Historic Testing Relevant to Disposal of Heat-Generating Waste in Salt

A summary of in situ *tests conducted in geologic salt, focusing on heated salt creep, heated brine migration, and crushed salt reconsolidation.*

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The history of siting nuclear waste repositories around the world has been complex because of the political nature of the topic. This article briefly summarizes the siting history of salt nuclear waste repositories as it relates to the research that has been conducted in support of this overall mission.

Pierce and Rich[1] presented a summary of late 1950s U.S. Geological Survey (USGS) regional salt characterization work, producing reports that included an inventory of U.S. salt deposits. These studies identified four regions as potentially suitable for a salt-based nuclear waste repository. The salt regions of interest were the following:

- 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.
- Paradox Basin anticlines, primarily in southeastern Utah and southwestern Colorado.

Johnson and Gonzales[2] later confirmed these results through more detailed studies of salt deposits. 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 United States.[3]

Project Salt Vault was a solid-waste disposal demonstration in bedded salt performed by Oak Ridge National Laboratory (ORNL) in Lyons, Kan. The U.S. Atomic Energy Commission (AEC) intended to convert the project into a pilot plant for the storage of high-level waste. Despite these intentions, nearby solution mining and questionably plugged oil and gas boreholes resulted in the abandonment of the Lyons site. With help from the USGS, in 1972 ORNL began looking in the Permian Basin for a different disposal site in Texas or New Mexico.[3]

Work on the Waste Isolation Pilot Plant (WIPP) project began after the abandonment of the Lyons salt repos-

The Salt Investigations Technical Expansive Database

The activity to develop the Salt Investigations Technical Expansive Database (SITED) included the design, selection, implementation, and population of an online bibliographic database. Initially, this database was populated from several Department of Energy sources (including Sandia National Laboratories Technical Library, the Los Alamos National Laboratory Research Library, and the DOE Office of Science and Technical Information's Information Bridge [www.osti.gov/bridge/] and Energy Citations Databases [www.osti.gov/energycitations/], and was supplemented during the review process from several external sources (including the European Union Bookshop [http://bookshop.europa.eu/]). Electronic copies of reports are attached to entries whenever they are available. The records in the database were reviewed and ranked according to their potential relevance to current salt research and development related to the disposal of heat-generating waste.

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 (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 do the following:

- Access the interface from outside Sandia National Laboratories (SNL) via the public Internet.
- Allow the creation or editing of database records by authorized personnel.
- Allow for searching/querying existing records by authorized personnel (potentially a different group from those allowed write access).
- Allow for bulk record import from primary sources.
- Allow the attachment of multiple files (e.g., PDF, ASCII text, or data) to each record.

Several commercial and free open-source alternatives were considered. Refbase was chosen because it fulfilled the above requirements and was freely available as source code (PHP scripting language) for customization, when necessary, to the specific needs of the project. 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 landing page for the database is publicly accessible, but SITED requires explicit access permissions from the author to read or edit the database.

itory project with a view to developing a geologic repository for transuranic (TRU) wastes from the defense program. The WIPP project was discontinued in 1974 in favor of concentrating efforts on a Retrievable Surface Storage Facility. After the demise of that project in 1975, work resumed on WIPP and its scope was temporarily expanded to include defense HLW.[4]

A location a few miles 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). Sandia National Laboratories (SNL) became the project lead on the New Mexico salt repository and undertook a major geological site characterization effort for the Los Medaños area.[5] After early geologic complexities and pressurized brine were encountered in the ERDA-6 borehole, the site was moved southwest to its current location.

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Initial WIPP conceptual design involved two waste handling buildings and two waste storage levels, the existing level for TRU waste and a lower level for defense HLW. By May 1978, as the conceptual design for WIPP was being completed, a revised HLW mission was being developed that included one waste-handling building and experimental (temporary) HLW storage. In the summer of 1979, Congress and the U.S. Department of Energy redesigned the WIPP project yet again, eliminating the HLW component (and the lower disposal level) altogether.[4] At this point, the DOE began work on WIPP's environmental impact statement, which was completed in 1981, allowing WIPP site construction to finally begin.

Many salt locations were drilled or sampled as part of an HLW salt repository siting process in the United States[3] from the late 1970s until 1985. These sites often had deep, large-diameter boreholes drilled to provide salt cores used in laboratory creep tests and brine characterization studies. By 1985, the salt repository siting process had narrowed the search down to the following sites:

- Palo Duro Basin (bedded salt) in northern Texas (including the Deaf Smith and Swisher sites).
- Paradox Basin (salt anticline) in eastern Utah and western Colorado (including the Davis Canyon and Lavender Canyon sites).
- Richton and Cypress Creek domes in Mississippi.
- Vacherie Dome in northern Louisiana.
- Oakwood Dome in east Texas.

In 1986, the list of potential repository sites was reduced to three sites, including the Deaf Smith, Texas, site and the two nonsalt sites at Hanford, near Richland, Wash., and Yucca Mountain, in Nye County, Nev. In 1987, the Nuclear Waste Policy Act Amendments called for the phase-out of all site-specific HLW activities at all sites other than Yucca Mountain.

The History of Salt Research

In 1955, the AEC convened an expert panel to investigate options for the disposal of radioactive waste. Salt was recommended as the best disposal medium, with a preference for the disposal of liquid reprocessing waste directly into salt caverns.[6] Concurrent with this panel's work in the mid-1950s, researchers at ORNL and the University of Texas investigated the design principle of direct liquid disposal of reactor reprocessing waste into caverns in salt domes for the AEC.[7] They carried out significant laboratory strength, creep, and permeability tests on salt samples at a range of elevated temperatures (up to 410 °C) and also performed closure measurements in the Grand Saline salt mine, which is located about 50 miles east of Dallas.

Project Salt Vault involved the first significant *in situ* research on the disposal of radioactive waste in salt in the United States. This was both a research project and a demonstration of solid HLW disposal. Early Salt Vault tests had shown direct liquid-waste disposal in salt to be impractical because of concerns about vaporization, loss of containment, and waste-rock interactions.[3] In the early 1960s, Salt Vault was carried out by ORNL for the AEC in abandoned Carey Salt Company bedded salt mines in Lyons and Hutchinson, Kan.[8] From 1965 to 1967, large-scale heater tests were conducted in three sets of seven vertical boreholes, measuring brine inflow to the boreholes and incorporating radioactive sources. Large amounts of brine inflow were observed in boreholes intersecting shale layers (Room 5). The Salt Vault research project also included heated pillar experiments, waste package corrosion studies, and extensive laboratory tests on brine migration and salt creep at elevated temperatures. Once the Lyons site was rejected as a repository location, focus shifted to the Los Medaños area.

In 1975, SNL became the lead laboratory on the southeastern New Mexico disposal project that had been started by ORNL. SNL continued laboratory salt creep testing, begun by ORNL on salt cores collected from the AEC-7 and AEC-8 boreholes.[9] Because limited salt was available for testing from these boreholes, larger samples and tests were sought from the nearby Mississippi Chemical Corporation (MCC) potash mine, located in an upper region of the Permian Salado Formation, where WIPP was eventually constructed. Instrumentation was installed

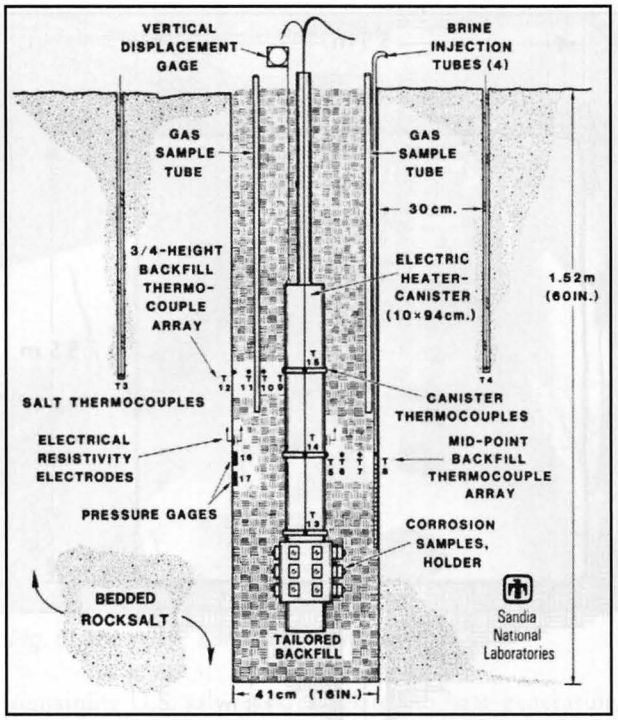

Fig. 1. A waste package test in the Mississippi Chemical Corporation potash mine.

to monitor creep closure of the potash mine workings, and *in situ* tests were carried out,[10] including closure tests in high-extraction areas of the mine (approximately 90 percent extraction ratio), heated brine migration tests, and a suite of six waste package corrosion and backfill consolidation studies (Fig. 1).

Laboratory tests began immediately in 1978 on larger salt samples (1-meter cylinders weighing 1700 kilograms each) collected from the MCC potash mine to investigate brine migration and the thermal properties of salt. The Salt Block I and II tests determined thermal properties of the bedded potash-bearing salt. These laboratory tests included extensive brine-migration analysis during different heated stages of the tests (Fig. 2). Post-test analysis of the salt near the heater showed that brine inclusion migration was a small component of the overall brine collected in the heated borehole.

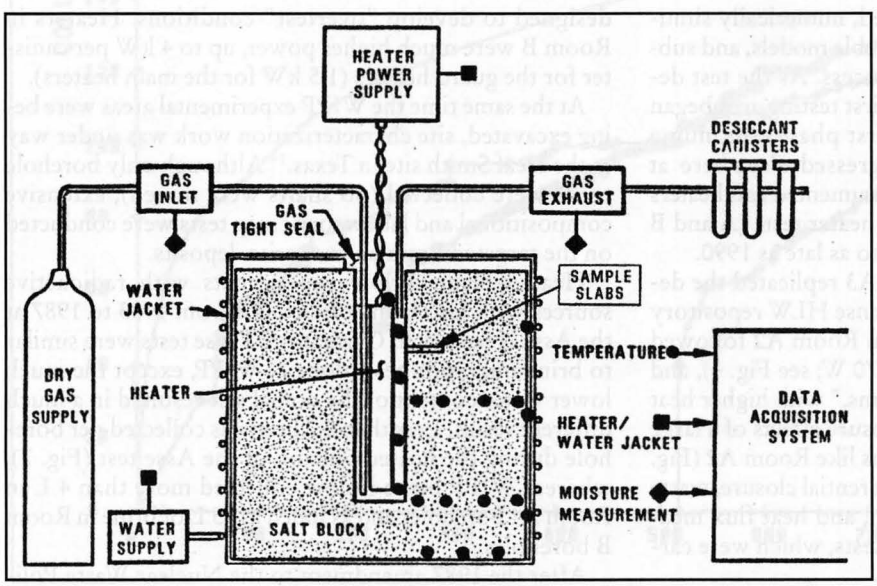

Fig. 2. The Salt Block II experiment on a 1700-kg salt sample.

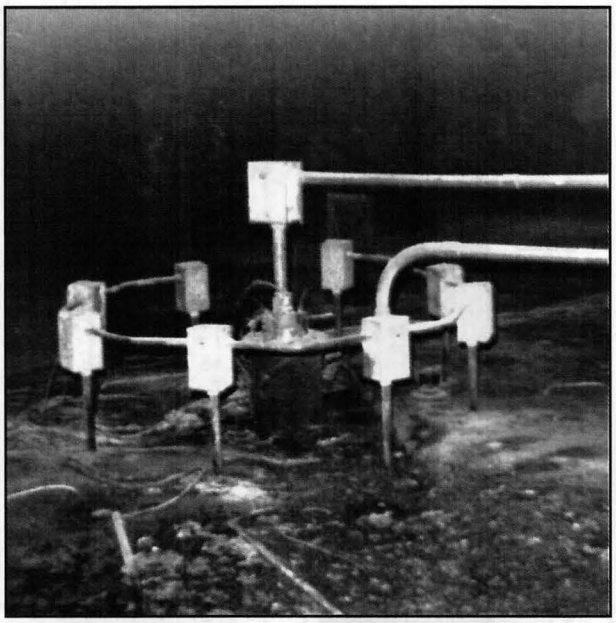

Fig. 3. The Avery Island Site C Test with eight guard heaters.

In 1978, *in situ* heated salt tests began at the Avery Island salt mine to investigate commercial HLW disposal in salt domes.[11] They performed long-duration (1858 days) heated borehole studies (up to 9.6 kilowatts; see Fig. 3), a set of three brine migration experiments (including deuterium-marked tracer studies), gas permeability studies of heated salt, and accelerated borehole closure (core-jacking) tests.

Laboratory creep and thermal testing of salt samples continued using core from WIPP, Avery Island, and several candidate salt dome HLW repository sites. The first underground excavations at the WIPP site were completed in 1981. Site preliminary design validation work by Bechtel continued through 1983, including the first WIPP closure measurements and detailed site geology.[12] 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.

Portions of the *in situ* tests at the Avery Island[11] and the MCC potash mine 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 the Thermal/Structural Interactions (TSI) program, the Waste Package Performance (WPP) program, and the Plugging and Sealing Program (PSP).[13] The plans

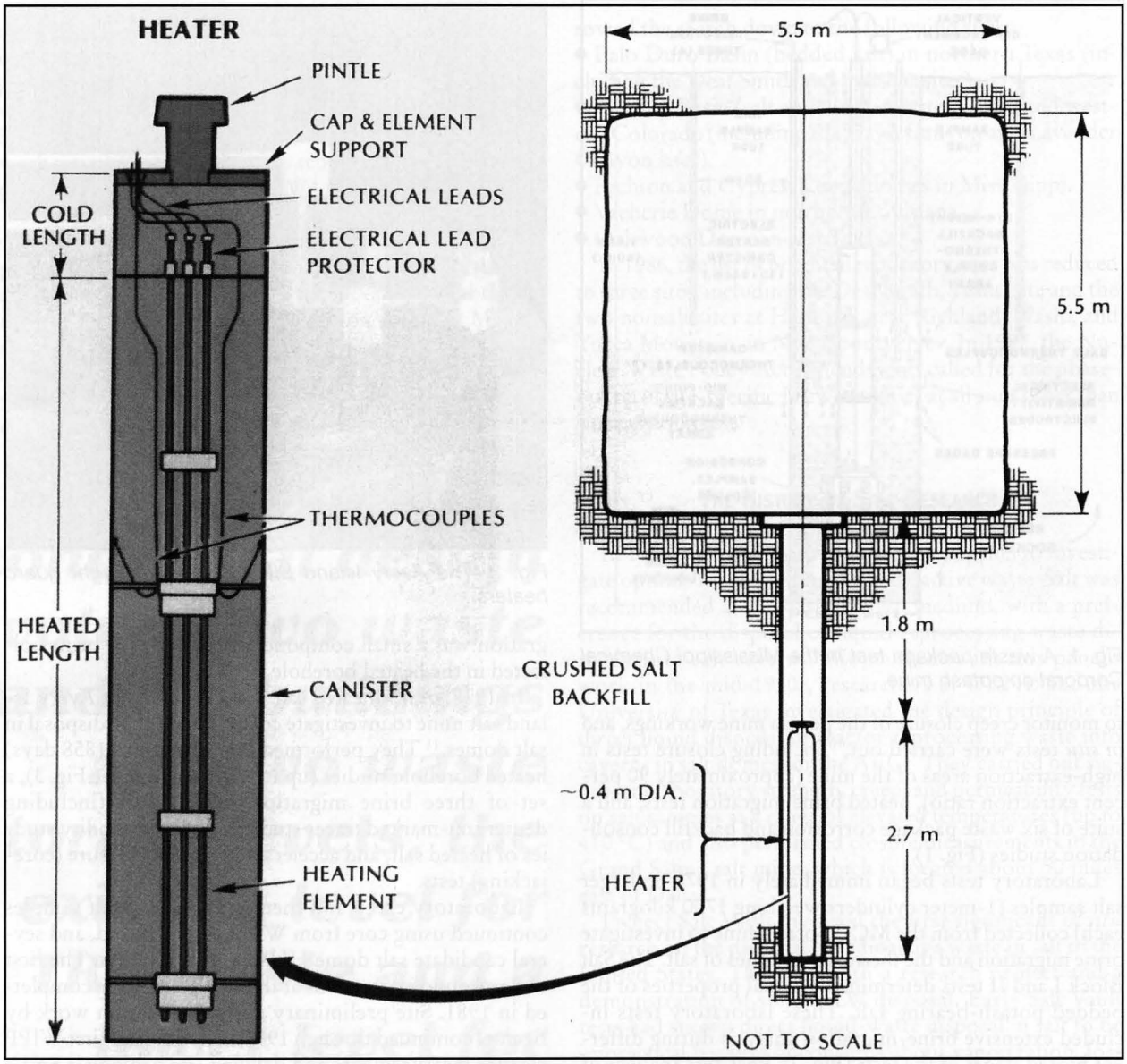

Fig. 4. A typical heater in the WIPP Thermal/Structural Interactions (TSI) Room A and B tests.

for these tests were well documented, numerically simulated beforehand using the best available models, and subjected to a rigorous peer-review process. As the test designs were finalized, mining of the first testing area began with Room D in 1984, with the first phase continuing through 1986. While mining progressed elsewhere at WIPP, experimental rooms were instrumented and heaters were installed, with the first *in situ* heater tests (A and B rooms) turned on in 1985, running to as late as 1990.

The tests in Rooms A1, A2, and A3 replicated the design thermal load specified for a defense HLW repository (18 watts per square meter). Central Room A2 followed the design layout of heaters (each 470 W; see Fig. 4), and Rooms A1 and A3 were "guard rooms," with higher heat loads to recreate the thermal and closure effects of a large repository consisting of many rooms like Room A2 (Fig. 5 and Fig. 6). Extensive thermal, differential closure, waste package corrosion, brine migration, and heat flux measurements were made during these tests, which were carried out over several years.

Room B was a single room with much higher heat loads, designed to develop "overtest" conditions. Heaters in Room B were much higher power, up to 4 kW per canister for the guard heaters (1.5 kW for the main heaters).

At the same time the WIPP experimental areas were being excavated, site characterization work was under way at the Deaf Smith site in Texas.[14] Although only borehole cores were collected (no shafts were mined), extensive compositional and laboratory creep tests were conducted on the targeted Permian evaporite deposits.

Heated brine inflow experiments with radioactive sources were also being carried out from 1983 to 1987 at the Asse II facility in Germany.[15] These tests were similar to brine migration tests done at WIPP, except the much lower water content of the domal salt resulted in a much different result. Less than 0.2 liter was collected per borehole during the heated portion of the Asse test (Fig. 7), whereas WIPP brine inflow collected more than 4 L in Room A1 boreholes and as much as 35 L of brine in Room B boreholes.

After the 1987 amendment to the Nuclear Waste Policy Act, the Deaf Smith site was abandoned, and the only

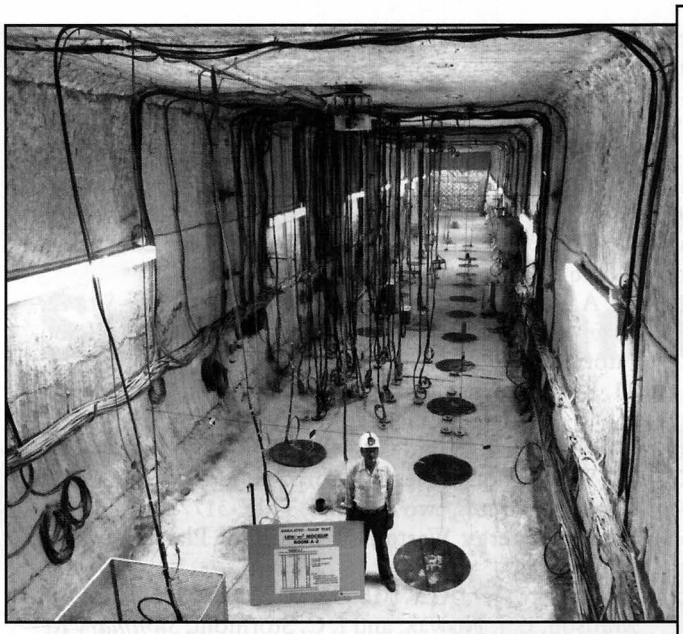

Fig. 5. The WIPP TSI Room A2 heater test.

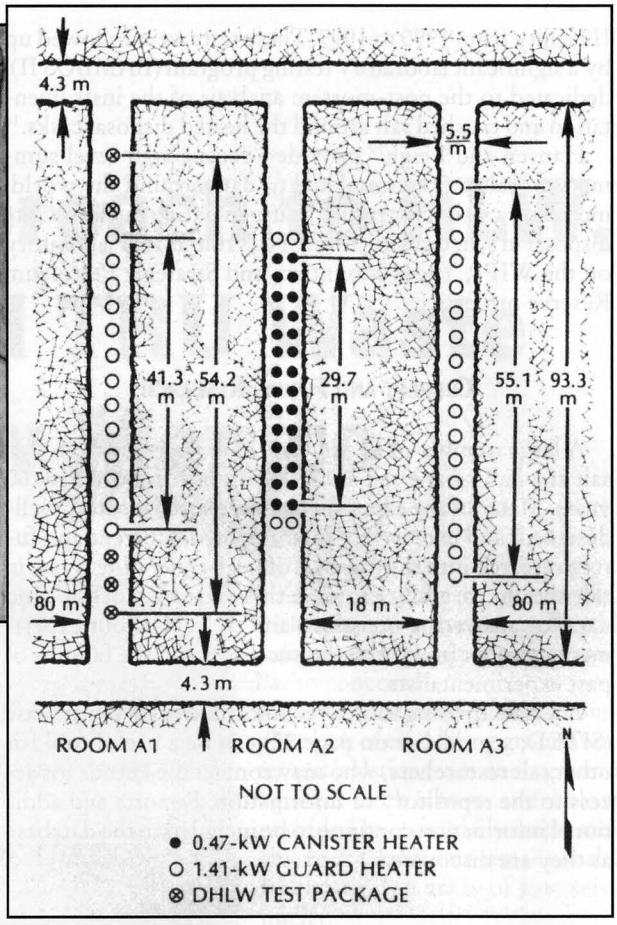

Fig. 6. The WIPP TSI Rooms A1, A2, and A3 layout.

remaining U.S. salt research related to heat-generating waste was defense HLW research that was already ongoing at WIPP, including TSI tests and defense HLW WPP tests, which were ordered to finish as soon as possible. Salt research related to the WIPP TRU waste mission continued, including the PSP studies–for example, large-scale Room Q brine inflow, small-scale mine-by study, and intermediate-scale borehole tests.

Drift-scale heated salt tests were conducted at the Asse

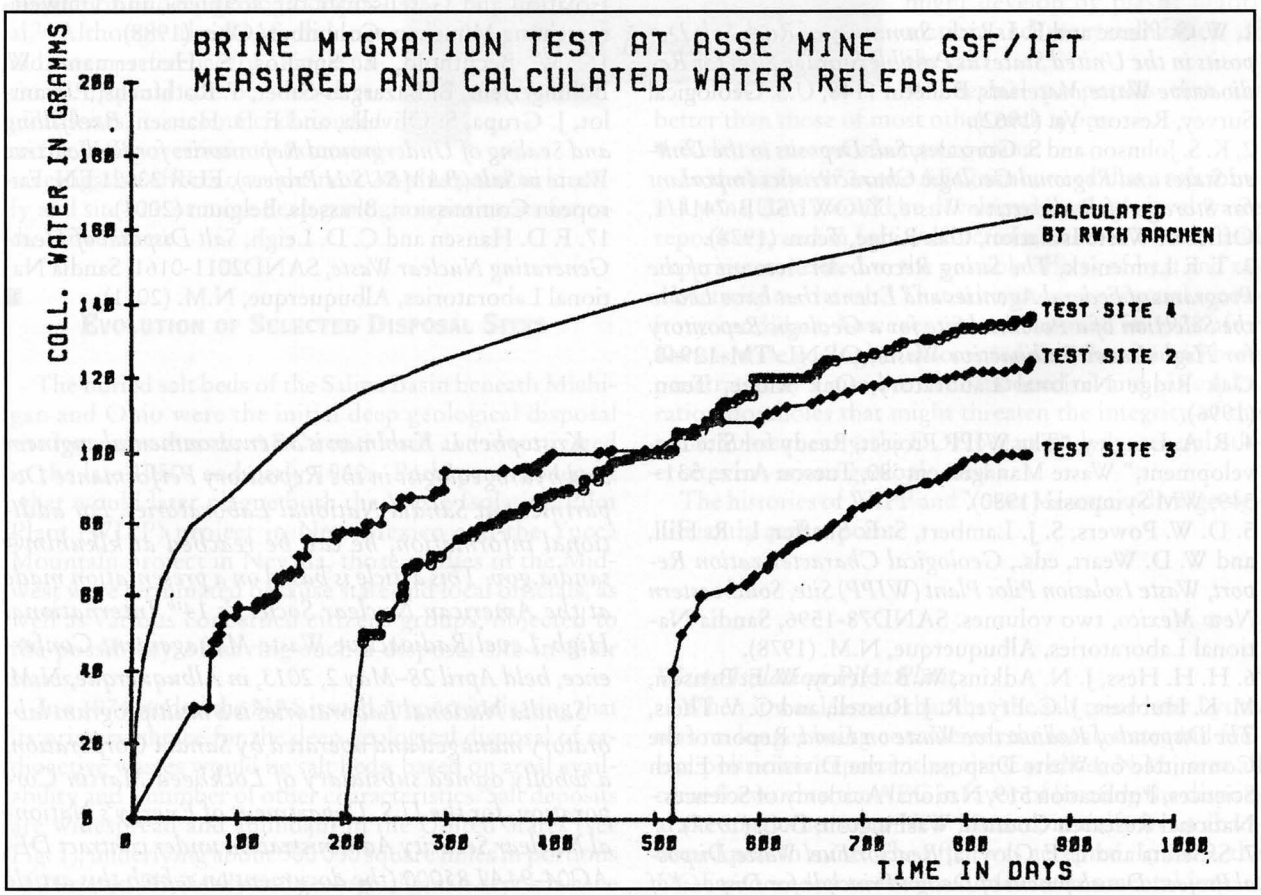

Fig. 7. Heated brine migration test results at Asse II.

II 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.[16]

Hansen and Leigh[17] provide a recent high-level summary of salt work completed to date around the world, including 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.

Current and Future Research

A large number of *in situ* tests have been conducted in salt at a half-dozen salt study locations for more than 60 years. Many of the experiments were sophisticated, well-designed, and extensively instrumented. Current and future research into the disposal of heat-generating waste in salt should carefully examine this existing work to find data for answering questions and to learn about experimental design from both the successes and the failures of past experimentalists.

The Salt Investigations Technical Expansive Database (SITED; see sidebar on page 22) can be a useful tool for other salt researchers, who may contact the author for access to the repository of information. Reports and additional information continue to be included in the database as they are discovered.

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