increased the salt temperature to 60° C.
3. The MCC potash mine was an interim salt test bed, before the first exploratory WIPP shaft was constructed in 1981 (see Section 5.4 on page 16). Several heated experiments were carried out in support of the WIPP DHLW.
    a. Several brine inflow tests used 2-kW heaters, monitoring brine before and after heating.
    b. Six package material tests used 1.5-kW heaters operated at various power levels with crushed salt to accelerate exposure of metal samples set in boreholes.
4. Several WIPP-run laboratory tests were performed in the late 1970's to investigate brine migration in heated salt (see Section 5.6.2 on page 21).
    a. Several small laboratory tests (1-kg experiment, and smaller thermal gradient tests) were performed under heated conditions at controlled temperatures and thermal gradients to investigate the migration of brine inclusions.
    b. Salt decrepitation experiment heated two 1.6-kg salt cores beyond the point where cracking occurred due to the thermal expansion of water changing to steam (approximately 250° C).
    c. Salt Block I and II experiments were 1-m cylindrical blocks of salt heated by axial 1.5-kW heaters to investigate thermal (I) and brine migration (II) properties of salt.

5. Three major heated WIPP TSI tests were performed in the late 1980's (see Section 5.6.3 on page 23).
    a. Rooms A1-A3 were the DHLW Mockup experiment. This test emplaced 64 0.47- and 1.41-kW heaters into vertical boreholes in the floor, for a total power of 64 kW between three adjacent rooms (1985-1990).
    b. Room B was the DHLW Overtest experiment. This test emplaced 29 1.5-, 1.8-, and 4.0-kW heaters into vertical boreholes in the floor, for a total power of 58.6 kW in a single room (1985-1989).
    c. Room H was the Heated Axisymmetric Pillar Test. This test wrapped a cylindrical pillar in strip heaters and blanket insulation, operational from 1986 to 1995.
6. The WIPP WPP tests included heated aspects of materials corrosion and leaching experiments (see Section 5.6.4 on page 37).
    a. The MIIT in Room J was a metal, glass, and salt leaching test that operated in 50 heated boreholes in the floor of WIPP Room J. Most boreholes were filled with brine, and all were maintained at 90° C for five years (1986-1991).
    b. CH TRU waste package tests in Room J were operated with heaters in a brine pool that kept the room at high humidity and elevated (40° C) temperature to simulate overtest repository conditions.
    c. RH TRU waste package tests in Room T were operated in eight horizontal boreholes in the walls, each with a 300-W heater to simulate the proposed thermal load of RH canisters.
7. The Asse II repository in Germany has operated three large-scale heater tests as part of an investigation into the disposal of heat-generating waste in salt (see Section 5.7.2 on page 58).
    a. 1968 heater tests in Asse were reported with few details.
    b. An extensive brine-migration test was conducted in four sets of vertical boreholes with 3-kW heaters (1983-1987).
    c. The TSDE experiment involved the emplacement of six 6.4-kW heated waste casks in two drifts, backfilled with crushed salt (1990-1999). The BAMBUS II project included excavation and testing of the material around the heaters, beginning in 2000.

6.2 Brine Migration Tests

These tests involve measurement of water (brine) inflow to boreholes under ambient or heated conditions.

1. The Lyons, Kansas, Project Salt Vault site (see Section 5.2 on page 10) was a HLW disposal demonstration that had both laboratory and in situ brine migration tests (1965-1967).
    a. Laboratory brine migration studies focused on proposed the mechanism of brine inclusion movement up a thermal gradient.
    b. Three sets of heated boreholes (rooms 1, 4 & 5) were monitored for brine inflow, resulting in the observation that a large pulse of brine occurs after heating ends.
2. The Avery Island salt dome site (see Section 5.3 on page 12) was a HLW salt research site that had both heated and unheated brine migration (1978-1983).
    a. Krause (ONWI) performed a set of brine migration tests under three sets of conditions for more than 200 days.
        i. AB – Natural brine movement under ambient temperatures
        ii. NB – Natural brine movement under elevated temperatures
        iii. SB – Synthetic brine movement under elevated temperatures
    b. Ewing (SNL) performed a heated set of brine migration tests
3. The MCC potash mine was an interim salt test bed, before the first exploratory WIPP shaft was constructed in 1981 (see Section 5.4 on page 16). A brine migration experiment was monitored for brine inflow before, during, and after heating.

4. Several WIPP-run laboratory tests were performed in the late 1970's to investigate brine migration in heated salt (see Section 5.6.2 on page 21).
    a. Salt decrepitation experiment heated two 1.6-kg cores while monitoring acoustic emissions, which were highest during cracking, but increased during the cooling phase as well.
    b. Salt Block I and II experiments were 1-m cylindrical blocks of salt heated by axial 1.5-kW heaters. Both tests were destructively post-test analyzed to observe brine migration effects.
    c. Several small laboratory tests (1-kg experiment, and smaller thermal gradient tests) were performed under heated conditions at controlled temperatures and thermal gradients to investigate the migration of brine inclusions.
5. The WIPP TRU WPP tests included a large brine pool in Room J for a material corrosion and leaching experiments (see Section 5.6.4 on page 37). Brine wicking into backfill and migration into underlying anhydrite layers was monitored during the extent of the test.
6. The WIPP PSP involved several heated and ambient brine inflow tests (see Section 5.6.5 on page 45).
    a. Heated moisture transport and release experiments were carried out in Rooms A1 and B, co-located in boreholes with the DHLW package performance tests. Heated boreholes produced a large amount of brine while heated, possibly due to geologic heterogeneity (1985-1987).
    b. Ambient small-scale brine inflow tests were monitored in 17 boreholes in Room T, Room L4, and the entrance to Room Q (1987-1991). Large amounts of brine, and a large amount of variability was observed, possibly due to damage heterogeneity from constructing the rooms and boreholes.
    c. The ambient large-scale brine inflow room (Room Q) test was a 129-m long cylindrical room constructed with a 2.9-m-diameter tunnel boring machine. Brine inflow was monitored for several years (1991-1997).
7. The Asse II repository in Germany operated a large brine-inflow test in as part of an investigation into the disposal of heat-generating waste in salt (see Section 5.7.2 on page 58). Borehole temperature, gas pressure, brine inflow mass, and brine chemistry were monitored during the test (1983-1987).

6.3 Salt Creep Tests

These tests include heated and unheated creep closure tests, potentially useful for future benchmarking exercises.

1. The Lyons, Kansas, Project Salt Vault site (see Section 5.2 on page 10) was a HLW disposal demonstration that had heated and unheated salt creep experiments (1965-1967).
    a. The model pillar laboratory tests were heated cylindrical cores of salt, with a groove cut along their circumference to simulate the geometry of a circular salt pillar.
    b. The heated pillar experiment monitored salt creep as a result of heaters placed at the base of a pillar between two rooms.
    c. A 11-kW room closure test was conducted by ORNL pre-Salt Vault in a Hutchinson, Kansas mine (1962-1965).
    d. Creep closure measurements were made in both the Hutchinson and Lyons Carey salt mines (Bradshaw & McClain, 1971: Tables 4.3 & 4.4).
2. ONWI had several comparative laboratory studies on the salt creep of cores collected from different candidate salt repository sites: including Paradox Basin Gibson Dome (UT), Vacherie Dome (LA), Richton Dome (MS), and Deaf Smith (TX) sites (see references in Sections 5.3 and 5.5).

3. WIPP had an extensive laboratory creep-testing program, which is reported for both salt and anhydrite samples (see Section 5.6.3.1 on page 24).
4. The Avery Island salt dome site (see Section 5.3 on page 12) was a HLW salt research site that had both heated and unheated accelerated borehole closure (corejacking) tests (1980-1983).
5. The MCC potash mine was an interim salt test bed, before the first exploratory WIPP shaft was constructed in 1981 (see Section 5.4 on page 16). An in situ large-scale deformation test was conducted to measure closure rates in an active mine with a high level of extraction (90%).
6. The WIPP site had extensive structural monitoring as part of the TSI testing plan (see Section 5.6.3 on page 23 and Figure 8).
    a. The South Drift of the SPDV area was a key set of early closure measurements in a long isolated drift at WIPP, these data showed numerical models under-predicted closure by a factor of three.
    b. Room D was a ventilation drift of the same dimensions as the heated Room B. This room was mined first, and was therefore a where WIPP instrumentation and installation methods were first tested.
    c. Rooms A1, A2, and A3 were heated rooms that were extensively monitored for differential creep closure. Early monitoring during the mining of Rooms A1 and A3 from the central Room A2 gave valuable information regarding mining effects on closure (1985-1990).
    d. Room B was heated at a higher rate than the A Rooms with similar instrumentation. Quicker closure rates were observed due to increase temperatures. Comparisons between closure rates observed in Rooms D and B have been made (1985-1989).
    e. Room H was heated and extensively monitored for differential creep closure during its long life (1986-1995).
    f. Room G was a long straight drift monitored for closure, and had hydraulic fracturing tests performed to determine principal stress directions.
    g. The Air-Intake Shaft (Shaft V) was monitored for closure soon after being mined with an up-ream miner (1988). These early closure measurements were invaluable for understanding creep closure of vertical salt boreholes.
    h. The 8 heated RH canisters in Room T were placed in horizontal boreholes in the walls and were monitored for closure.
    i. Room Q was monitored for vertical and horizontal closure as well as transient mining effects. This room provided a unique dataset, since it was rapidly constructed with a tunnel boring machine and did not have stress-concentrating corners.
    j. The pillar between rooms C1 and C2 contained the intermediate-scale borehole test, which provided data regarding creep closure of rooms at approximately 1/10 scale the scale of most WIPP drifts (1989).
7. The German Gorleben research repository (see Section 5.7.1 on page 56) was monitored for closure during its active period as a research facility.
8. The Asse II repository in Germany operated a large brine-inflow test (see Section 5.7.2 on page 58). Room closure was monitored during the test (1983-1987).

6.4 Crushed Salt Backfill Tests

These tests either tested crushed salt backfill or used it to backfill around heaters.

1. The Lyons, Kansas, Project Salt Vault site (see Section 5.2 on page 10) was a HLW disposal demonstration that had several heater tests (1965-1967). The two 10.5-kW heated salt tests used crushed salt backfill.
2. The Avery Island salt dome site (see Section 5.3 on page 12) was a HLW salt research site that used crushed salt in heater test Site C (1978-1983).

9. The MCC potash mine was an interim salt test bed, before the first exploratory WIPP shaft was constructed in 1981 (see Section 5.4 on page 16). Crushed salt backfill was used in the six Waste Package Materials tests.
3. The WIPP WPP test program used crushed salt in several tests (see Section 5.6.4 on page 37).
    a. The DHLW WPP tests used crushed salt backfill around heaters in vertical boreholes in Rooms A1 and B.
    b. The TRU WPP tests in Room J operated in or next to a brine pool under elevated temperatures (40°C), resulting in high humidity. Salt backfill was placed over TRU CH drums, allowing the brine from the pool to wick up into the backfill.
    c. The MIIT WPP test in Room J used samples placed in 50 heated boreholes in the floor. Initially, most of the boreholes were filled with brine (a few only used crushed salt). After 5 years of testing several of the boreholes had become encrusted with salt from evaporation of water from the brine.
    d. The TRU WPP CH drum tests in Room T were under normal WIPP conditions, including a backfill experiment that was half crushed salt. This experiment was not retrieved and remains in the WIPP underground.
    e. The TRU WPP RH package tests in Room T used various backfills (including crushed salt) around the heated RH containers in horizontal boreholes in the wall. This experiment was not retrieved and remains in the WIPP underground.
4. The WIPP PSP performed several laboratory and in situ studies on crushed salt reconsolidation (see Section 5.6.5.1 on page 46), including the development and refinement of a constitutive model for crushed salt reconsolidation.
5. The Asse II repository in Germany has carried out investigation into the disposal of heat-generating waste in salt (see Section 5.7.2 on page 58). The TSDE experiment emplaced six large heated disposal casks in two drifts, backfilling the drifts around the casks with crushed salt. After 9 years of heating, the follow-up BAMBUS II experiment excavated 2 heaters, analyzing samples of the reconsolidated crushed salt in the laboratory.

7 Consulting In Situ Test Leads and Employees

SNL has contracted with both existing and former employees who had experience with underground in situ testing. This consultation was done to confirm the understanding of project history, to provide a level of oversight, and to review project summaries included in this report. Due to time constraints this interim report has not been formally reviewed in its final form by the consultants, although we have obtained feedback on parts of the text. The consultants will review the final fiscal year 2013 report.

SNL consulted with four former SNL employees who were Principal Investigators on WIPP underground in situ testing. Rudy Matalucci was the underground test coordinator. John Stormont was the lead for the PSP. Darrell Munson was the principal for the TSI tests. Marty Molecke was in charge of TRU and DHLW WPP testing, and in situ testing in the MCC potash mine.

Rudy Matalucci, Darrell Munson, and John Stormont traveled to the SNL Carlsbad office June 26 & 27, 2012. They presented to an audience of SNL, LANL, and DOE employees regarding the TSI and PSP they carried out on salt at WIPP from the mid 1970’s to the mid 1990’s. Similarly Marty Molecke traveled to Carlsbad on August 16 and 17, 2012 and presented a summary of the DHLW and TRU WPP tests he led during a similar time period at WIPP to a similar audience.

Wes DeYonge is a current RE/SPEC employee who was involved in the instrumentation and execution of most WIPP in situ thermal/structural interactions tests and in situ tests at Avery Island, Louisiana. Wes provided personal photographs he took of operations at Avery Island, and he provided consultation on both WIPP and Avery Island testing.

8 Conclusions

Existing salt research has been summarized in this interim report. This report is the product of several months of intensive report review by the authors. Although we have tried to discuss all tests that we felt were relevant to the disposal of heat-generating waste in salt, the choice to include or leave out a particular test is subjective. In the final report we will fix any omissions, add hyperlinks to reports, and add more quantitative summary material including plots of results and a detailed graphical timeline of salt research.

Appendix A

Reviewed References by SITED Keyword

Reviewed References by SITED Keyword

This appendix lists reviewed report from SITED that scored high (4 or 5) in one or more SRDI keywords. SRDI keywords are listed in Table 3. Reports in the database that have not been reviewed or ranked highly do not appear in these lists, and reports that received a high ranking in more than one category will be listed more than once.

A-1. Laboratory

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Appendix B

SITED Implementation

SITED Implementation

This appendix describes the construction of SITED, as a specific implementation of the Refbase bibliographic database. SITED consists of a collection of PHP and shell scripts which interact with the database to generates hypertext markup language (HTML) pages dynamically. HTML pages are viewed using a web browser. Pages include forms and buttons that allow the user to request information from the database and submit new information to the database. Figure 32 illustrates the relation between the user, the database, and the software components of SITED. The SITED server uses the “Linux, Apache, MySQL & PHP” (LAMP) open-source software bundle to serve SITED to end users through its web interface, specifically the “XAMPP for Linux” distribution.

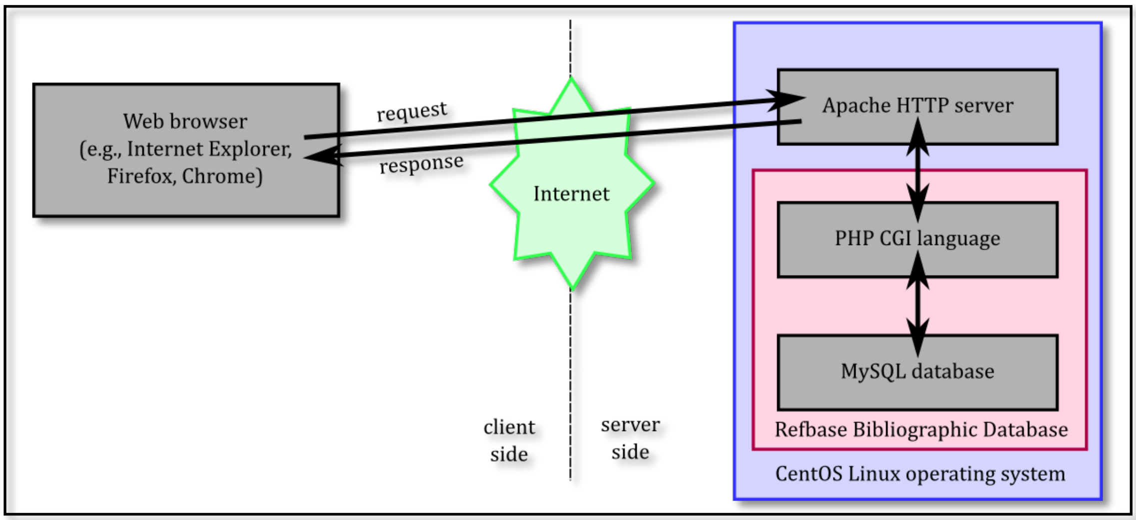

Figure 32. Diagram of SITED LAMP software bundle

B-1. Database: MySQL

The SITED MySQL database is the actual store of references and associated metadata. MySQL is an open-source relational database management system, an implementation of the Standard Query Language (SQL) relational database language. SITED uses a modern version of MySQL (version 5.0). The SITED database includes 16 tables, listed in Table 2, specified by the Refbase distribution. The primary table that stores the active references is the *refs* table.

Table 2. Tables in SITED refbase database

SITED Table	Description
auth	authorized usernames and passwords
deleted	references which are deleted from the refs table through the SITED interface are moved to this table
depends	high-level software dependencies
formats	importing and exporting formats (e.g., MODS XML, Bibtex, EndNote)
languages	list of which interface languages are used (e.g., English, German)
queries	list of saved queries
refs	references (main database table)
styles	citation styles which can be used (e.g., MLA, Chicago)
types	entry types (e.g., Report, Thesis, Map, Journal Article)
users	user metadata (e.g., email, affiliation)
user_data, user_formats, user_options, user_styles, user_types	user-specified information

Typically the user does not interface direction with the MySQL database. The SITED interface creates SQL queries from input and selections the user makes in their web browser. The results of these queries are used to populate the search results pages, also displayed in the user's browser. The SITED interface does allow the user to view the SQL statement used to obtain data from the database, through the "your query" link near the top of the search results page. SQL SELECT queries can also be specified directly through the "SQL search" option at the bottom of the home page. SQL queries that change the database (e.g., INSERT, UPDATE, and DELETE) are not possible through the SITED interface.

The MySQL database also can be accessed, browsed, and modified through a phpMyAdmin interface (version 3.4). It is password protected, and not available to normal users. It is an "expert user" interface that allows records to be modified in ways not accommodated through the Refbase SITED interface. Any valid SQL command can be executed through this interface. This is the most general and flexible way to import records to SITED in bulk. The phpMyAdmin interface allows a minor amount of graphical editing of the database using a PHP-based tabular interface.

B-2. Common Gateway Interface Language: PHP

The Common Gateway Interface (CGI) is a standard process for generating web pages dynamically. PHP is the CGI scripting language used by SITED as a "hypertext pre-processor" to create HTML pages dynamically, based upon interactions with the user and database. PHP interacts directly with the MySQL database, creating HTML pages based upon database content, and performing database queries based on user interaction with HTML forms. The PHP code is run on the server and the user never directly interacts with it (see Figure 32). SITED uses a modern version of PHP (version 5.4).

B-3. Webserver Application: Apache

The Apache webserver is the program that listens to the SITED web address, and delivers the HTML pages generated on the server using the PHP scripts that query the MySQL database (see Figure 32). SITED uses a modern version of Apache (version 2.2), an industry standard Hypertext Transport Protocol

(HTTP) server. An internal SNL requirement for externally visible webpages requires all SITED pages to be served as encrypted HTTP (https). SITED uses OpenSSL (version 1.0) to handle authentication and encryption for Apache.

B-4. Server Operating System: Linux

Linux is well suited for use in server settings and is an industry standard for HTTP/database/PHP servers. The database, CGI software, and HTTP server all run under the CentOS operating system (see blue box in Figure 32). The PDF, text, and data files linked from SITED entries reside in the file system of the SITED server. The SITED server runs the CentOS 6 operating system. CentOS is an open-source Linux distribution based on Enterprise Red Hat Linux. The operating system used by the server has little impact on the end user, but this choice was made based on the preference of the implementers, and to maximize flexibility and maintainability of the system.

The database, the uploaded PDFs and data files, and the server software are backed up daily to a separate computer in a scheduled process.

B-5. Client Web Browser

Mozilla Firefox, Google Chrome, and Microsoft Internet Explorer work with the SITED database interface. Older versions of Internet Explorer (in Windows XP) appear to have problems with some very long URLs generated when querying results from SITED, especially when navigating between query results. Since Firefox and Chrome do not have this problem, and are freely available for most computers, this problem is not a serious limitation.

Appendix C

SITED Data Sources

SITED Data Sources

SITED was initially populated using several sources of bibliographic information. Both references and electronic copies of reports were downloaded from DOE and international (mostly German) sources. This main dataset was augmented with references and documents from other sources during the review process.

Several public, large, well-maintained, DOE-sponsored bibliographic databases already exist. We are creating a new database to:

- combine widely available public content with hard-to-find content scanned specifically for this project;
- include data from in situ and laboratory tests when available; and
- include a project-specific report ranking system.

C-1. DOE-Sponsored Databases

Available sources of both bibliographic information and electronic copies of documents (PDFs) were ranked by their usefulness to the project, based on some initial queries and inspection of database contents (see Figure 33). The potential sources considered were

- WIPP Records Center databases;
- SNL Albuquerque Technical Library database;
- DOE Office of Scientific and Technical Information (OSTI) Information Bridge; and
- DOE Energy Citations Database (ECD).

Several search engines are available to query these databases (e.g., SNL or LANL library searching tools, Google Scholar, or commercial search engines), but only the primary source databases are discussed here.

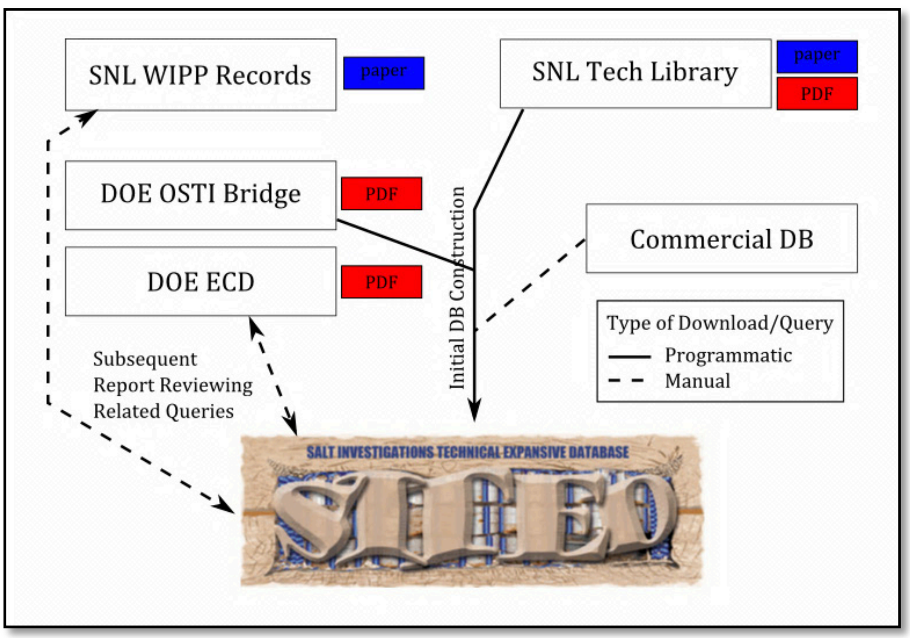

Figure 33. SITED data sources

The presence of electronic (PDF) copies of reports was an important criterion for databases that feed SITED. Another important criterion was the ability to programmatically query databases and readily manipulate their output. This allowed over 10,000 records to be queried and imported (also removing duplicates) in just a few weeks' time.

C-1.1 WIPP Records Centers

In Carlsbad, NM, there are three main WIPP-related records centers. They are maintained by the DOE Carlsbad Field Office, the WIPP site contractor (originally Westinghouse, now Washington TRU Solutions), and the SNL Carlsbad Programs Group. The DOE and site contractor records centers do not have electronically accessible or programmatically controlled interfaces, electronic copies of reports, or much material relevant to the SRDI project goals that is not also contained in the SNL WIPP records center.

The SNL WIPP records center includes paper copies of nearly all reports related to WIPP (both TRU and DHLW), including many of the references of WIPP reports. Additionally, the WIPP records center includes raw electronic media with data, copies of memos, draft copies of reports, field notebooks, maps, photographs, and other miscellaneous salt- and WIPP-related information.

The electronic database used to organize the SNL WIPP records center has a web-based interface. Access to the database requires an SNL intranet password and account permission from the SNL records center database manager. Records cannot be queried programmatically from the WIPP records center and they can only be extracted in bulk by creating a table report from the results of a manually entered query, then performing a copy/paste from this table into a spreadsheet. The bibliographic entries in the database include author, title, some records-center specific data, and a unique ERMS identifier.

All three Carlsbad WIPP records centers store information redundantly on shelves (multiple physically separate locations) and these records are viewable in person, but most information must be obtained by scanning paper copies on demand.

C-1.2 SNL Albuquerque Technical Library Database

The SNL Technical Library database includes entries for all SNL-generated reports that have a "SAND" number, including "suffixed" SAND numbers (e.g., 'a'=abstract, 'c'=conference, 'r'=revision, and 'j'=journal), and external consultant reports submitted to SNL. SAND numbers are assigned to reports that go through the SNL corporate review process. Memos, test plans, and many things in the WIPP Records Center do not exist in the SNL Tech Library, since they were never formally reviewed. The Tech Library also has some general reference material and reports from other laboratories, when the report has an SNL co-author.

The SNL Tech Library has a web-based interface that includes records found at several physical locations (SNL tech library, Nuclear Waste Management Library, and the WIPP Records Center) that is only accessible from inside the SNL intranet. A large number of the documents in the Tech Library have PDF documents associated with them. Most SAND reports since the mid 1990's are available for download through the SNL intranet.

The SNL Tech Library does not have an interface that allows programmatic database queries by non-librarians, but Amy Rein, an SNL reference librarian, provided the results in an ASCII report-based format upon request. This output was configured for import to SITED, and available PDFs were downloaded through use of several text-processing Python scripts.

C-1.3 DOE OSTI Information Bridge Database

The DOE Office of Science's Office of Scientific and Technical Information (OSTI) Information Bridge (www.osti.gov/bridge/) is an online database of DOE-sponsored research, including all official reports from national laboratories, DOE site contractors, and universities working under DOE contracts. From SNL, OSTI Information Bridge has nearly all non-suffixed SAND reports, and some of the abstract and conference suffixed SAND reports ('a' and 'c'). This database was the main source for non-SNL reports. All references in the OSTI Information Bridge have PDF documents available for download (although many PDFs from the 1970's are poor-quality scans), and full-text search is available across all content.

The database can be programmatically queried, following their published guidelines (www.osti.gov/XMLDataServicesManual.PDF). The OSTI Information Bridge servers deliver XML documents based upon configurable queries and simple rules. Python text-processing scripts were used to format the records for import to SITED and download available PDFs.

C-1.4 DOE Energy Citations Database

The DOE Office of Science Energy Citations Database (ECD) (www.osti.gov/energycitations/) is an online database of DOE-sponsored work, more focused on energy-related topics than the DOE OSTI Information Bridge. All entries in the ECD have abstracts and many have PDFs available (mostly the entries that are common with the OSTI Information Bridge). This database was not programmatically queried for content to add to SITED, but was checked manually when an abstract or bibliographic information was needed during the review process (e.g., details regarding a conference or abstracts).

C-2. Commercial databases

Los Alamos National Laboratory (LANL) used its subscription to the Thomson Reuters Web of Knowledge^{SM} through its research library (int.lanl.gov/library/) to query the following databases:

- Web of Science® (sciences, social sciences, arts, and humanities);
- BIOSIS® (life sciences and biomedical research);
- Inspec® (physics, nuclear engineering and geophysics);
- Journal Citation Reports® (sciences, physics, nuclear science and technology);
- Engineering Index® (engineering);
- SciSearch® (Thompson Reuters) (scientific and technical journals);
- Thompson Reuters Conference Proceedings (proceedings papers at international and technical conferences and covers the same disciplines as SciSearch but limits its contents to conference literature); and
- Social SciSearch® (social sciences literature).

These databases were queried through the LANL internal web-based interface and the results were imported into SITED. The majority of references only contained basic bibliographic information and an associated abstract since they are mainly copyrighted content (i.e., scientific journals, proceeding, and conferences). When the full text of these records is needed, the user should obtain the document of interest directly from the publisher, through their institutional or personal subscription.

C-3. Project-Specific Bibliographies

When project-specific bibliographies were available, they were added to SITED. A keyword in SITED, under "Report Type" is used to flag bibliographies (see Appendix D). For the WIPP Project, the bibliography by Powers & Martin (1993; SAND92-7277) was an invaluable resource; it contains summaries for 941 reports, including many hard-to-find early reports and 43 annotations. All entries in this bibliography were checked against SITED, and abstracts were added for many old reports from this source. Aside from the index and cross-referencing, all the content in Powers & Martin is included in SITED.

Appendix D

Report Review Procedure

Report Review Procedure

Queries for SRDI-related reports were made from the SNL Technical Library, the DOE OSTI Information Bridge, and the commercial databases discussed in Appendix C. Once all the entries were in a common tabular format for importing into SITED, the database was populated with records in bulk to the SITED server using the PHPMyAdmin interface (see Figure 33). PDF documents were uploaded in bult to SITED using secure copy (scp) from the computer where they were programmatically downloaded from the original sources.

After SITED was initially populated with bibliographic information from the databases, the reports were reviewed and summarized. When a report was needed that was not available electronically from online sources, it was scanned from a hard copy in the SNL WIPP records center, the SNL Technical library, or the SNL Nuclear Waste Management Library. Over 100 1970’s and 1980’s reports and test plans were added to the database this way.

The reviewing procedure was iterative, since the last step of the report review was to check the bibliography for further reports, which was a key way to finds more reports. The process began with a search on a sub-topic, author, or keyword (e.g., “creep”, “Room A”, or “Munson”). The database has thousands of entries, more than could be reviewed in a few weeks, but the report searching, reviewing, and adding loop was quite fruitful in identifying key reports and data sources.

1) **Skim Report:** When a paper or PDF report copy was available, the reviewer read the abstract and conclusions. This level of review allowed confirmation that the report was topical to the interests of SRDI, and an indication of what subjects it covered.
2) **Correct/Update Bibliographic Information:** Information in SITED was checked for correctness and completeness against the original report. Often conference details were entered, which were not in the database or were only in the “notes” field as a comment.
3) **Check Report Relevance to SRDI Project:** If a report was not relevant to the SRDI project goals, the review process was finished at this step. Reports that were even marginally germane to SRDI continued with the following steps:
    a) Read report more thoroughly (taking notes when appropriate).
    b) When a PDF was missing or very poor quality, a quality PDF copy of the report was uploaded to SITED or the report was added to the list “to be scanned” by library personnel.
    c) Copied the abstract from the PDF into the *abstract* field of SITED, to increase SITED search utility. If the scanned PDF report did not have a text layer, optical character recognition was used to add this information to the PDF before uploading.
    d) Copied keywords from PDF or manually add any non-SRDI keywords to the *keywords* field of SITED to increase search utility.
    e) Picked and ranked relevant SRDI-specific keywords (see Table 3 to illustrate logical grouping.).

Zero is the default value for all keyword fields, meaning “not applicable” or unreviewed. Five is the highest ranking for a subject, and was used when a report is essential reading related to that topic. Other numeric values are interpolated between the extremes of not applicable and very important. Although the rating system is somewhat subjective, it provided a degree of quantification beyond a binary “yes/no” system. The references that were ranked highly for specific keywords are listed in Section 6, beginning on page 65. Keywords are arranged in columns in Table 3 for organization.

Table 3. SITED keyword organization

timing	**location/scale**	**report type**	**topic**	**specific features**	**waste**
pre-test	laboratory	summary	salt creep	anhydrite layers	DHLW
in test	in situ	data report	geophysics	argillaceous layers	TRU
post-test	modeling	test plan	heated salt	disturbed rock zone	
	regulatory	bibliography	brine chemistry	backfill	
	field (non-underground)	benchmark	waste packages	crushed salt	
		QA	geology	seals	
			gas flow		
			brine flow		
			mining effects		
			instrumentation		
			shaft		

5) Checked and recorded if tabular data or program source code were listed in the report or elsewhere (e.g., appendices or in the records center).
6) Wrote 1-2 sentences about report in *notes* field, especially capturing any information, features, or keywords not in the abstract or keywords fields to improve SITED search functionality.
7) Checked the document references entries against SITED. To reduce required effort, this was typically limited to cases where a document scored five for one or more SRDI keywords. Added relevant documents listed in report bibliography to SITED, or added to the list “to be found and scanned”.

D-1. Find and Review Electronic Data

The process of finding, accessing, copying, scanning, and annotating electronic data relevant to SRDI has been deferred until fiscal year 2013. Data include tables and listings of creep closure, temperature, stress, corrosion, pressure, and brine inflow observations collected during both in situ and laboratory salt investigations.

The process of creating SITED, bringing it online, and making it visible outside the SNL intranet took approximately two months. The process of populating the database, reviewing reports, and talking with former WIPP PIs has revealed where data should be found, but obtaining the data will require further effort. The proposed procedure is as follows:

1. For electronic media:
   1.1. Find media at WIPP records center, SNL library, or other external sources, if available (e.g., optical disks, magnetic tapes or zip drives).
   1.2. Read electronic media using available computers and equipment at SNL. Reading magnetic tapes, floppy disks, and other obsolete media may require acquiring specific hardware or external contracts with data-recovery service companies.
2. For data only reported in tabular form (hard copy with no electronic media):
   2.1. Scan best quality copies of printed data at a high resolution;
   2.2. Use optical character recognition software to create electronic tables; or
   2.3. When critical data can only be found in printed charts and graphs, data points will be digitized to re-create the original data.
3. Copy electronic data to SITED database server for central archiving.

4. Create short description assessing each dataset that includes:
    4.1. Success/failure reading electronic media, and exact nature of original media;
    4.2. Size of data read;
    4.3. Number of files/directories read;
    4.4. Names and types of files read (e.g., file format);
    4.5. Identify programs/software needed to read data; and
    4.6. Reports and data identified as “critical” to SRDI project will be further examined, plotted, and described as warranted.