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Salt Disposal of Heat-Generating Nuclear Waste

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ABSTRACT

This report summarizes the state of salt repository science, reviews many of the technical issues pertaining to disposal of heat-generating nuclear waste in salt, and proposes several avenues for future science-based activities to further the technical basis for disposal in salt. There are extensive salt formations in the forty-eight contiguous states, and many of them may be worthy of consideration for nuclear waste disposal. The United States has extensive experience in salt repository sciences, including an operating facility for disposal of transuranic wastes. The scientific background for salt disposal including laboratory and field tests at ambient and elevated temperature, principles of salt behavior, potential for fracture damage and its mitigation, seal systems, chemical conditions, advanced modeling capabilities and near-future developments, performance assessment processes, and international collaboration are all discussed. The discussion of salt disposal issues is brought current, including a summary of recent international workshops dedicated to high-level waste disposal in salt.

Lessons learned from Sandia National Laboratories' experience on the Waste Isolation Pilot Plant and the Yucca Mountain Project as well as related salt experience with the Strategic Petroleum Reserve are applied in this assessment. Disposal of heat-generating nuclear waste in a suitable salt formation is attractive because the material is essentially impermeable, self-sealing, and thermally conductive. Conditions are chemically beneficial, and a significant experience base exists in understanding this environment. Within the period of institutional control, overburden pressure will seal fractures and provide a repository setting that limits radionuclide movement. A salt repository could potentially achieve total containment, with no releases to the environment in undisturbed scenarios for as long as the region is geologically stable. Much of the experience gained from United States repository development, such as seal system design, coupled process simulation, and application of performance assessment methodology, helps define a clear strategy for a heat-generating nuclear waste repository in salt.

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NOMENCLATURE

CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
DRZ	disturbed-rock zone
EPA	U.S. Environmental Protection Agency
FEP	feature, event, or process
HLW	high-level waste
IRZ	isolation rock zone
NAS	National Academy of Sciences
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
PA	performance assessment
SNL	Sandia National Laboratories
THM	thermal-hydrologic-mechanical
TRU	transuranic waste
UNF	used nuclear fuel
WIPP	Waste Isolation Pilot Plant

1 INTRODUCTION

While the need for increased use of nuclear power in the United States (U.S.) has been recognized, the questions of when and how to dispose of the resulting used nuclear fuel (UNF)[1] and high-level nuclear waste (HLW), a necessary last step in the cradle-to-grave philosophy of radioactive waste management, still eludes satisfactory answers. In the 1987 amendment to the Nuclear Waste Policy Act of 1982 (NWPA), Congress selected Yucca Mountain in Nevada to characterize for waste disposal of UNF and HLW. Over the next 21 years, the U.S. Department of Energy (DOE) investigated the site, evaluated its feasibility, confirmed its viability (DOE 1998), made a site recommendation (DOE 2002a, 2002b, 2002c), and prepared a license application for construction authorization (DOE 2008a). The license application was submitted to the U.S. Nuclear Regulatory Commission (NRC) in June 2008 and docketed for review that September. In 2009 during the NRC review of the license application, the Obama Administration recommended and Congress provided funding only for answering NRC questions as they prepared their Safety Evaluation Report. All other activities ceased. In 2010, the DOE formed the Blue Ribbon Commission on America's Nuclear Future. The DOE has filed a motion to withdraw the license application, which is under legal review, but the project has nevertheless been totally disbanded.

Given the developments at the Yucca Mountain Project, it is prudent to anticipate that the U.S. will begin the process of developing a new radioactive waste management policy. Many of the policy issues debated in the 1970s and early 1980s will be revisited. The public debate over UNF/HLW disposal will focus on potential reprocessing, interim storage, geologic disposal, and repository siting, particularly with regard to environmental justice and intergenerational equity. While certain alternatives being discussed, like reprocessing of UNF and/or interim storage would change the volume and/or radioactivity of waste needing disposal, there will ultimately be a residual fraction of the waste stream that must be permanently disposed. This residual fraction of waste will be high-heat-generating, chemically active, radioactive waste. Geologies for permanent deep disposal of HLW, like shale, granite, clay, and salt, have been proposed over the years both in the U.S. and in other countries. All of these geologic formations or geologic media exist in the U.S., but a suitable site for disposal of HLW has yet to be chosen (other than Yucca Mountain).

From a study of the historical approach toward selecting a HLW disposal site, DeKay (1999) has suggested three patterns in the national management of nuclear waste. First, concerns over water are an integral component of the public's fear of nuclear waste in geologic media, and this fear has impacted the search for a

[1] With the current reevaluation of reprocessing in the United States, the term *used nuclear fuel* (UNF) has supplanted *spent nuclear fuel* (SNF) as the preferred terminology for fuel discharged from a nuclear reactor. In this document, the term *high-level waste* (HLW) is used to denote heat-generating nuclear waste.

suitable repository site. Second, according to DeKay (1999) there are always other immediate concerns that take precedence over the nuclear waste issue. Third, nuclear-waste-management decisions are based on political expediency rather than making long-term decisions for developing a nuclear waste repository. While in 1987 Yucca Mountain was selected as the sole site for the potential development of a repository, its selection has been controversial. Therefore, while a technical commentary can be provided regarding the adequacy of each geologic medium for permanent disposal of HLW, the ultimate decision will be a social and political one involving the disposal location or locations.

Sandia National Laboratories (SNL) has conducted performance analyses for disposal of HLW in deep boreholes basement rock (Brady et al. 2009) and in a mined geologic repository in clay/shale (Hansen et al. 2010) and has a long history of performance-assessment analyses for disposal of non-heat-generating waste in salt. This report contributes to the national discussion regarding geologic disposal by synthesizing technical information regarding salt disposal of HLW. It agrees with a well-known study by the National Academy of Sciences National Research Council in the 1950s (National Academy of Sciences Committee on Waste Disposal 1957) that states,

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

Over time, a considerable body of research has been conducted to advance the state of knowledge with respect to waste isolation in salt. The work embodied in this report further amplifies that salt is a viable geologic setting for permanent waste isolation in the U.S. Much scientific and technical knowledge about disposal in salt has accumulated since the initial conclusions made by the National Academy of Sciences. This report updates the technical basis for disposal in salt and discusses the performance issues that should be addressed when considering disposal of HLW in salt.

1.1 Background and Regulatory Framework

To evaluate the performance of any potential repository and decide whether to proceed with a disposal concept, it is necessary to adopt or develop a regulatory standard by which the performance of the site can be measured. This section provides background information about development of pertinent regulations for radioactive waste disposal to date and establishes the general regulatory framework that is considered in this report.

The search for permanent disposal for radioactive waste began in 1955 when the Atomic Energy Commission (AEC), predecessor agency to the Energy Research and Development Agency and the DOE, asked the National Research Council of the National Academy of Sciences to examine the disposal issue. In 1957, the National Academy of Sciences Committee on Waste Disposal (1957) reported that deep geologic disposal in salt formations was the most promising method to explore for disposing of HLW resulting from reprocessing of UNF. The National Academy of Sciences reaffirmed that position in 1961 and 1970 (NAS-NRC 1961; National Academy of Sciences Committee on Waste Disposal 1970).

By 1974, the AEC's regulatory programs had come under attack, and Congress decided to abolish the agency. Supporters and critics of nuclear power agreed that the promotional and regulatory duties of the AEC should be assigned to different agencies. The Energy Reorganization Act of 1974 created the Nuclear Regulatory Commission (NRC); it began operations on January 19, 1975. The NRC focused its attention on several broad issues that were essential to protecting public health and safety. The promotional duties of the AEC were later incorporated into the DOE when it was established in 1977.

The Nuclear Waste Policy Act of 1982 (NWPA) created a timetable and procedure for establishing a permanent underground repository for UNF and HLW from civilian nuclear reactors. Congress assigned responsibility to the DOE to site, construct, operate, and close a repository for the disposal of UNF and HLW. The U.S. Environmental Protection Agency (EPA) was directed to set public health and safety standards for releases of radioactive materials from a repository, and the NRC was required to promulgate regulations governing construction, operation, and closure of a repository.

In 1986, the DOE selected three candidate sites for HLW disposal, each in different geologic media: basalt at the Hanford Reservation, Washington; volcanic tuff at Yucca Mountain, Nevada; and bedded salt at Deaf Smith County, Texas (DOE 1986). In 1987, Yucca Mountain was specified[2] as the sole site for the potential development of a HLW repository. Over the next 21 years, the U.S. continued site investigations, conducted performance assessment (PA), supported modeling activities, and started design for a repository at Yucca Mountain.

In the meantime, the EPA standard 40 CFR 191 was promulgated.[3] In 40 CFR 191, the primary performance criterion is the cumulative release of radionuclides, and its measure is the mean complementary cumulative distribution function of the cumulative release of radionuclides that reach the accessible environment within ten thousand years after disposal, normalized by (a) EPA-derived limits for specified radionuclides and (b) the mass of radionuclides placed in the repository. The risk of release is limited to be the same or less than that posed by the ore body from which the radioactive material was produced.

[2] The 1987 amendments to the NWPA restrict consideration of geologic repositories in the U.S. to a single site in volcanic tuff at Yucca Mountain in Nevada.

[3] The EPA also passed 10 CFR 194*, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations*, which is not discussed here because it is specific to the Waste Isolation Pilot Plant and transuranic wastes.

Also, the NRC promulgated 10 CFR 60, *Disposal of High-Level Radioactive Wastes in Geologic Repositories.*[4] Specific technical criteria are addressed in Subpart E of 10 CFR 60, including various categories such as performance objectives, siting criteria, design criteria for repository operations, and design criteria for the waste package. Under these regulations, the waste package is required to contain HLW for a period between 300 and 1,000 years after closure of the repository. The repository must not allow annual radionuclide releases in excess of one part in 100,000 of the inventory of radionuclides calculated to be present at 1,000 years from closure. Also, pre-emplacement groundwater travel time along the fastest path of likely radionuclide travel to the accessible environment must be more than 1,000 years. Neither 40 CFR 191 nor 10 CFR 60 is a dose-based standard.

In 1995, the National Research Council of the National Academies of Science and Engineering recommended using risk as the primary long-term performance measure for a Yucca Mountain repository (National Research Council 1995). The International Commission on Radiation Protection (ICRP) made a similar recommendation in 1997 (ICRP 1997), and the International Atomic Energy Agency (IAEA) model standard issued in 2006 uses a standard of dose, or dose-equivalent risk, for deep geologic disposal of radioactive waste (IAEA 2006).

Consequently, EPA standard 40 CFR 197, specifically written for a repository at Yucca Mountain, specifies the performance measure as the expected (mean) peak dose to a reasonably maximally exposed individual living along the predominant groundwater flow path 18 kilometers from the site. Though 40 CFR 197 initially specified a performance period of 10,000 years, it was remanded by federal court in 2004 because of inconsistency with the National Academy of Sciences recommendation to regulate to the time of peak dose at the period of geologic stability (about 1 million years for Yucca Mountain). It was reissued in 2008, retaining the 15 millirem limit for the first 10,000 years and adding a limit of 100 millirem for the period from 10,000 to 1 million years.

There is currently no performance standard for disposal of HLW in salt. At a minimum, consideration of HLW disposal in salt would require changes to the legal framework specified in the NWPA. In principle, existing regulations from the 1980s that predate the selection of Yucca Mountain (i.e., 40 CFR 191 and 10 CFR 60) could be applied without modification. However, these early regulations are inconsistent with recommendations provided in 1995 by the National Academy of Sciences (National Research Council 1995) at the request of Congress and may, therefore, be viewed as inadequate. More likely, new standards for disposal of HLW in media other than volcanic tuff at Yucca Mountain, Nevada, would need to be considered.

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[4] The NRC also promulgated 10 CFR Part 63, *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain*, *Nevada*, which is not discussed here because it is specific to Yucca Mountain.

To the extent that regulatory guidance has bearing on the technical basis for disposal of HLW in salt, the following assumptions are made:

- This analysis focuses on the isolation provided by the disposal formation and avoids speculation about site-specific aspects of geology closer to the ground surface.
- EPA standards and NRC regulations pertaining to HLW disposal in salt would place specific requirements on PA models that are intended to demonstrate compliance with regulatory performance objectives.
- Screening criteria for potentially relevant features, events, and processes (FEPs) would be defined through regulation and would be similar to those summarized in Appendix A.
- New regulatory requirements would be developed for human intrusion scenarios, which depend more on the overall setting of the repository than on the geologic medium being considered.
- Requirements in both the EPA standards and the NRC regulations specific to the retrievability of waste would be met by the existing technologies available for HLW disposal in salt.

1.2 Salt Formations in the United States

Use of salt formations for nuclear waste disposal has been a widely embraced concept for more than 50 years. Disposal of nuclear waste in salt remains a viable concept in the U.S., as has been successfully demonstrated by virtue of more than ten years of successful operations at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. As shown in Figure 1 and Table 1, the conterminous U.S. has many salt formations, including bedded and domal salt. For repository considerations and other uses, such as petroleum storage, salt formations are often categorized as "bedded" or "domal." Bedded formations of salt (sodium chloride) are found in layers interspersed with materials such as anhydrite, shale, dolomite, and other salts such as potassium chloride. These formations are tabular and can range across enormous land areas (see Figure 1). Bedded salt formations are often between 200 to 600 meters thick, but in some cases they can have thicknesses of up to 1,000 meters in the U.S. Domal formations (i.e., salt domes) form from salt beds when the density of the salt is less than that of surrounding sediment. Under such conditions, the salt has a tendency to move slowly upward toward the surface. As the buoyant salt moves upward, it deforms plastically into mushroom-shaped diapirs and many other cylindrical and anticlinal shapes. The top of some domal salt can be near surface, while the root may extend to a great depth. Typically the diameter of a salt dome is on the order of 5 kilometers.

Advantages of salt for HLW disposal

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

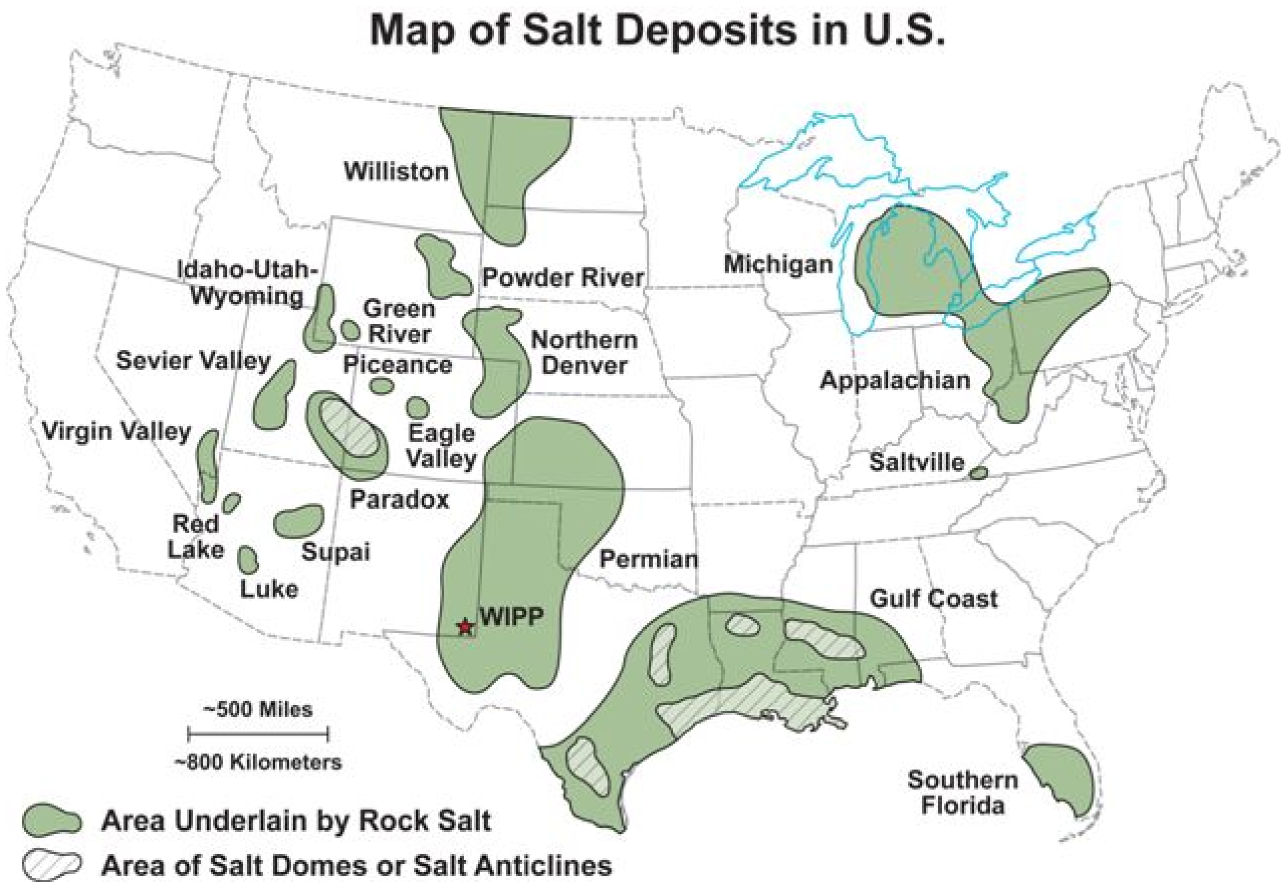


Figure 1. Salt deposits in the United States (Johnson and Gonzales 1978).

The five major regions of the U.S. where salt formations are found include (1) the Gulf Coast, (2) the Permian Basin, (3) the Michigan-Appalachian Region, (4) the Paradox Basin, and (5) the Williston Basin. Domal salts are found in the Gulf Coast region, and bedded salts are present in the remaining four major salt regions.

Screening of the entire U.S. in the 1960s and 1970s identified the following large regions underlain by rock salt of sufficient depth and thickness to accommodate a repository:

- **Salt domes on the Gulf Coast.** Using technical screening criteria, the Cypress Creek, Richton, and Vacherie Domes were identified as potentially acceptable sites.

- **Bedded salt in Utah.** Based on technical screening criteria, Davis Canyon and Lavender Canyon were identified as potentially acceptable sites.

Table 1. Salt and potash mines in the continental United States

Name	Salt Type	Location	Company	Depth (ft)	Mined Height (ft)
Cayuga	Bedded	Ithaca, NY	Cargill	1,800	13
Whiskey Island	Bedded	Cleveland, OH	Cargill	1,850	28
Lyons	Bedded	Lyons, KS	Lyons Salt	< 1,000	16
Kanopolis	Bedded	Kanopolis, KS	Independent Salt	< 1,000	16
Hutchinson	Bedded	Hutchinson, KS	Vaults and Storage	1,000	16
Detroit	Bedded	Detroit, MI	Detroit Salt	1,800	18
Fairport	Bedded	Fairport, OH	Morton Salt	1,850	13
Hampton's Corner	Bedded	Geneseo, NY	American Rock Salt	1,100	15
East North	Bedded	Carlsbad, NM	Intrepid Potash	700–2,000	6–7
Nash Draw	Bedded	Carlsbad, NM	Mosaic Potash	900–1,200	6–7
Avery Island	Domal	Avery Island, LA	Cargill	Vertically very deep with limited lateral extent	25–100
Weeks Island	Domal	Weeks Island, LA	Morton Salt		25–100
Cote Blanche	Domal	Louisia, LA	Compass Minerals		25–100
Hockley	Domal	Hockley, TX	American Salt		25–100
Grand Saline	Domal	Grand Saline, TX	Morton Salt		25–100

- **Bedded salt in western Texas and southeastern New Mexico.** Permian bedded salt deposits in the Texas panhandle and western Oklahoma were found to be technically suited for waste disposal, and locations in northeastern Deaf Smith County and north-central Swisher County, Texas, were initially identified as potentially acceptable.

In 1985, the Secretary of Energy nominated three salt formation sites from among the five sites taken forward for further consideration as repositories: Deaf Smith County, Texas, Davis Canyon, Utah, and Richton Dome on the Gulf Coast. Subsequently, in 1986, the Deaf Smith County site was selected to fully characterize. However, site characterization was not completed prior to the enactment of the 1987 amendments to the NWPA, which left only the Yucca Mountain site for full characterization.

Mining experience in different salt terrains and at different depths demonstrates successful underground operations and extensive knowledge of isothermal conditions that would be considered in design of mined openings for disposal in salt. In the U.S., repository development would likely not involve conversion of operating salt mines into repositories because of the specific design requirements desired for HLW disposal. Rather, a concept of operation would be developed drawing from a wealth of mining experience and a new facility designed for the repository. Table 1 lists production salt and potash mines in the U.S. (not including solution mines), illustrating the regional availability of salt resources.

1.3 History of Salt Disposal Research for Heat-Generating Nuclear Waste

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

1965–69. The first integrated field experiment for the disposal of HLW was performed by Oak Ridge National Laboratory in bedded salt near Lyons, Kansas. This test, named Project Salt Vault, used one set of irradiated fuel assemblies from the Engineering Test Reactor at Idaho Falls as a source of intense radioactivity, while electrical heaters were placed in boreholes in the floor to simulate decay heat generation of HLW. The tests simulated the heat flowing into the base of the pillar from a room filled with waste with the primary focus on rock mechanics of floor, ceiling, and pillar deformation.

The tests also studied potential structural effects of radiation and found that there were none. Farbe centers (F centers) are often associated with radiation damage that creates blue and black salt crystals by virtue of a stoichiometric excess of sodium. Sonnenfeld (1995) explains the several possible causes for colored salt, but no physical or mechanical behavior of importance to repository performance is attributed to radiation effects on salt.

These pioneering tests with live UNF and simulated electrical heaters produced pillar temperatures of less than 50°C. Brine accumulation was observed after the electrical heaters were turned off, which initiated the lingering issues of moisture behavior in such a setting. Possible brine inclusion migration and vapor transport phenomena were not completely resolved by these field experiments (Bradshaw and McClain 1971). These tests established that salt was an acceptable host rock for radioactive waste disposal, but local factors, both technical and political, resulted in abandonment in 1972 of an AEC proposal to construct a repository at the Lyons, Kansas, site.

1968. Field experiments with electrical heaters were performed in the Asse salt mine to investigate the near-field consequences of emplaced HLW. These early experiments evaluated thermal-mechanical properties of the Stassfurt Halite. Later repository options were investigated, including vertical borehole disposal of steel canisters and horizontal placement of steel casks surrounded with crushed-salt backfill. Emplacement of radioactive canisters was never realized; however, a placement system was successfully tested without radioactive material, and the system was approved by the responsible mining authority. In all, three large-scale "heater" experiments were performed in the Asse mine, which yielded important data for the validation of material and computer models needed to assess the coupled long-term behavior of rock salt and crushed salt backfill in a salt repository. The Asse experiments provided important lessons and guidance for future testing (Brewitz and Rothfuchs 2007, Kühn 1986).

1979. Also in Germany, the Gorleben salt dome was investigated from 1979 until a moratorium beginning October 2000. In 1998, the German government expressed certain doubts with respect to the suitability of salt as a host rock in general and of the Gorleben site in particular. All exploration activities were halted by the end of 2000, and a moratorium was imposed for up to 10 years (Brewitz and Rothfuchs 2007). The moratorium ended in September 2010, so German repository scientists are poised to ramp up the salt repository investigations at Gorleben. Like the salt testing in the U.S., German research has provided a wealth of information on salt disposal research which is being and will be considered in future collaboration efforts (see Section 4.7).

1979–82. Brine migration tests were performed by RESPEC for the Battelle Memorial Institute (BMI) Office of Nuclear Waste Isolation (ONWI) in the Avery Island salt mine in Louisiana. The migration of brine inclusions surrounding a heater borehole was studied on a macroscopic scale by investigating gross influences of thermal and stress conditions in situ. Field tests were augmented in the laboratory by microscopic observations of fluid inclusion migration within an imposed thermal gradient. The maximum temperature reached in the field test was 51°C. Moisture collection during heater tests amounted to grams of water per day. When the heaters were shut off, cooling caused changes in tangential stress, which led to microcracking, opening of grain boundaries, and moisture release. It was concluded that much of the moisture released was a result of this cooling process (Krause and Gnirk 1981).

1983–85. A bilateral U.S.-German cooperative Brine Migration Test in the Asse salt mine investigated the simultaneous effects of heat and radiation on salt. This field experiment used cobalt-60 (^{60}Co) sources and heater arrays. The maximum temperature in the salt was 210°C, and the maximum temperature gradient was approximately 3°C/cm. The low moisture values measured suggest that the predominant migration mechanism in Asse salt is vapor migration. Similar to the Avery Island test results, a steep increase in brine release was noted because of cool-down cracking caused when the heaters were shut off (Rothfuchs et al. 1988).

1984–1993. Three separate simulated HLW heater tests were performed at WIPP: (1) 18 W/m^2 DOE high-level waste (DHLW) mockup, (2) DHLW over-test, and (3) the Heated Axisymmetric Pillar test. The 18 W/m^2 DHLW mockup and DHLW over-test were designed to identify how the host rock and the disposal room respond to the excavation itself and then to the heat generated from waste placed in vertical holes in the drift floor. These tests imparted a relatively modest thermal load in a vertical borehole arrangement and did not use crushed-salt backfill or explore reconsolidation of salt. They primarily focused on the mechanical response of the salt under modest heat load. The results can be used, for example, to validate the next-generation high-performance codes over a portion of the multiphysics functionalities. The Heated Axisymmetric Pillar test involved an isolated, cylindrically shaped salt pillar and provides an excellent opportunity to calibrate scale effects from the laboratory to the field, as well as a convenient configuration for computer model validation (Matalucci 1987).

1985–1990. A set of moisture transport and release tests were part of the borehole plugging and sealing test series at WIPP and were designed to measure moisture release associated with heated boreholes and to evaluate transport mechanisms. Each borehole contained a nitrogen flow and a water vapor collection and measurement system. Water vapor flowing in the nitrogen was collected and weighed (Nowak and McTigue 1987). These data characterizing brine movement and accumulation were interpreted in terms of a model for flow in a saturated porous medium. Comparisons between model calculations and brine inflow rates showed order-of-magnitude agreement for permeability in accord with independent in situ determinations of permeability in the salt. Expected accumulations of brine in typical WIPP waste disposal rooms were calculated by numerical methods using a mathematical description for the brine inflow model. Brine accumulation in a disposal room was calculated to be in the range of 4 m^3 to 43 m^3 in 100 years. The maximum expected accumulation, 43 m^3, is 1.2% of the initial room volume, about the same as the quantity of brine in the salt that was removed by mining the room (Nowak, McTigue, and Beraun 1988).

1986–1991. An in situ test of simulated HLW glass and other waste package components was conducted at WIPP beginning in 1986 in a program known as the Materials Interface Interactions Test (MIIT). The MIIT involved approximately 1,900 samples in 50 test boreholes, with specimens that included 16 variations of simulated HLW glass, 11 potential canister metals, rock salt, and two brine solutions (Wicks and Molecke 1988). The MIIT included a 5-year study of the burial of simulated waste glasses and the resulting long-term waste-glass leaching behavior. Brine analyses were performed on samples from selected boreholes containing simulated waste-glass specimens, resulting in release rates of less than one part in 100,000 for all elements investigated (Wicks 2001).

1.4 Analogues for Salt Disposal

As this report acknowledges, some key issues pertaining to HLW disposal in salt need attention if a salt disposal option is selected. These remaining issues should not be misconstrued to imply the scientific basis for salt disposal is weak. It is not. Salt disposal remains a very favorable option for the U.S. The most likely future for HLW salt disposal includes permanent, dry encapsulation.

Considerable qualitative support for this strong impression derives from pertinent analogues.

Many anthropogenic and geologic analogues provide insight into permanent nuclear waste disposal in salt. Anthropogenic analogues derive from over 7,000 years of salt excavation by mankind and wide use of salt formations, including storage of fluid hydrocarbons. Fifty years ago the unique sealing capability of salt was dramatically demonstrated by the most severe test possible: containment of nuclear detonations in salt horizons. In addition to anthropogenic evidence from mining experience and nuclear detonations, nature itself showcases the encapsulating ability of salt formations penetrated by high-temperature magmatic dikes. The analogues summarized here provide qualitative evidence that salt formations have the capacity to contain a wide variety of severe conditions permanently.

Sealing a nuclear waste repository and waste corrosion are considered two primary issues with salt disposal. Anthropogenic evidence associated with vast and pertinent mining experience provides important qualitative assessments of preserved artifacts. The Hallstatt area in Austria supported prehistoric salt mining. Archeological re-excavation has recovered organic material such as leather, wood, clothing and even an unfortunate Celtic miner preserved in the salt for 3,000 years. More recent analogues spanning 50 or 100 years of mining experience offer convincing evidence of structural, mechanical, and hydrological behavior of the underground salt environment. The salt and potash mining industry has placed functional seals in underground workings, backfilled, and reconsolidated crushed salt in active mining operations. Within the potash basin in southeastern New Mexico mining operations, machinery which is not brought back to surface suffers almost no corrosion after more than 50 years.

The most dramatic man-made analogues—considered beyond-worst-case analogues—are nuclear detonations in salt (Rempe 1998). The USA has detonated three nuclear devices in salt: one at the Gnome Site near WIPP and two at the Salmon Site at Tatum Dome in Mississippi. The 3.1 kiloton Gnome shot, which unintentionally breached drift seals and sent radioactive steam up the shaft, was cleaned up by dumping the surface material down the shaft and thereafter recommended for public release (Gardner and Sigalove 1970). The Gnome shot was situated near the top of the Salado Formation, roughly half as deep as the WIPP repository. No migration has been detected outside the experiment's boundary for half a century. The Tatum tests involved two sequential devices; the second was detonated in the cavity created by the first. By virtue of monitoring results, the radioisotopes were determined to be confined to the test cavity, i.e., the test cavity was determined not to be leaking radioactivity (DOE 1999). The Tatum shots were executed at a depth of 2,700 feet. Salt formations have been shown to seal and confine nuclear detonations.

Geologic analogues also supply strong evidence of the confining nature of salt formations. Examples of natural geologic analogues include salt formations in

New Mexico and Germany that have been intersected by magmatic dikes (Loehr 1979; Knipping 1989; Knipping and Herrmann 1985; Steinmann and Stille 2004). Despite the severe nature of such magmatic intrusions, there are only very thin alteration zones at the contact between the high-temperature igneous intrusion and the salt. No evidence of significant fluid (inclusion) migration toward the heat source has been reported from field observations.

Analogues involving massively disruptive events within a salt formation create accessible evidence of salt containment over very large spatial domains and lengthened time periods. As such, these analogues are tantamount to qualitative performance assessment arguments for complete containment of nuclear waste disposal in salt. Obviously, there are no engineered barriers involved with entombment and isolation demonstrated by analogues. Properties of salt itself allow the geological formation to absorb the intrusion and naturally seal and encapsulate it.

It is the opinion of the technical repository community that the U.S. could construct suitable permanent repositories in a variety of geological disposal media including salt (Hansen, Hardin, and Orrell 2011). Table 2 provides a qualitative comparison of salt to other geologic media. Because of the long and visible salt history, these formations have exhibited many characteristics favorable to permanent isolation. Many of these parameters for salt will reviewed in Section 2.

Table 2. Qualitative comparison of geologic media as HLW repository host

	Salt	Shale	Granite	Deep Boreholes
Thermal Conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on the scale of decades	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemistry	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

Favorable quality | Average or variable quality | Unfavorable property

2 TECHNICAL BASIS AND CHARACTERIZATION

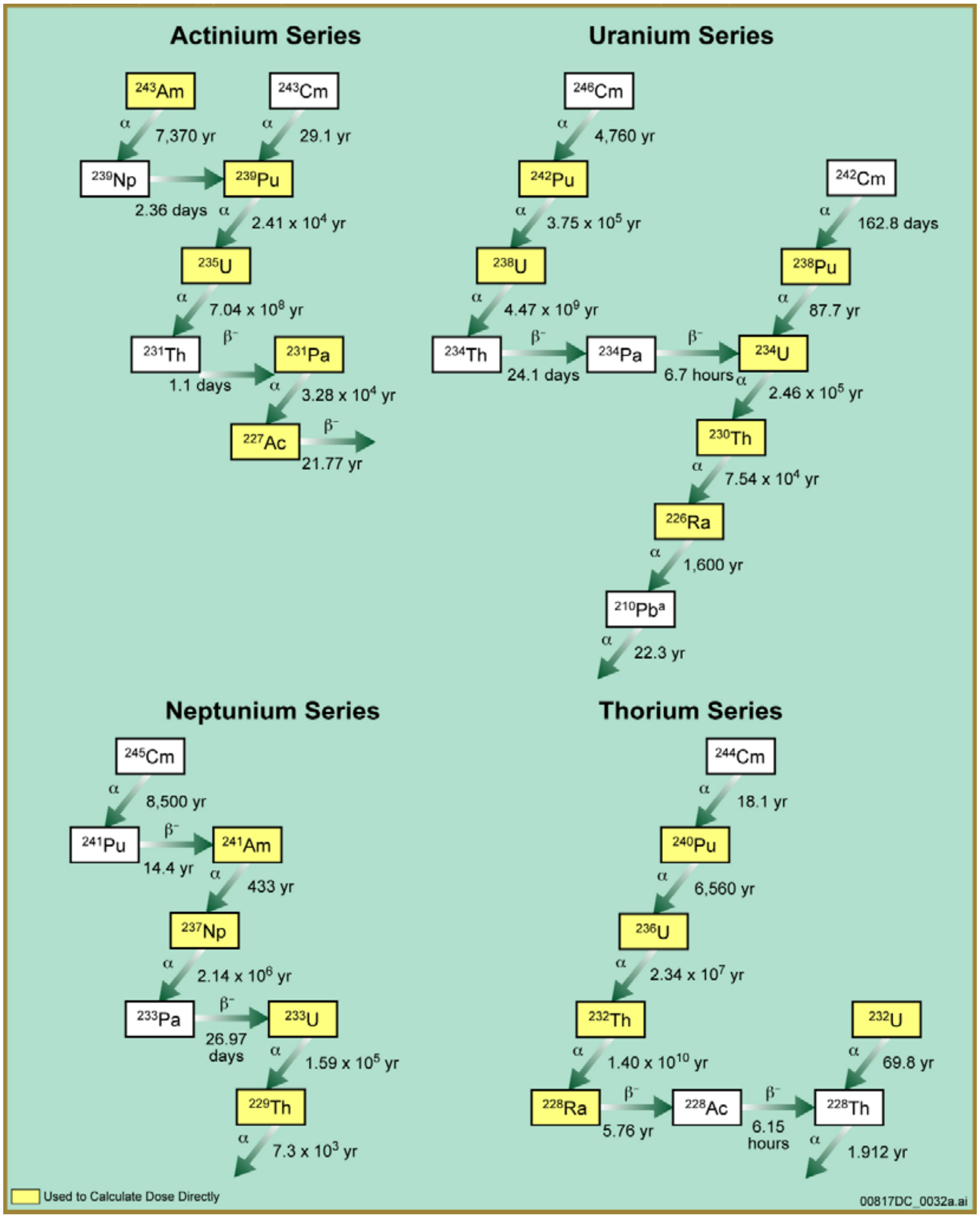
Underlying a decision to proceed with disposal in a particular geologic medium is the technical basis pertaining to that medium, the waste inventory and the design concept. In this particular instance, the primary emphasis is on the salt medium. A specific repository design is not suggested although experience and lessons learned are reviewed. A shaft seal system for a salt repository has been designed, reviewed, and accepted, so that successful body of work is included in this section. Salt mining experience, salt repository operations, and the scientific investigations supporting them provide a considerable technical basis for elucidation of the thermal-hydrological-mechanical conditions for the host rock. Perspectives on the geochemical behavior of salt are offered.

2.1 Nuclear Waste Characteristics

In the U.S., waste designations are not only linked to the level of radioactivity in the waste, but also, in some cases, to the source of the waste. In other countries, waste designations vary from those in the U.S. It is not the intent of this report to develop a new waste designation nor is it the intent to specify which wastes specifically can be disposed in salt. It is clear, however, from the technical basis established in this report that many forms of thermally-hot nuclear waste could be permanently and safely disposed in salt. The waste forms to be disposed could include HLW and/or UNF. In 2008, the DOE estimated that 109,300 metric tons heavy metal (MTHM) of HLW and UNF in the U.S. will ultimately need to be stored (DOE 2008b). This inventory consists of 70,000 MTHM that is included in the Yucca Mountain license application, with the remainder from future production.

The inventory includes commercial spent nuclear fuel (CSNF), DOE spent nuclear fuel (DSNF), and high-level waste glass (HLWG). The inventory consists of actinide elements in several radionuclide decay chains (Figure 2) along with a number of fission products. By weight, CSNF from once-through light-water reactors is about 97% ^{238}U, with contributions of 0.3–0.8% from ^{235}U, ^{236}U, ^{239}Pu, and ^{240}Pu. All other radionuclides contribute less than 0.1%. The importance of the various radionuclides changes with time due to the effects of decay and ingrowth.

HLW could include multiple waste forms: uranium dioxide (UO_2) pellets, borosilicate glass, ceramics, or metal. UO_2 pellets would result from direct disposal of UNF. Borosilicate glass and/or ceramics would result from disposal of HLW, and metals would result from direct disposal of activated metals. The waste form after long-term storage prior to disposal will not differ from waste disposed promptly after generation. Thus, the inventory consists of chemical elements from several sources as shown in Table 3.



Source: Sandia National Laboratories 2008, Figure 6.3.7-4.
[a] A series of short-lived daughters between ^{226}Ra and ^{210}Pb are not shown. Also, ^{210}Pb is not used to calculate dose directly, but its biosphere dose conversion factor is included with that of ^{226}Ra in performance assessments.
[b] The value listed under each radionuclide is the approximate decay half-life for the radionuclide.

Figure 2. Decay chains of the actinide elements for HLW isotopes

Table 3. Chemical elements to be considered in a HLW chemical model	
Element	***Sources***
Al	Host rocks, waste form
Am	Actinide element in waste
B	Waste form
Ba	Daughter of ^{137}Cs, which is fission product in waste form
Cm	Actinide element in waste
Co	Canisters
Cs	Fission product in waste form
Fe	Canisters and backfill materials
I	Fission product in waste form
Mn	Permanganate used for removal of Sr and actinides prior to vitrification
Ni	Activation product in waste form
Pb	Canisters
Pd	Fission product in waste form
Pu	Actinide element in waste
Se	Fission product in waste form
Si	Waste form, backfill materials, and host rocks
Sn	Fission product in waste form
Sr	Fission product in waste form
Te	Daughter of ^{125}Sb, which is fission product in waste form
Ti	Monosodium titanate used for removal of Sr and actinides prior to vitrification
Th	Actinide element in waste
U	Actinide element in waste
Y	Daughter of ^{90}Sr, which is a fission product in waste form
Zr	Fission product in waste form

Heat generation is one of the primary characteristics of HLW. Heat is generated because of the radionuclides contained in the waste. For UNF, ten years after removal from a reactor, approximately 77% of the thermal power originates from the decay of ^{137}Cs and ^{90}Sr and their daughters, with almost all of the remaining heat from actinide decay. In the short term, such as cooling times less than 50 years, the decay of ^{90}Sr and ^{137}Cs continue to produce the majority of the overall heat from UNF, and maximum heat output values are experienced during this time frame (Michaels 1996).

Over periods longer than 100 years, after heat generation from the ^{90}Sr and ^{137}Cs has tapered off, it is the alpha decay of various actinides—principally Pu and Am—that dominates the total heat output of UNF. The actinides account for about 80% of the cumulative heat that is generated over the first 1,000 years. For time frames beyond 1,000 years, actinides contribute about 99% of the additional heat generated in a repository. In the context of overall bulk temperatures of large volumes of the repository site, decay of actinides with intermediate half-lives dominates long-term heat production, not the decay of fission products such as ^{90}Sr and ^{137}Cs (Michaels 1996). However, as explained in the following sections, the relatively rapid response of salt and the early evolution of the disposal room dominate the long-term performance assessment.

The nuclear waste material to be permanently disposed has been well characterized and would be further evaluated if salt media are selected for disposal investigations. The concept of operations for salt disposal can be readily engineered to accommodate a broad spectrum of waste volumes, types, and heat generation capacities. Salt repository design, as described in Section 2.2, can include many systems because design approaches for disposal in salt are not predicated on any particular waste form or package. If the nuclear waste can be safely transported to the shaft station, it can be disposed in salt with no further packaging or treatment.

2.2 Salt Repository Design

A mine layout for HLW disposal in salt can be quite flexible. For example, the well-known concept of operations utilized at WIPP includes stacking of contact-handled (CH) waste on the floor and horizontal disposal of remotely handled (RH) waste in pillars as shown in the photograph in Figure 3. Internationally, Germany has taken a leading role in underground waste disposal in rock salt formations, as recounted in Section 1.3. Since 1967, a former salt mine (Asse) in north-central Germany fulfilled the technical criteria of a radioactive waste repository. The Asse mine was also used as a research facility for a number of years. The feasibility of both borehole and drift disposal concepts has been demonstrated by about 30 years of testing in the Asse mine (Brewitz and Rothfuchs 2007). At the Asse mine, large-scale disposal operations included stacking drums, covering them with salt, and then stacking more drums on top. The German reference disposal concept for HLW is horizontal placement of POLLUX casks (Bechthold et al. 2004); however, recent developments have outlined a new disposal technology for disposal in vertical boreholes in the salt room floor (Filbert et al. 2010).

Figure 3. Disposal operations for TRU waste at the WIPP

Since 1978, the former German Democratic Republic disposed low- and intermediate-level wastes in the Morsleben potash and salt mine (also known as ERAM). Morsleben employed several techniques including in situ solidification of liquid waste, stacking, and dumping of solid wastes. Solidification of the liquid used brown coal filter ash as a binding agent. Disposal ceased altogether in 1998, and designs for closure have been developed since operations were terminated. For two decades, the Gorleben salt dome in north-central Germany had been investigated for its suitability to host all categories of radioactive waste, including heat-generating HLW. Although no country has a repository for HLW in salt, the experiments and disposal demonstration attest to the flexibility of the concept of disposal operations.

2.2.1 Concept of Disposal for HLW in Salt

A recent conceptual salt repository study called the generic salt repository for HLW advanced a new disposal concept based on lessons learned from the WIPP, Asse, and Morsleben (Washington Savannah River Company et al. 2008). The generic study involved a conceptual mining layout that was developed for a high-thermal-load salt repository based on experience and mining observations. First a rough layout was proposed based on waste handling, convenience, expectation of standup time, and other criteria. A thermal calculation was run to evaluate temperature distribution, especially maximum temperatures. The mining layout was adjusted to accommodate a selected design basis throughput and balance the thermal load in the underground. This scoping study for a generic salt repository was not a design optimization study, and dimensions and disposal options were based on design guidance gained from practical experience.

Contributors to the generic salt repository study developed a possible repository layout and also generated some basic operational and structural conclusions, including (1) use rubber-tire disposal vehicles, (2) avoid use of predrilled holes, (3) do not use shielded containers for disposal, and (4) use narrow room widths to improve mining efficiency and structural stability.

The study concluded that the alternative of using rail for moving waste to the disposal zone would be difficult operationally. Rail systems would need to be constructed and then remain readily functional in a deforming salt medium. A rubber-tire fork lift machine can readily haul payloads to the disposal zone.

The disposal system should be made simple without sacrificing safety. WIPP disposal operations experience led to the conclusion that the concept of operations should not involve placing waste canisters in predrilled boreholes. Drilling such holes adds a logistical step to the disposal process, while emplacing waste packages into such holes is time consuming because of alignment requirements. Predrilled horizontal disposal holes require wide room span, and vertical holes in the floor would have to accommodate the drilling rig and emplacement equipment. The combination of rubber-tired equipment and emplacement without boreholes led to the selection of a simple disposal scheme that placed the canisters at the end of a mined alcove. The trade-off between drilling holes and mining alcoves for disposal favored the alcove disposal concept.

The alcove disposal concept can also accommodate disposal of unshielded containers. The waste could be transported in a shielded container but disposed unshielded. The alcove disposal concept requires that mine-run crushed salt be placed over the waste canisters for radiological shielding. The operation of placing the crushed salt over the waste would involve remote controlled load-haul-dump machinery similar to that used in salt mining today.

Width of the main disposal drifts and alcoves was selected for mining convenience. The typical continuous miner used at WIPP today cuts nominally 11-foot swaths. Therefore, the mining system would involve essentially one-pass mining. The stand-up time under ambient conditions associated with roughly 11-foot dimensions was not calculated, but based on WIPP experience structural stability would endure for many years without bolting.

The width-to-height ratio, extraction ratio, depth, and geometry govern underground standup time. Pillars take up the load when excavations are created. The width-to-height ratio of the pillar controls the pillar strength. Shorter pillars are stronger than taller pillars because of the confining effects experienced at the ends. For this generic salt repository layout, a nonspecific room height from seven to ten feet could be readily mined with current equipment.

Other recommendations included avoiding sequential co-disposal of remotely handled waste and contact-handled waste. The disposal sequence should proceed from the most distal excavations inward. This avoids having to transport past filled disposal rooms and promotes modular panel isolation. The concept of disposal in salt can be flexible. Heat generation, though important, can be readily accommodated by design.

2.3 Seals

This section describes a shaft sealing system design for the WIPP, which has been reviewed and certified by the EPA regulator. The system is designed to limit entry of water and release of contaminants through the existing shafts after decommissioning. The design approach applied redundancy to functional elements and specifies multiple, common, low-permeability materials to reduce uncertainty in performance. The system comprises 13 elements that completely fill the shafts with engineered materials possessing high density and low permeability. Laboratory and field measurements of component properties and performance provided the basis for the design and related evaluations. Hydrologic, mechanical, thermal, and physical features of the system were evaluated in a series of calculations. These evaluations indicated that the design effectively limits transport of fluids within the shafts, thereby limiting transport of hazardous material to regulatory boundaries. Additionally, the use or adaptation of existing technologies for placement of the seal components combined with the use of available, common materials ensure that the design can be constructed (Hansen and Knowles 2000).

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

An acceptable seal system can be designed and constructed using existing technology, and the seal system can readily meet requirements associated with repository system performance. These goals would be met by using a set of guidelines that incorporates seal performance issues, and with a commitment that the seal system design would implement accepted engineering principles and practices. These guidelines were formalized as design guidance for the shaft seal system:

- Limit waste constituents reaching regulatory boundaries
- Restrict formation water flow through the seal system
- Use materials possessing mechanical and chemical compatibility
- Protect against structural failure of system components
- Limit subsidence and prevent accidental entry
- Utilize available construction methods and materials.

The shaft seal system would limit entry of formation water into the repository and restrict the release of fluids that might carry contaminants. Seals are designed to limit fluid transport through the opening itself, along the interface between the seal material and the host rock, and within the disturbed rock surrounding the opening. The shaft seal system design for WIPP was completed under a quality assurance program that meets EPA regulations, including review by independent, qualified experts. Technical reviewers examined the complete design including conceptual, mathematical, and numerical models and computer codes. The design reduces the impact of uncertainty associated with any particular element by using multiple sealing system components and by using components constructed from different materials.

The sequence of repository operations would include site construction, waste emplacement, seal installation, repository closure, and abandonment. However, owing to the potentially long time periods involved, considerations such as loss of institutional control enter into the design and concept of operations. Events such as war or natural disaster may lead to premature repository abandonment. These hypothetical futures have been considered by many, if not all, repository programs. The impact of these potential situations is minimized by sealing emplacement drifts in modular compartments in due course of disposal operations. Therefore, in addition to the shaft seal system, a nuclear waste repository design would likely include a modular concept whereby the whole repository comprises sections or modules that are sequentially partitioned and isolated with horizontal panel closures (i.e., seals). The repository modules would be separated from one another by sufficient distance that thermal, hydrologic, and other possible modes of interference are inconsequential. After the repository is filled with emplaced waste and horizontal panels are closed, seals would be installed in the access shafts.

Similar to the WIPP shaft seal design, from the disposal horizon upward, the shaft seal system would include the following components:

- Shaft Station Monolith—The base of the shaft will be sealed with salt-saturated, Portland cement-based concrete. It will be placed by tremie line techniques against nonremovable (committed material) forms, which could be fabricated from concrete block or other abutments.

- Clay Column—A sodium bentonite compacted clay component is placed on top of the mass of concrete. Alternative construction methods including block placement and dynamic compaction are viable. Clay columns effectively limit formation water movement from the time they are placed. The stiffness or swelling pressure associated with the clay column is sufficient to promote healing of fractures in the surrounding rock near the bottom of the shafts, thus effectively removing the proximal damage zone as a potential pathway.

- Salt Column—A crushed salt element for the shaft seal system has been thoroughly evaluated for salt application. The performance has been established from the microstructural scale to the full construction scale. Very low permeability is attained by the crushed salt in laboratory time, which is an excellent basis for concluding the crushed salt element will become impermeable in a matter of decades.

- Asphalt Column—Asphalt is a widely used construction material with properties considered desirable for sealing applications. Asphalt is readily adhesive, highly waterproof, and durable. Furthermore, it is a plastic substance that provides controlled flexibility to mixtures of mineral aggregates with which it is usually combined. It is highly resistant to most acids, salts, and alkalis. A number of asphalts and asphalt mixes are available that cover a wide range of viscoelastic properties and which can be tailored to design requirements.

- Earthen Fill—The upper shaft is filled with locally available earthen fill. Most of the fill is dynamically compacted (e.g., by the method used to construct the compacted clay column) to a density approximating the surrounding lithologies. The uppermost earthen fill is compacted with a sheep-foot roller or vibratory plate compactor.

As described among the analogues summarized in Section 1.4, three atomic explosions were detonated in salt. No special seal provisions were made in any case. In the fifty years since the nuclear tests in salt, there is no detectable release. For sealing a salt HLW nuclear waste repository, the engineering and material specifications developed for the WIPP can be translated with minor modifications of functional and operational requirements. The seal material specifications, construction methods, rock mechanical analyses, and fluid flow evaluations already developed and approved remain applicable. This design concept is not the only possible combination of materials and construction strategies that would adequately limit fluid flow within the shafts; however, its high performance with common materials and technologies and functional redundancy proved to the regulators and stakeholders that the salt repository will be totally isolated after closure.

A major intrinsic advantage of a salt repository is the lack of groundwater to seal against. Even though regional aquifers may be proximal to the host unit, the shaft seal system would be designed to perform in contact with groundwater. If water flow occurs within the repository openings or in the disturbed-rock zone (DRZ), the chemistry of water or brine could impact engineered materials. However, the geochemical setting will have little influence on the concrete, asphalt, and clay shaft seal materials. Each material is durable with minimal potential for degradation or alteration. Microbial degradation, material interactions, and mineral transformations are often incompletely understood, and therefore continue to be the focus of ongoing research. Degradation of concrete is possible, but unlikely as only small volumes of groundwater will ever reach the concrete. Moreover, in a closed system, such as the hydrologic setting for these shafts, cement phase transformations would decrease the permeability of concrete seal elements.

Asphalt used as a seal component deep in the shaft will occupy a benign environment, devoid of ultraviolet light or an oxidizing atmosphere that could degrade the sealing capability of asphalt. Assurance against possible microbial degradation in asphalt elements used in a salt shaft seal design could be provided with addition of lime. For these reasons, it is believed that asphalt components can retain their design characteristics for an indefinitely long period.

Natural bentonite is a widely used, geologically stable sealing material. Three internal mechanisms, illitization, silicification, and ion exchange, could affect sealing properties of bentonite. Illitization and silicification are thermally driven processes unlikely to occur in the salt environment over the period of regulatory concern. Significant degradation due to ion exchange would require extensive fluid transport of calcium through the bentonite and sodium away from the seal, which is unlikely. Wyoming bentonite—the specified material for the seal system—has existed unaltered for well over a million years in its natural environment.

The shaft seal system described above could be constructed using off-the-shelf technology. A more comprehensive treatment and specific analyses are available in Hansen and Knowles (2000). The seal design system described by Hansen and Knowles could be readily modified, perhaps simplified, and construction alternatives may be implemented during repository development. This section provides frame of reference for shaft seal design and analysis for a potential salt repository for HLW in the U.S.

2.4 Thermal-Hydrologic-Mechanical Conditions in the Host Rock

Salt formations have naturally low permeability and self-sealing characteristics favorable to waste isolation. This section describes observations and experience in salt mines, in situ testing, laboratory testing, salt repository science, and geomechanics research nationally and internationally to establish a range of salt characteristics pertinent to a salt repository. This wealth of experience provides a firm foundation for advanced salt repository sciences. It also provides the basis for defining applied research needs to further the science in areas that are specific to the thermal aspects of HLW disposal. These considerations lead to approaches for representing thermal, mechanical, hydrological, and geochemical conditions possible in a salt repository for HLW.

2.4.1 Excavation/Construction Effects

Excavation geomechanics are a starting point for demonstrating the technical viability of nuclear waste disposal. Design and operation of the facility and the assurance of long-term isolation rely on knowledge of the geomechanical response. This section summarizes current treatment of the damaged rock around excavated openings as related to disposal operations, isolation of wastes, and performance assessment. Geomechanical creep in salt has long been recognized as favorable for nuclear waste isolation. Attributes of plasticity and impermeability provide assurance that once emplaced within salt disposal rooms, the radioactive wastes will be isolated from the accessible environment essentially forever.

Much of the salt geomechanics knowledge in the U.S. derives from site characterization for the WIPP facility, situated in the Salado Formation, a Permian bedded-salt formation in southeastern New Mexico. Background information can be accessed from the WIPP website (http://www.wipp.energy.gov). The WIPP is a disposal facility for defense-generated TRU waste from across the nuclear complex. First receipt of waste occurred in March 1999, following the original certification by the EPA that the facility complies with the regulations. Compliance was recertified after five years of operations, and recently EPA issued its second recertification.

2.4.1.1 Elements of the Disturbed Rock Zone (DRZ)

The DRZ constitutes an important geomechanical element of salt behavior and is explicitly included in seal design and performance assessment. The PA philosophy incorporates features, events, and processes (FEPs) into conceptual and numerical models used to predict probable future states of the repository over the regulated period. This section reviews the DRZ information base and experience because the DRZ is among the prominent FEPs associated with waste disposal in salt.

Salt, being a plastic medium at repository depth, exhibits a virgin lithostatic (isotropic) state of stress. Creation of underground openings perturbs the static equilibrium of the mined regions sufficiently to cause fracturing in rock proximal to the excavations. The DRZ comprises the region near an excavation that experiences changes in hydrologic or mechanical properties. The properties that typically define a DRZ include (1) dilational deformation ranging from microscopic to readily visible, (2) loss of strength evidenced by rib spall, floor heave, roof degradation and collapse, and (3) increased fluid permeability via connected porosity. The DRZ can play an important role in the geomechanical response of salt rooms or openings underground, particularly where structures are placed to retard fluid flow. Although stress differences tend to decrease over time in a plastic medium such as rock salt, fractures continue to grow and coalesce in an arching pattern around drifts and develop preferential orientations parallel to the opening.

Technical DRZ discussions begin with first principles and expand into laboratory test results, small-scale in situ experiments, and full-scale analogues from industry experience and international collaborations. These technical arguments provide reasoning for parameter distributions and model improvements that incorporate recent advancements in characterization of the DRZ. The discussion below concentrates on rock salt damage, modeling, and properties, and shows that the theory and practice of DRZ modeling are sufficient to support performance analyses for a salt repository at ambient temperature and potentially at elevated temperature.

The three important properties of the DRZ that contribute to the amount and rate of brine flow into the repository are extent (thickness), porosity, and permeability. Characterization of the DRZ has continued by means of laboratory testing, theoretical developments, modeling, and observations. Current understanding of the DRZ in salt indicates that the DRZ will be limited in extent over the regulatory period (Hansen 2003). Extensive laboratory salt creep data demonstrate that damage can be expressed in terms of volumetric strain and principal stress in the range applicable to a salt repository at appropriate depths. Stress states that create dilation are defined in terms of stress invariants, which allow reasonable models of DRZ evolution and devolution. The stress-invariant dilatancy model has been used in structural calculations for many years. Stress-state calculations can be post-processed from numerical analyses to predict disturbed or damaged zones around a typical waste disposal room. The stress-invariant model tracks the stress states such that dilating and healing conditions can be visualized. The salt nearest an opening is expected to undergo the greatest damage and experience the greatest increase in permeability. Salt farther from the opening undergoes much less damage and, as a result, experiences smaller change in permeability. Damage is rapidly reversed as shear stresses diminish and mean stress remains essentially constant (Van Sambeek, Ratigan, and Hansen 1993).

Healing conditions are created once the salt begins to compress the waste in the rooms. Models of the creation, growth, and healing of the DRZ replicate observations and are based on firm physical understanding of the salt mechanics involved. Hansen and Stein (2006) elaborated on how room evolution can be modeled to more accurately represent the empirical evidence, including an updated DRZ treatment.

Based on the technical information discussed here, it is possible that the DRZ of a HLW repository in salt could heal completely within the 100-year period when administrative controls are assumed to prevent intrusion into the repository. Heat from the waste has been postulated to create a dry halo that could severely limit corrosion of the waste packages. Rapid healing of the DRZ would prevent brine from resaturating the salt around the package. Also, without brine, production of gas through radiolysis could be limited.

2.4.1.2 Principles of Salt Deformation

The geologic settings for many of the salt-bearing regions shown in Figure 1 are tectonically stable and aseismic, and given the viscoplastic behavior of salt, the in situ stress condition prior to excavation is lithostatic (i.e., $\sigma_1 \approx \sigma_2 \approx \sigma_3$). Upon excavation, the rock closest to the opening experiences deviatoric (or shear) states of stress ($\sigma_1 > \sigma_2 > \sigma_3$). In salt, deviatoric states of stress activate elastic, inelastic viscoplastic flow and damage-induced deformation. Elastic deformation occurs instantaneously (time-independent) in response to changes in stress state, while the other mechanisms are time-dependent, which gives salt its well-known creep characteristics.

Viscoplastic flow of salt has been extensively measured and characterized by U.S. and German salt repository programs and other salt-based programs such as the Strategic Petroleum Reserve or the Solution Mining Research Institute. Plastic deformation occurs by dislocation motion within the salt lattice and includes processes of dislocation multiplication, glide, cross slip, and climb. Because viscoplastic flow is an isochoric or incompressible process, it does not induce damage to the salt matrix. Damage occurs when the deviatoric stresses are relatively high compared to the applied mean stress and manifests through the time-dependent initiation, growth, and coalescence of microfractures. Modeling approaches have been suggested for the microfracturing process. Predictions of damage zones surrounding openings in salt represent directly what can be observed underground. Point-wise geophysical measurements often validate the geometry and other characteristics predicted by damage models.

For HLW repository applications, one of the most important features of salt as an isolation medium is its ability to heal previously damaged areas. Healing arises when the magnitude of the deviatoric stress decreases relative to the applied mean stress. The healing mechanisms include microfracture closure and bonding of fracture surfaces. Microfracture closure is a mechanical response to increased compressive stress applied normal to the fractures, while bonding of fracture surfaces occurs either through crystal plasticity, a relatively slow process, or pressure solution and re-deposition, a relatively rapid process (Spiers, Urai, and Lister 1988). Evidence for healing has been obtained in laboratory experiments, small-scale tests, and through observations of natural analogues.

Cooperative research with the European Union and German research scientists has been instrumental in advancing the technical assessment of salt damage evolution. In November 2003 (Davies and Bernier 2005) and again in 2010 (Rothfuchs et al. 2010) the European Union sponsored a conference addressing the specific issue of the DRZ as it relates to repository sciences. Information contained in this section also draws on experience gained from these international collaborations.

The discussion of salt behavior and deformation processes around salt openings leads to the following general observations:

- Microfracturing of the salt initiates immediately upon excavation of the openings and continues with time.

- Microfracture density and growth rates are highest near the opening and decrease with distance away from the opening

- Fracture growth in the DRZ is anisotropic with fractures aligning parallel to the most compressive stress.

- Fracturing will coalesce leading to salt failure, including floor heave, roof fall, and rib slabbing.

- Salt damage is reversible.

Characteristics of these features and examples constitute major considerations for an HLW salt repository.

2.4.1.3 Hydrologic Properties of Damaged Salt

Salt porosity and permeability increase as a result of dilation. Intergranular fractures align with the maximal principal stress, increase connectivity, and subsequently increase fracture apertures. Generally, the relationship between permeability and volumetric strain ($K = \varepsilon_{dv}^{n}$) has been observed to be bimodal: at low porosity values, n equals ~4, and for high porosity values, n equals ~0.2, where (ε_{dv}) is the dilatant volumetric strain equivalent to $\Delta V/V$, with ΔV and V representing the change in volume due to dilation and the initial volume, respectively. Peach (1991) studied the effects of salt dilation on permeability using percolation theory and found that small levels of dilation (as little as 0.05%) were sufficient to develop an interconnected pore network that formed primarily along grain boundaries, and permeability through this network was found to be proportional to $(\varepsilon_{dv})^3$. Pfeifle, Brodsky, and Munson (1998) conducted permeability tests on Salado salt specimens that had been deformed in the laboratory to volumetric strains of the order of 0.5% and estimated permeability from 10^{-15} to 10^{-14} m^2, some seven orders of magnitude higher than observed for undamaged salt in the field by Beauheim and Roberts (2002). These results emphasize the extreme sensitivity of salt permeability to small dilatant volumetric strains.

Damage anisotropy complicates the utility of this model. Fractures in salt develop preferential orientation with respect to the stress state, parallel to the drift and perpendicular to the minimum principal stress. Permeability along the fractures parallel to the drift would be much higher than permeability perpendicular to the drift. The anisotropic nature of fractures and the sensitivity to damage (i.e., the permeability increases by orders of magnitude with relatively low levels of damage) are two features that complicate development of a damage/permeability relationship for field applications. The findings of Rothfuchs et al. (2010) agree exactly with these concepts. In addition, one has to keep in mind that the network of microcracks is generally expanding parallel to the maximal principal stress and the transport properties will be anisotropic as well. As long as the porosity is modeled as a scalar parameter, the anisotropy in the network of microcracks and, therefore, the anisotropy in permeability are not described properly. This complexity in the recovery behavior of damaged rock salt should be investigated further (Rothfuchs et al. 2010).

Because of the sensitivity between salt permeability and dilation, the DRZ is expected to exhibit high permeability immediately adjacent to the excavation and decrease away from the opening in direct relation to the level of induced damage and deviatoric stresses. The microfracturing will also relieve pore pressure. At the free surface of the opening, the pore pressure will be atmospheric, while at depth, the pore pressure would approach lithostatic pressure (approximately 15 MPa at the repository horizon). The pressure gradient through the DRZ promotes brine release into the opening. Because healing processes reduce porosity, permeability is expected to decrease when hydrostatic states of stress activate healing processes, particularly in the vicinity of rigid drift closures, also termed geotechnical barriers in many European publications.

Brine is an important factor in the overall evolution of a salt repository. For example, waste isolation performance at the WIPP depends closely on the availability of brine to mobilize radionuclides. In the performance assessment model brine is also essential to corrosion of iron and other metals and for sustained microbial activity. In the absence of brine, a salt repository is virtually unaffected by these processes.

Brine availability may be largely determined by the properties of the DRZ. As discussed previously, the DRZ will be limited in extent and will readily heal to a state approaching in situ permeability. Potentially, the hydraulic gradient between the far field and the excavated room is initially very high. For as long as DRZ permeability is high enough to allow brine flow, brine contained in the DRZ can flow into the waste emplacement rooms. Because maximal stress differences occur immediately upon creating the opening, the maximum extent of the DRZ manifests quickly, and the brine migration (i.e., dewatering) process begins shortly after excavation. During the operational period, the accessible brine will tend to migrate down the stress gradient and evaporate into the ventilation air.

These processes are observed in underground openings at WIPP. Soon after mining, moist areas were noticed by geotechnical personnel, and it was apparent that not all brine was bound to hydrous minerals or sealed inside fluid inclusions. The clear or purer salt contains the least water by weight (0.3%), argillaceous salt contains somewhat more (1.5%), and clay by itself contains the most (>2.2%). A brine sampling and evaluation program (BSEP) was adopted to investigate the origin, hydraulic characteristics, extent, and chemical composition of brine in the Salado Formation at the repository horizon and the seepage of that brine into excavations at the WIPP. The BSEP program noted, however, that after 11 years of study, brine was remarkably hard to find in the WIPP excavations (Deal et al. 1995).

Beauheim and Roberts (2002) performed an evaluation of Salado Formation hydrology and hydraulic properties. They conclude,

> *On the time scale of the operational period of WIPP (decades), the far field lacks the capacity to fill all of the newly created porosity in and around the repository, much less pressurize it to near lithostatic pressure. After WIPP is closed, far-field flow toward the repository will continue, but the overall "healing" of the formation around the repository (closure) and compaction of the crushed-salt backfill will act to reduce both the hydraulic gradient and the porosity present near the waste. Thus, the amount of brine that ever comes into contact with waste will be controlled by the relative rates at which brine flow and repository closure occur.*

As salt creep closes a disposal room, the stress gradient decreases, fractures heal, and crushed salt (if present) reconsolidates. Thus conditions in a repository would evolve to significantly limit brine flow to the waste disposal areas.

2.4.1.4 Laboratory Studies of Salt Damage

Laboratory studies provide the most readily attainable setting for testing material properties. Extensive research has been conducted in the laboratory to determine both the deformational and hydrological behavior of natural salt. Early work focused on the characterization of the elastic and inelastic viscoplastic flow properties of salt (e.g., Hansen and Mellegard 1977, Wawersik and Hannum 1979, Hansen and Mellegard 1980, Senseny 1986, Mellegard and Pfeifle 1993). Most of the early studies provided parameters for the constant-volume creep model, which was validated against large-scale thermal-mechanical experiments.

Van Sambeek, Ratigan, and Hansen (1993) reexamined the extensive creep data existing from years of experiments on salt and evaluated volumetric strain in terms of principal stresses. Stress states that led to dilation were defined in terms of the first invariant of the traditional Cauchy stress tensor, I_1, and the second invariant of the deviatoric stress tensor, J_2. These invariants are related to mean (or confining) stress and deviatoric stress, respectively, and are defined as follows:

$$I_1 = 3\sigma_m = \sigma_1 + \sigma_2 + \sigma_3$$

$$J_2^{1/2} = \left\{ \frac{1}{6} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \right\}^{1/2}$$

where σ_m is the mean stress and σ_1, σ_2, and σ_3 are the three principal stress components for a particular type of test. Using these definitions, Van Sambeek, Ratigan, and Hansen (1993) demonstrated that a clear delineation in the $I_1 - J_2$ stress space exists between conditions that cause dilation and those that do not, regardless of the type of salt or type of test considered. They suggested an empirical relationship to divide dilating stress states from nondilating stress states and expressed this relationship as follows:

$$\sqrt{J_2} = 0.27 I_1$$

This relationship is called the stress-invariant model and has been used for several applications in analyses for of drift geotechnical barriers and shaft seal systems.

The investigations of damage evolution have benefited from collaborations with international researchers. SNL has a long-standing collaboration with peers in European salt programs, most notably with the *Bundesanstalt für Geowissenschaften und Rohstoffe* (BGR). Salt researchers at the BGR have led development of a constitutive relationship between dilatancy and permeability (e.g., Cristescu and Hunsche 1998, Hunsche and Schulze 2000, Schulze 2007). Their experiments and theory show that dilatancy (also called volume change or damage) is linearly increasing with creep deformation under dilatant conditions and decreasing or healing with time in the compressive domain.

The stress-invariant dilatancy model has been used in structural calculations for approximately 10 years and remains a viable tool for engineering purposes and can be coupled with numerical analyses to predict disturbed or damaged zones around a typical waste disposal room. The stress-invariant model quantifies neither the level of damage nor the increase in permeability associated with the DRZ. These and other questions remain with respect to DRZ healing and affect the uncertainty of repository performance analyses, particularly with HLW.

2.4.1.5 Laboratory Healing Studies

In laboratory tests Costin and Wawersik (1980), Brodsky (1990), and Pfeifle and Hurtado (1998) demonstrated that the damage evolution process in salt is reversible through crack closure and healing. In the Costin and Wawersik (1980) study, a series of short-rod fracture toughness strength tests were performed to determine the tensile load required to initiate and propagate fractures in salt. The fractured test specimens were subsequently compressed hydrostatically and then retested in a second series of fracture toughness tests. The study showed that the healed specimens regained from 70% to 80% of their initial fracture toughness strength.

Using the well-known correlation between wave velocity and crack development in geologic materials, Brodsky (1990) used compressional ultrasonic wave measurements to study crack initiation, propagation, and healing of salt. In general, velocity decreases with increases in rock dilation and increases in response to crack closure and/or porosity reduction. Microcracks were introduced into the salt specimens during constant-strain-rate, triaxial compression tests conducted at low confining pressure. After specified damage levels were induced, hydrostatic compressive stresses were applied to promote healing. During both the loading and healing stages of the tests, ultrasonic wave transducers monitored wave velocity parallel and perpendicular to the maximum principal compressive stress. During loading, wave velocity parallel to the maximum principal stress decreased 1% to 2%, while velocity perpendicular to the maximum principal stress decreased by as much as 10%. In contrast, velocity measurements made during healing (or fracture closure) increased, with the rate of increase depending on the initial level of damage and the magnitude of the applied hydrostatic stress. Velocity recovery generally occurred within a few days.

Pfeifle and Hurtado (1998) studied salt healing through a series of gas and brine permeability tests conducted on damaged natural salt specimens subjected to compressive hydrostatic stresses. Damage was initially introduced through constant-stress creep tests conducted at low confining pressure. The damaged specimens were then loaded hydrostatically to promote healing, and permeability measurements were made as a function of time. Permeability decreased as a function of time, with larger decreases corresponding to higher hydrostatic stress levels and specimens saturated with brine rather than gas.

2.4.1.6 Field Measurements

A considerable body of geophysical investigative work has been completed in the WIPP underground in the period since the initial certification (Holcomb 1999, Hardy and Holcomb 2000, Holcomb and Hardy 2001). In most investigations, Holcomb and coworkers delineated the DRZ as a function of depth orthogonal to a drift wall and along vertical and horizontal paths parallel to the wall. In one campaign, they measured velocity in holes oriented at angle to the walls. The borehole array and the transducer assemblies allow measurement of elastic wave velocities necessary to detect the anisotropy of cracking associated with the DRZ. Velocity and attenuation of elastic waves in the salt are a function of the density of cracks, as is the permeability.

Cross-hole and same-hole velocity measurements give a consistent picture of the DRZ around a rectangular drift. The DRZ is well developed at mid-height on the rib, extending into the rock approximately 2 meters. Near the back and floor, the DRZ is shallow (1 meter or less) or not detectable. Compressional mode waves (i.e., P waves) in same-hole measurements are most sensitive to the DRZ because of the orientation of particle motion perpendicular to the cracking. Changes in V_P as large as 22% were observed for P waves propagating perpendicular to the drift axis at room mid-height. The physical extent of the disturbed zone can be determined by propagating elastic waves through successive portions of the formation until an undisturbed zone is reached, as indicated by a constant velocity with increasing depth from the rib.

While the laboratory data provide convincing evidence for healing, damage regions described from geophysical velocity measurements are meters in dimension. Damage of concern for seal systems in salt involves much larger scales and uncertainties associated with up-scaling properties. Thus, damage and healing information are more meaningful when acquired in situ. A series of sealing experiments in the WIPP underground were executed over a ten-year period from 1985 to 1995. The tests most pertinent to seal systems involved salt-based concrete placed in 1-meter holes in the floor and rib of the repository horizon. The seal system consisted of the seal material, the seal/host rock interface, the zone of rock immediately surrounding the seal, and the far-field host rock. The seals were tested for gas and brine permeability from 1985 to 1987 and again from 1993 to 1995 (Knowles and Howard 1996). Gas permeability determined in 1985–1987 ranged from 10^{-17} to 10^{-20} m^2 and improved to 10^{-19} to 10^{-23} m^2 when retested in 1993–1995. Additional geophysical and petrographic studies conducted in concert with the flow testing of the concrete seals (Knowles et al. 1998) provided evidence that the damage existed on both sides of the concrete plug. The authors concluded that the rigid concrete inclusion provided the requisite back stress to heal the extant DRZ.

2.4.1.7 Full-Scale Damage Healing in Salt

Salt damage healing has been demonstrated in the laboratory and in 1-meter-scale field tests. Field evidence of damage healing on a large scale is sparse. German researchers have published a notable example of healing around a rigid enclosure. This case study is known as ALOHA (*Untersuchungen zur Auflockerungeszone um Hohlräume im Steinzalzgebirge*). These investigations were conducted in the Asse salt mine near Braunschweig, Germany (Wieczorek and Zimmer 1999). In situ permeability tests were conducted on the 700-meter level of the Asse salt mine, where a cast steel bulkhead was placed in a drift during the 1920s. Gas and liquid injection tests were conducted in open sections of the drift and behind the steel liner. Permeability magnitudes behind the liner are lower than 10^{-18} m^2, at least three orders of magnitude less than the equivalent measurements made in the adjacent open drift. These full-scale permeability measurements are evidence of progressive DRZ healing around a rigid structure at depth in salt. Evaluation and modeling are ongoing.

Additional analogue observations regarding bulkheads in Canada and other case studies are reported by Eyermann, Van Sambeek, and Hansen (1995). An experience at the Rocanville mine involved drift seal construction of brine-based concrete, analogous to possible panel closure construction for a salt repository room or panel. The Rocanville bulkhead was constructed in halite, following water inflow from an overlying aquifer. A concrete bulkhead was designed to contain the inflow and prevent additional inflow into the mine. A “temporary” bulkhead located 30 meters from the face (i.e., the point of inflow) was constructed and has functioned perfectly since its emplacement in 1985. Total hydrostatic head is monitored by various accesses through the bulkhead. Design and construction of the bulkhead took only a few weeks, and the conditions for the construction were less than ideal. Despite these factors, the bulkhead has resisted water pressures approaching 10 MPa since construction. This does not unequivocally demonstrate that a DRZ developed and then healed, but it does show that a full-scale, salt-based concrete bulkhead in salt can be constructed and remain impermeable to a full hydrostatic head.

The most important issues summarized in this section are the descriptions and documentation of salt damage properties, updates to technical knowledge pertaining to the DRZ, and the possible direct application of this information to salt repositories for HLW. Predictions of the one-way evolution of the DRZ replicate underground observations. The size and shape of the DRZ around an opening based on a stress-invariant criterion are similar to the size and shape derived from sonic velocity studies and from microscopy of core damage. An example calculation is shown in Figure 4, which is a two-dimensional finite-element model of a room with waste placed inside. The regions around the room depict the extent of the DRZ. As the room closes upon the waste inside, stress differences are reduced, and the damaged salt heals. In this particular isothermal calculation, room closure is nearly complete in 60 years. These calculations of the evolution (i.e., growth and healing) of the DRZ replicate observations made in the WIPP underground. The predicted size and shape of the DRZ around an opening based on a stress-invariant criterion (Figure 4) are similar to the size and shape derived from sonic velocity studies and from microscopy of core damage (Hansen 2003). The model output does not provide permeability directly, but the trend and magnitude of permeability around salt openings are understood in considerable detail. For salt repository sealing applications, the high-permeability zone surrounding a drift or shaft is a potentially important design issue. For performance assessment and supporting simulations, over-estimation of the extent of the DRZ could produce significant artifacts if modeled unrealistically.

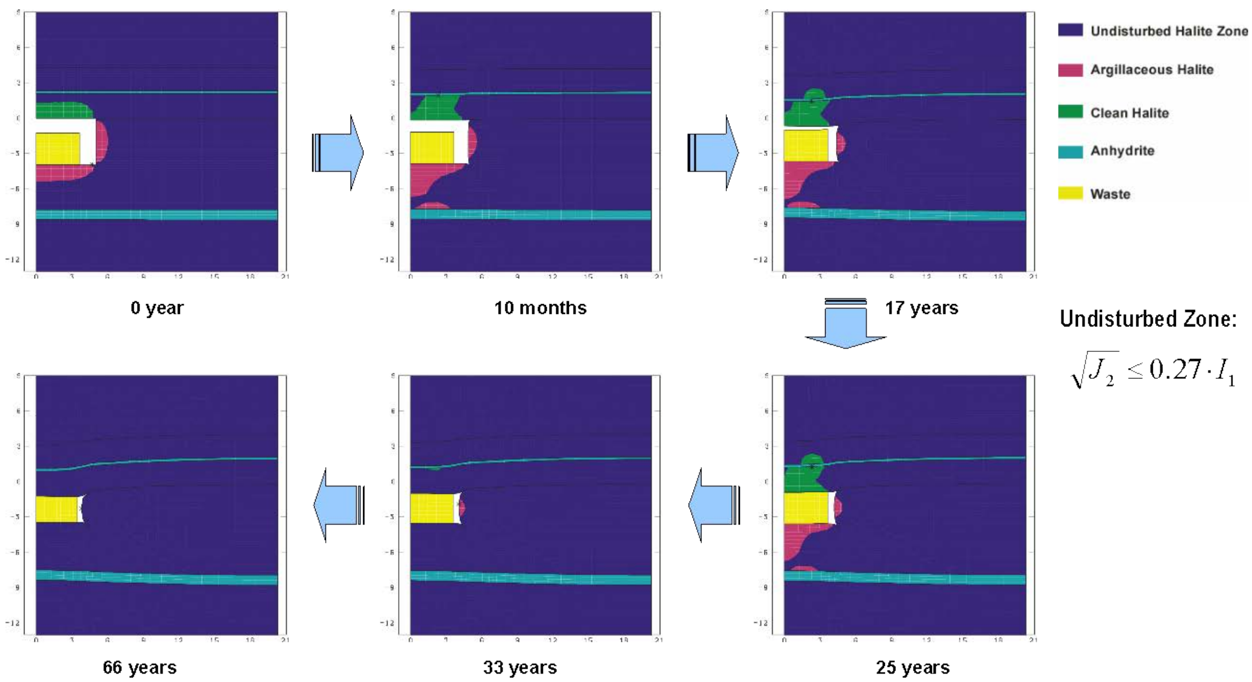


Figure 4. DRZ development and healing around a disposal room (from Park and Holland 2007)

2.4.2 Thermal Effects

Thermal effects are very important to room closure because heat promotes faster creep rates without creating fractures. Evolution of the disposal rooms will involve a thermal pulse from the HLW. Temperature effects on salt deformation are dramatic because salt deformation is dominated by plastic behavior at elevated temperatures. Figure 5 plots strain-versus-time curves for creep tests on natural salt specimens conducted at identical stress condition but at different temperatures. Temperature has an exponential influence on the creep rate of intact salt specimens owing to thermally activated deformation mechanisms: the elevated temperature in a HLW repository will enhance deformation upon placement of the heat-generating waste in the rooms.

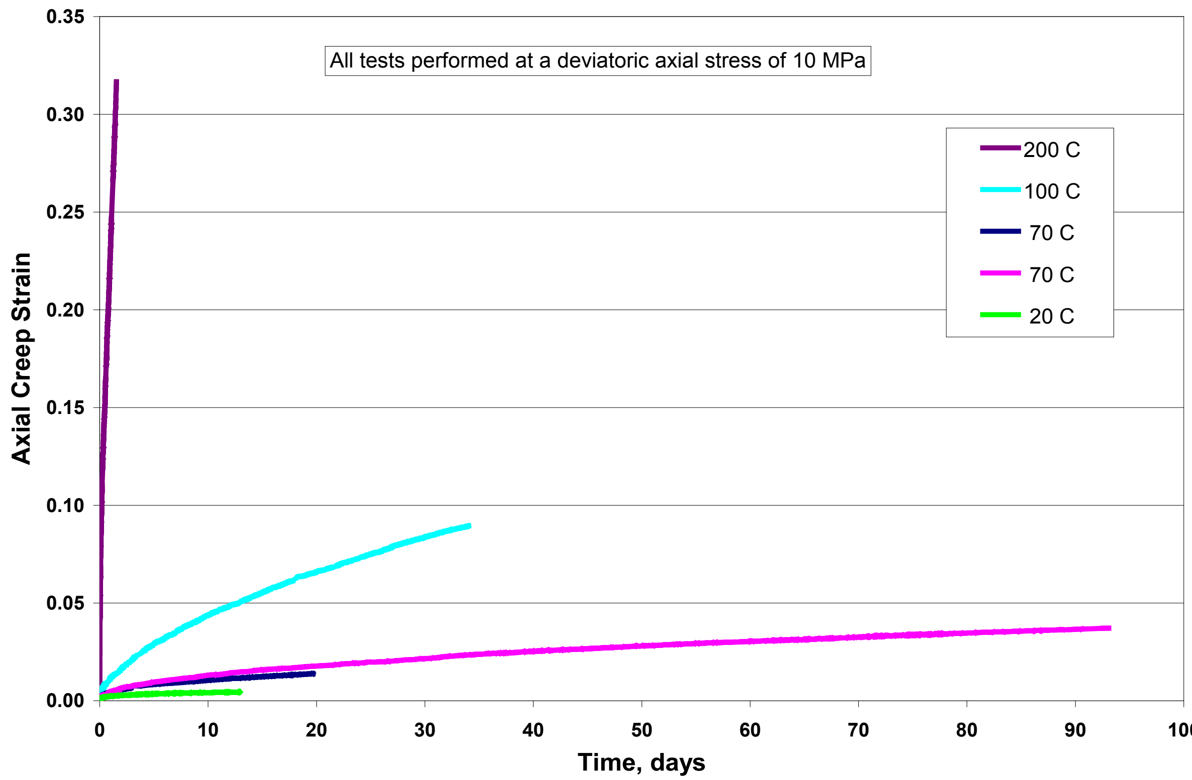


Figure 5. Temperature effects on salt creep

Accurate prediction of repository response can be made through application of a valid model. In the case of the structural response of the host medium, a valid model must first represent observed physical phenomena. For example, the strain rate should be a function of stress difference, temperature, and structure. Deformation of salt subjected to expected repository conditions has been shown to be very sensitive to temperature and stress: when stress differences or temperatures increase, the strain rate increases. Studies show that history effects, normal transient response (where strain rate decreases), inverse transients (where strain rate increases), and dependence of creep rate on stress difference and temperature are *all* a direct consequence of existing and evolved substructures. Therefore, a constitutive law that describes salt deformation must account for stress, temperature, microstructure, and the physical processes that account for the deformation.

The physics of plastic deformation of salt is governed by several processes at the atomistic scale called deformation mechanisms. The definitions of various mechanisms are usually clear only for ideal conditions, such as homogeneous composition or single crystals. For repository purposes, it becomes necessary to understand the deformation of polycrystalline materials by extending the knowledge gained from single crystals. With the addition of fabric, impurities, and grain boundaries, the motion of crystal defects is likely to be impeded; whereas, small amounts of water occurring in natural aggregates may enhance mobility of the same defects. The deformation mechanisms at the atomistic level can be limited, changed, or otherwise complicated by many natural variables although stress and temperature have been found to be most important and explicitly incorporated into salt constitutive models.

Deformation of natural rock salt under repository conditions produces consistent substructures. Examples of deformed salt and the microscopic substructure are shown in Figure 6. The upper half of Figure 6 (two plates, left and right) shows deformed laboratory samples of a relatively impure salt (left) and a relatively clean salt (right).

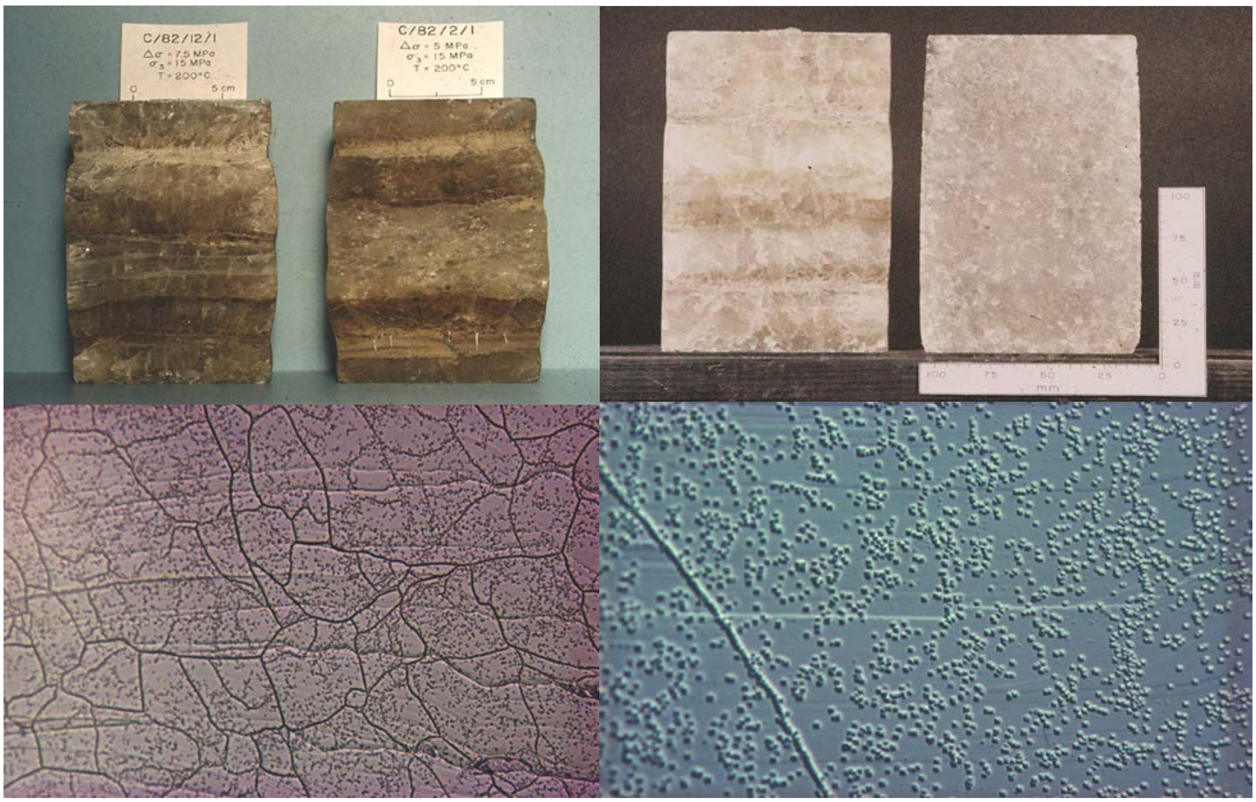


Figure 6. Deformed salt samples and their microstructure (Hansen 2010)

The first substructural change evident at low stresses, temperatures, and strain levels is an increase in dislocation density, which is exhibited on the etched cleavage chip shown in the lower right micrograph of Figure 6. An increase in dislocation density over the natural, undeformed state occurs at small strain levels. As strain increases, dislocations cluster along preferred crystallographic planes. As test conditions become more severe, particularly as temperature increases, the individual bands become wavy and cross-link. At temperatures above one-third of the melting temperature and strain of a few percent, polygons form as shown in the lower left photomicrograph of Figure 6.

The first manifestation of salt deformation under repository conditions is dislocation density increase upon application of stress. Plastic deformation entails dislocation movement, but plastic deformation can also be retarded when the dislocation density becomes high. Therefore, dislocation multiplication is a transient, evolutionary phenomenon. If other mechanisms cannot transport or annihilate dislocations to relieve internal stresses, the material will harden as dislocation density increases. The occurrence of strain hardening during experimental deformation of rock salt is well documented: under certain conditions when creep recovery is relatively slow, an increase in stress is needed to affect an increase in strain. In laboratory experiments, samples often undergo appreciable transient creep before the onset of steady-state creep. The transient response is, therefore, a reflection of the evolution of steady-state substructure wherein the transient response is eventually balanced by recovery processes that allow steady-state creep to ensue.

Elevated temperatures and deviatoric stress states in the vicinity of the waste will enhance dry-out of the underground opening by promoting brine liberation through the combined effects of heat and fractured rock. In some extreme cases, elevated temperature in the near-field environment could cause local salt decrepitation in addition to stress-induced fracture. It is possible that both phenomena could have a positive effect on long-term performance because they enhance liberation and removal of the small amounts of brine next to the waste canisters. Resaturation of this nearby salt would be impeded as the DRZ rapidly heals.

2.4.3 Coupled Thermal-Hydrologic-Mechanical Effects

The thermal-hydrologic-mechanical (THM) conditions for an HLW salt repository can be reasonably described. This section reviews coupled consequences from mechanical, thermal, and hydrological coupling. Heating of the host rock will begin as soon as the thermally hot waste is emplaced. The addition of heat will activate thermal deformation mechanisms and initiate accelerated creep, cause possible release of brine near the heat source, and affect other processes specific to waste disposal in salt. Stress redistribution near excavated openings will reduce strength and increase deformation. Although research into thermally driven processes in salt has waned over the past decade, the state of the art is widely recognized. Salt repository programs are well poised to describe a science-based path forward for advancing the state of knowledge and modeling capabilities.

In the years leading up to the WIPP *Compliance Certification Application* in 1996, scientists working on the repository project conducted an extensive suite of laboratory and field experiments. Full-scale experiments established performance standards and expectations, while the fundamental science of salt deformation was explored in the laboratory. Field experiments included several at elevated temperature to ascertain salt response under conditions anticipated for the operating repository, which at the outset included heat-generating defense waste. Simulations and predictions of the field tests were made using finite-element computer codes that incorporated sophisticated models for salt deformation. Parameters for the salt model were derived from laboratory experiments on natural salt extracted from the repository horizon. All of these science investigations provided confidence in the predicted behavior of the salt.

2.4.3.1 Impact of Coupled Thermal-Hydrologic-Mechanical-Chemical Processes

A recent international conference held in Luxembourg (Rothfuchs et al. 2010) addressed the FEPs associated with thermally driven processes in a salt repository. The conference focused on the appraisal of the current capabilities of coupled models used by numerical simulators for the assessment of the long-term evolution of geological repositories for high-level radioactive waste. One of the most important topics concerned the interplay between the DRZ (also called the excavation damaged zone or EDZ) and the engineered barrier systems. Creation and development of the DRZ is well characterized as described above. However, the reversal and healing of the DRZ and the attendant reduction of permeability is less well understood. These relationships are important to long-term performance assessments, particularly because of a new approach to the concept of disposal performance, discussed below.

The German approach to repository performance relies on *complete isolation* within the salt formation (called the isolation rock zone or IRZ). Complete isolation is predicated on the long-term integrity of the IRZ and proof of functional efficacy and robustness of the engineered barrier system. This concept is entirely consistent with the *expectation* of salt performance assessment for undisturbed cases, as discussed above, in which there are no credible releases from a properly designed and situated salt repository. This new approach of complete containment adds to past performance assessments that calculated releases and compared results to limits set by regulation.

To attain complete isolation, the lifetime performance of the geologic medium and the engineered barriers need to be established. Specifically, the shaft seal system and the geotechnical barriers must prevent intrusion of brine into the disposal cells. Defense in depth is the key to attaining complete isolation. Multiple barriers in a series ensure that the safety function is preserved even in the remote event that one of the seal components fails. The German concept conservatively assumes that the engineered geotechnical barriers will function only to the early postclosure stage, whereupon the long-term seal function is performed by the reconsolidating crushed salt backfill. The granular salt backfill has no sealing function at the time of placement; therefore, the reconsolidation permeability/porosity functional relationship is fundamental to the complete isolation concept.

In repository application, the time period needed for DRZ reduction and reconsolidation may extend beyond the capacity to explore it experimentally. Therefore, the safety concept must rely on supporting models. To reduce uncertainty in model predictions, the stress/strain conditions and constitutive properties of the system components need to be determined. The development and confirmation of better, more reliable models for prediction of DRZ reduction and backfill compaction are, therefore, major tasks within the development of a safety case. Research continues to investigate damage healing, coupling between damage and permeability, evolution dependence on stress and time, and the influence of pore pressure effects on the mechanical behavior; i.e., coupling of thermal-hydrologic-mechanical-chemical processes (Rothfuchs et al. 2010).

2.4.3.2 State-of-the-Art Modeling

Stone et al. (2010) have taken a leading role in developing coupled process models. Recent investments in the SNL SIERRA Mechanics code suite have supplied the basic building blocks for realizing a multiphysics capability for repository systems engineering. These simulation tools provide an adaptive multiphysics framework for addressing the disparate time and length scales associated with geomechanics problems such as waste disposal. To demonstrate this developing technology, a three-dimensional, coupled, thermal-mechanical analysis of a generic salt repository for HLW was performed. Some of the discriminating features of this highly nonlinear, thermal-mechanical analysis include the use of large-strain, large-deformation mechanics and the use of both thermal and mechanical contact surfaces.

New simulation capabilities have been applied to model disposal room evolution. Past analyses of salt creep and room closure have been constrained by the computational effort and complexity associated with coupled processes. Advanced simulations of HLW disposal in salt were run at SNL using the SIERRA Mechanics suite of codes, with massively parallel computing hardware. This scoping study described the evolution of a generic salt repository containing heat-generating wastes from a modern UNF recycling facility (Washington Savannah River Company et al. 2008). The study simulated a repository consisting of a series of underground panels, each containing individual rooms with many alcoves. The disposal strategy assumes placement of one HLW package near the end of each alcove, covered by crushed salt backfill for radiation shielding of personnel accessing adjacent alcoves. The backfill insulates the waste package, locally increasing waste package and near-field repository temperatures.

A three-dimensional finite-element model of a single disposal alcove and the adjoining access room was developed using planes of symmetry through the alcove and the access room. These thermal-mechanical analyses include the use of thermal contact surfaces to model the effect of room closure on heat transmission. The mechanical effect of the large deformation is also captured through the use of contact surfaces in the mechanical calculation. In addition, the effect of thermal radiation between heated surfaces within the alcove and access room is modeled using a capability to recompute radiation view factors as the openings deform. The mechanical response of the salt is modeled using a power law secondary creep model with an Arrhenius term to account for changes in creep strain rate due with temperature. The compaction behavior of the crushed salt backfill is modeled with a nonlinear pressure vs. volume strain relationship. These are widely used constitutive models, selected for demonstration purposes.

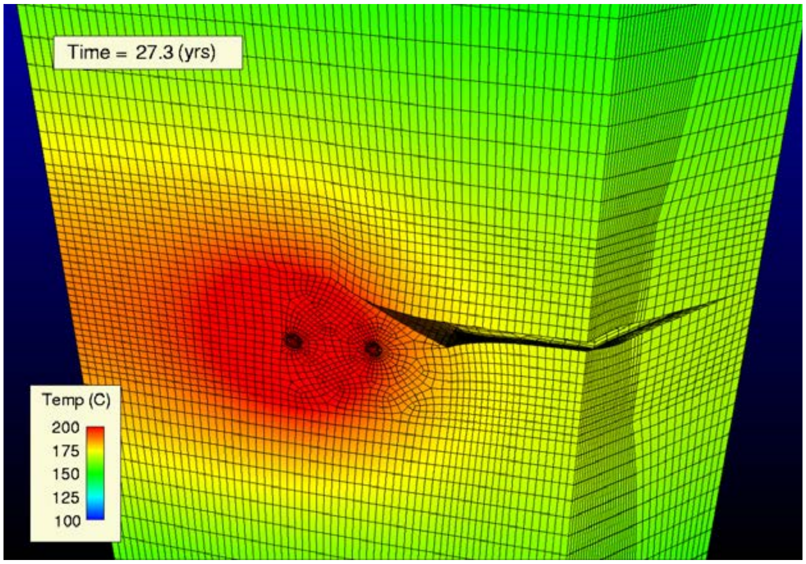


Figure 7. Temperature in the deformed salt repository at 27 years (Stone et al. 2010)

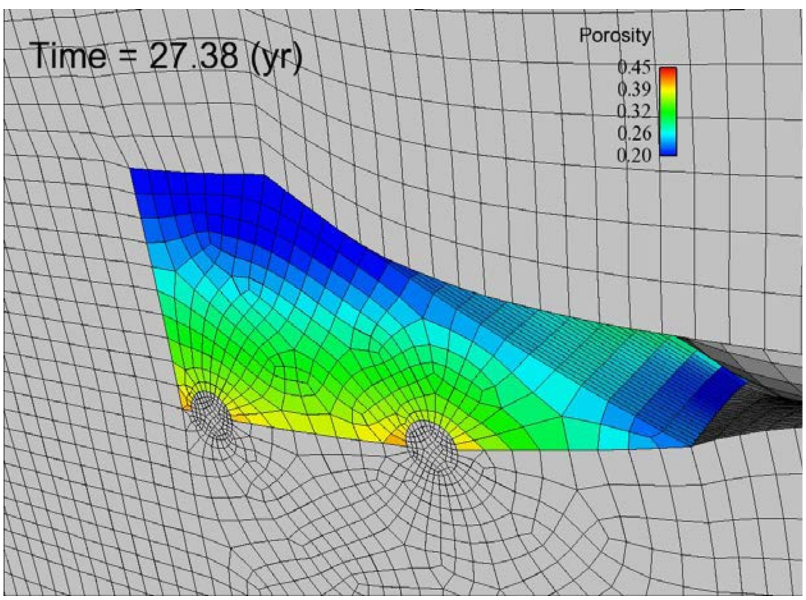


Figure 8. Porosity in the crushed salt backfill at 27 years, from an initial porosity of 0.42 (Stone et al. 2010)

The thermal properties of the crushed salt backfill correspond to unconsolidated salt, which produces higher waste and salt temperatures than if the crushed salt were assumed to have thermal properties of intact salt.

A deformed mesh plot with contours of temperature is shown in Figure 7 at 27 years after waste emplacement. In this example, the access room and alcove are almost completely closed by 27 years. The need for the large-deformation, large-strain mechanics formulation is clearly shown by the magnitude of the simulated deformation. The maximum temperature at the canister/salt interface is 408°C occurring at 4.0 years, which is consistent with the formation of a dry halo of salt around the waste.

Figure 8 displays porosity in the crushed salt backfill at 27 years after emplacement. The crushed salt backfill develops a nonuniform porosity with most of the compaction occurring near the roof of the alcove. This variation of compaction is in qualitative agreement with measurements of porosity in the backfill made in the Bambus II project (Bechthold et al. 2004). The minimum porosity is 0.12, which is substantially reduced from the initial emplaced value of 0.42.

These fully coupled thermal-mechanical calculations help to show how salt ductility is increased by heating and the effect on temperature and physical properties. The disposal alcoves become isolated from the adjacent mining and disposal areas because the salt aggregate consolidates to an impermeable solid and will be drier than the native salt because of the heat pulse. Stress differences in the near-field salt and backfill would be relatively quickly relieved because the deforming salt reestablishes isotropic stress conditions. Simulated isotherms eventually peak—this demonstration calculation produced peak temperatures at about 16 years (Washington Savannah River Company et al. 2008)—and then diminish such that the waste is always hotter than the surrounding rock.

These results are examples of an emerging capability that is anticipated to be of great utility if salt formations are considered for HLW disposal. There are several research and development organizations (Hampel et al. 2010) pursuing the latest advances in modeling capabilities, including coupled constitutive models and the new frontier that high performance computational platforms provide to salt repository studies.

2.4.3.3 International Salt Modeling

Hampel et al. (2010) recently summarized numerical simulations for the design and stability analysis of underground openings in rock salt. The geomechanical and hydraulic behavior of the host rock is described with constitutive models. In recent decades, various advanced models and procedures for the determination of salt-type-specific parameter values and for handling numerical simulations have been developed. Between 2004 and 2010, six project partners have been funded by the German Federal Ministry of Education and Research in two joint projects to document, check, and compare their constitutive models for rock salt. The results of specific benchmark calculations demonstrate that the models describe correctly the relevant deformation phenomena in rock salt under various influences; i.e., transient and steady-state creep, the evolution of dilatancy and damage, short-term failure and long-term creep failure, post-failure behavior, and residual strength. This ensures a high reliability of simulation results that may be applied to long-term prediction of integrity of the geological barrier around an underground repository for hazardous wastes, radioactive wastes, and other applications.

Hampel et al. (2010) provided several pertinent conclusions regarding the state of the art in salt modeling. Their benchmark calculations and comparisons of the results in joint projects showed that the constitutive models captured deformational phenomena in rock salt below and above the dilatancy boundary. These benchmark calculations modeled an isothermal case. For a nonisothermal HLW repository, results from a well-conceived in situ test result would be important for model validation. Collaborative research can build from the previous work of Hampel et al. (2010) and improve tools for assessment of secure disposal of radioactive wastes in rock salt. Such collaboration is poised to determine the best constitutive models to describe the thermal-mechanical and hydraulic behavior of host rock salt under various influences and to extrapolate that behavior to long-term simulations.

Recent projects in Germany focused on disposal of non-heat-generating hazardous wastes in rock salt, considering only mechanical behavior at ambient temperature. For disposal of HLW, the strong temperature dependence of mechanical behavior and hydraulic properties must be described effectively by constitutive models in repository simulations. Comparison of different constitutive models and their theoretical bases is identified as one of the first activities recommended if the U.S. opts for a salt disposal option. Modeling collaborations can begin with coupled, thermal-mechanical three-dimensional benchmark simulations. These calculations would compare the evolution of stresses, strains, dilatancy (i.e., volumetric strains), damage, and permeability in rock salt under the influence of elevated and changing temperatures.

To summarize, the developments at SNL with the SIERRA Mechanics codes and the developments described by several German salt researchers provide ample experimental data and simulation capability for mechanical deformation of rock salt. Several advanced constitutive models have been developed and applied. However, for elevated-temperature repository applications, the strong temperature dependence of mechanical deformation behavior needs to be reevaluated if the salt disposal option is selected.

2.5 Chemical Conditions in the Host Rock

Near-field geochemistry in a salt repository is controlled by the potential interactions between the salt formation brine and the waste, packaging, and emplacement materials. To the extent that brine is available to react with these materials, the pH, oxidation/reduction conditions, gas fugacities, and dominant aqueous species present would evolve over time. This evolution would be influenced by temperature, especially during the thermal period of a HLW repository in salt.

This section discusses potential geochemical interactions in the near field that would determine the source term for radionuclide release <u>if</u> brine is available to react with the waste.

2.5.1 The Thermal Period

It is only during the thermal period that the geochemistry of the near-field environment of a HLW repository in salt has the potential of being substantially different from what has already been studied within the context of the national and international isothermal salt repository programs.

Definition of the thermal period is uncertain due to possible variations in the geometry of the disposal room, the heat generating capacity of the waste, and the emplacement configuration for the waste. In the most general sense, the thermal period can be defined as the time when temperatures are elevated above those of an isothermal repository. Elevated temperatures below 100°C cause aqueous salt solubilities to increase, gas fugacities to change in a closed system, and reaction rates to increase. These trends apply from ambient temperature up to dryout at 107°C (for NaCl brine at 1 atm) or higher temperatures (for Na-Ca-Cl and/or total pressure > 1 atm). A range from 100°C to 110°C is an important transition that is compositionally dependent for reasons alluded to above.

Geochemistry of the near field during the thermal period, because of its strong dependence on the thermal-mechanical performance of the repository and the availability of brine, has bearing on decisions that are made during repository design and on repository performance. For example, given the information presented in Section 2.4, it is anticipated that salt will deform rapidly to enclose the waste, the heat will dry out the salt by boiling or general heating (i.e., accessible brine will be driven away from the thermal source, leaving the salt around the waste drier), and contact between brine and the waste packages will thereby be diminished during the thermal period. If this is, indeed, the case, geochemistry during the thermal period would have little impact on repository performance except in the case that a postulated disruptive event breaches the repository. Further, it is acknowledged that uncertainty in the estimates of the geochemistry of the near-field environment during the thermal period would contribute to the uncertainty of the overall performance of a HLW repository in salt.

The scientific basis for, and likelihood of, thermally enhanced encapsulation could play a role not only for performance assessment, but also for selection of the ultimate disposal concept. For example, if the salt rapidly encapsulates the waste and keeps the waste dry during the thermal period, it may be possible that certain waste forms could be disposed without a waste package (i.e., borosilicate glass logs or calcined waste logs). The focus of scientific research in this case would demonstrate that in the absence of brine, these waste forms would not degrade at high temperatures, and even if the waste form did degrade, the resulting degradation products would not be mobile.

Further, if the salt rapidly encapsulates the waste and keeps the waste dry during the thermal period, reducing chemical conditions in the near field of a salt repository may not prevail (however, if waste environment is dry there is no liquid to solubilize the waste). Generally, reducing chemical conditions that are expected in the near field reduce the solubility of actinide elements and possibly other elements, a benefit for repository performance. This is one of the features that makes the WIPP a robust repository for TRU waste. However, bedded and domal salt formations by themselves do not generally provide reducing environments, but they do provide a highly impermeable system that allows the reaction of materials to deplete any oxidants introduced into the system during operations.

A HLW repository in salt would be expected to have reducing near-field conditions during the thermal period only if reducing materials such as steel are sufficiently reacted with brine. Reducing near-field conditions would not be expected if corrosion-resistant alloys such as Alloy 22 or TiCode 12 were used for the waste packages (or if no waste packages were used) because reaction would be much less with such materials. An additional mechanism for producing reducing conditions is the reaction of brine with UO_2 in UNF disposed of in the repository. This is less likely because it would represent a breach of a waste package, but the UNF would represent a large mass of reducing material if exposed.

There may also be an oxygen demand by dry corrosion processes. With very little oxygen present, the local conditions are likely to be reducing. Once the waste package is penetrated by corrosion, the waste is exposed, which is likely to keep the oxygen and H_2O fugacities low. Thus the presence of brine is not necessarily required to ensure a locally reducing environment.

If thermal-hydrologic-mechanical models indicate that heated salt may not completely encapsulate the waste in a dry environment and that there remains a possibility that brine is accumulated in the near field during the thermal period, it is likely that the design basis of a HLW repository in salt would include waste packages engineered to survive the thermal period. This approach represents the philosophy of defense in depth for radioactive waste disposal. Brines from the surrounding bedded or domal salt formation or brines introduced by human intrusion would then interact with the waste packages and not with the waste form itself.

Corrosion of the waste packages could eventually proceed to waste package failure, allowing brines to interact with the waste form. Understanding the failure mechanisms, failure rates, and by-products of corrosion should be the focus of research in this area. High-temperature interactions between brine and the waste are less likely if the waste package is designed to survive the thermal period.

In preparing the technical basis for a HLW repository in salt, there may be a finite likelihood that some small percentage of the waste packages could fail prematurely, and that high-temperature brine could come in contact with a waste form during the thermal period. As such, some of the research effort should evaluate this scenario to have a developed basis for predicting what concentrations and species of radionuclides would be released. The extent of the research program on high-temperature brine-waste form interactions can be limited if sensitivity studies show that conservative simplifying assumptions do not result in significant, deleterious effects on the predicted performance of the repository. An example from the WIPP is the assumption that actinide concentrations in brine reach equilibrium with phases whose solubilities control their dissolved concentrations, and that equilibrium is obtained instantly upon closure of the repository. This idealized assumption obviated the need for expensive, long-term kinetic experiments and results in estimates of repository performance that meet safety standards.

2.5.2 After the Thermal Period

After the thermal period, the geochemical model details may differ from what is currently being modeled for existing salt repository programs, but the near-field geochemistry modeling approach would be the same as it is now for salt repositories using thermodynamic models. For example, some of the constituents listed in Table 3 differ from what is included in the current geochemical models for salt repositories. When additional, major constituents (i.e., those that expand the chemical system) are introduced, the emphasis of geochemistry research would be the consistent compilation/derivation of the relevant thermodynamic data and other parametric values needed for representing concentrated brine systems (e.g., Pitzer parameters).

One of the overriding advantages of salt disposal is the absence of brine. However, it may be possible to develop a scenario by which the repository resaturates after the thermal period. The volume of brine depends on the mechanism bringing brine into the repository and whether or not the repository has removed nearly all the void space by plastic deformation and reconsolidation. For a disturbed scenario where an aquifer in the vicinity of the repository may be breached in some way, open and connected repository space could fill with brine. Important chemical conditions occur only if ample brine is available to the system.

Chemical conditions in a repository can be described based on the predicted chemical reactions among the solids, liquids, and gases present in the system. For a salt repository, this translates into characterizing the reactions among the solid phases found in the salt formation, the solid phases that are the waste, the waste package and the emplacement materials, the brines that are in equilibrium with the salt formation solid phases, and the gases that may be present as part of the formation or may be introduced into the repository during construction.

The host rock of a bedded salt repository is, typically, dominantly composed of halite ($NaCl$) with significant amounts of anhydrite ($CaSO_4$), polyhalite ($K_2MgCa_2(SO_4)_4 \bullet 2H_2O$), and clay minerals as minor phases. The thermodynamic properties of halite and anhydrite are well known. To the extent that polyhalite and clay minerals are present in the formation, their thermodynamic properties would be part of a geochemical model, and their associated uncertainties would contribute in a fractional manner to the overall uncertainty in the results.

Salt formation brines tend to have high concentrations of sodium, calcium, and chloride. Lesser amounts of sulfate and carbonate are present. Some brines also have high magnesium concentrations. Recently, ongoing research has shown that borate is an important component in WIPP brines.

The in situ pH of brines is slightly acidic (i.e., about 6.0 to 6.5). Mineral components of the salt formation buffer the pH to their in situ values. The pH of brines after interaction with steel waste packages at low temperatures would probably be similar to that characteristic of the brucite “half buffer” used at WIPP (pH of about 9). The pH of brines in contact with steel waste packages at high temperatures may need to be determined. Heating the brine would change the pH. If buffered by mineral or gas equilibria, the pH would shift with temperature according to the applicable equilibrium constants in a predictable manner. Buffer materials would also have an impact on the pH, and one might consider adding a chemical buffer if the alteration-phase assemblage does not sufficiently constrain the system.

The gas introduced during the construction of a repository is primarily atmosphere, with nitrogen and oxygen as the major components. If brine reacts with steel waste packages, the oxygen is consumed, and the closed repository becomes anoxic. In the absence of oxygen, water could react with steel or other metallic components of the waste packages and produce hydrogen (H_2) gas via anoxic corrosion. Anoxic corrosion is the corrosion of steel or other metals by the oxygen in H_2O instead of by free molecular O_2 in the aqueous or gaseous phase (Haberman and Frydrych 1988; Simpson and Schenk 1989; Grauer, Knecht, and Simpson 1991).

If HLW waste form(s), canisters, and/or backfill materials interact with brines, substantial changes could occur. For example, alteration of oxide wastes or backfill materials, degradation of glass and/or ceramic waste, and corrosion of waste metals or metal canister materials might alter the oxidation state and pH of the near field. These processes may also change the nature of the solubility controlling phases for radionuclide solubilities.

If UNF (~95 % UO_2) reacts with brines under reducing conditions in salt repositories, the dominant alteration phase is likely to be coffinite ($USiO_4 \bullet nH_2O$). The formation of coffinite is favored in the presence of silica. The source of silica required for the formation of coffinite can be from dissolution of clay minerals and quartz in salt formations and from dissolution of borosilicate glass in the waste. Typical borosilicate glass consists of 20% of fission product oxides, 50% of silica, and 30% of boric acid. Borosilicate glass is inherently thermodynamically metastable solid, and therefore will convert to a more stable assemblage of crystalline phases upon reaction with brines. In natural uranium deposits, coffinite is observed as a major alteration phase of uraninite (UO_{2+x}) under reducing conditions. In addition, niobium and rare earth elements are present in spent nuclear fuel as fission products. When they are dissolved in brines, they could combine with dissolved uranium(IV) to form brannerite as an additional alteration phase.

The solubility controlled dissolved concentrations of radioelements under hypothesized salt repository conditions define the source term for releases (e.g., any sort of direct brine release or advective transport to the biosphere). The key factors that establish the concentrations of dissolved radionuclides are the following:

- redox chemistry
- pH, aqueous complexes, and speciation
- intrinsic colloid and pseudocolloid formation

In the case of the actinides, the solubilities of reduced species (+III and +IV oxidation states) are significantly lower than those of the oxidized forms (+V and/or +VI). For a given oxidation state, the pH and complexing agents present define the speciation and hence, the solubility of a radioelement solid in the brine. Complexants are either in the pre-emplacement environment or exist in the HLW waste form(s). In addition, some of the key radioelements in HLW in their expected oxidation states tend to form colloids (intrinsic colloids) or strongly associate with colloids that may be present because of the presence of clay seams in the salt formation (pseudocolloids). Thorium intrinsic colloids have been shown to form at low temperatures in brine (Altmaier, Neck, and Fanghänel 2004; Altmaier et. al. 2005; Altmaier et al. 2006). Plutonium(IV) intrinsic colloids have also been shown to be important under some conditions.

The oxidation-state-specific solubilities of key radioelements in brines have been established for isothermal repositories like WIPP and Asse, but these solubilities are less constrained at high temperatures. If elevated temperatures persist when brine potentially comes in contact with the waste form, the temperature dependency of radioelement solubilities would be evaluated as part of the research associated with establishing a salt repository for HLW. The overall goal of such work would be to establish the magnitude of the temperature effect on radioelement solubilities.

2.5.3 State-of-the-Art Geochemical Modeling

A geochemical model facilitates quantitative and reproducible estimates of the solution chemistry and radionuclide phase solubilities in a complex repository system. Typically, geochemical models applied to repository systems are thermodynamic rather than kinetic models and use thermodynamic data derived specifically for the application The supporting thermodynamic data do not always exist at large in the public domain. The geochemical model here consists of the code as a numerical engine, the particular database that is used to support it, and the concepts used to describe the system.

Such is the case for geochemical modeling for an HLW salt repository. A salt repository may have high ionic strength brines that interact with a wide variety of system components, like actinides, fission products, and activation products, as well as some less abundant elements like titanium and beryllium. Thus the geochemical model for a salt repository will be distinct depending on repository design, waste form characteristics, and the chemical characteristics of the salt formation surrounding the repository.

Some general information about geochemical models for salt repositories can be inferred from the work that has been performed to date. First, for high-ionic-strength brines like those that would exist in a salt repository, the geochemical model has to be able to evaluate concentrated aqueous solutions. This means the model will be able to evaluate non-ideal solution behavior using some form of activity coefficient model for aqueous species. Several different activity-coefficient models exist (e.g., the Davies equation, the B-dot equation, Pitzer's equations) (Wolery 1992). The use of Pitzer's equations to model ionic interactions is appropriate for salt repositories and has been applied at WIPP.

Pitzer's equations have been incorporated into many geochemistry, atmospheric chemistry, and chemical engineering codes. These equations and the models based on them are widely used and accepted. In geochemistry, Pitzer-based models have been incorporated into EQ3/6 (Wolery 1992, Wolery and Daveler 1992, Wolery and Jarek 2003), the U.S. Geological Survey codes PHRQPITZ (Plummer et al. 1988) and its successor PHREEQC (version 2.12, see http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc), and The Geochemist's Workbench (Bethke 1996; see also http://www.rockware.com). These are some of the better-known examples and are used by geochemists worldwide. They have been applied to a wide variety of problems in aqueous geochemistry including mineral-water interactions in many different settings, brine generation by evaporation, and deliquescence of salts. The Pitzer approach presently has widespread application in the technical community although alternative approaches such as Extended UNIQUAC (Thomsen 2005) do exist and are drawing increasing interest.

The Fracture-Matrix Transport (FMT) code (Babb and Novak 1995, Babb and Novak 1997, Wang 1998) was used for modeling geochemical interactions in the WIPP repository. The geochemistry part of this software uses Pitzer's equations (Pitzer 1973, 1975, 1991) to represent the thermodynamic activity coefficients of aqueous species, including both solutes and the solvent, water. The standard form of the Pitzer equations is based on molalities and requires data for interaction parameters for pairs and triplets of the solute species included in the model (interaction parameters explicitly involving the solvent, water, are not employed). The FMT model is based on the classic Pitzer model of Harvie, Møller, and Weare (1984) for the "sea-salt" system at 25°C and has been extended by adding data for organic complexants (e.g., oxalate, citrate, ethylenediaminetetraacetate [EDTA]) and actinides.

The WIPP project has migrated to EQ3/6 in order to facilitate future analyses of their salt repository system. The EQ3/6 package of geochemistry codes has been well tested during its widespread usage. For equilibrium analyses, the package includes the EQ3NR code, which accepts the usual kinds of inputs describing an aqueous solution, such as solute component molalities and pH. The EQ6 code allows evaluation of irreversible mass-transfer reactions among liquids, solids, and gases with relative or specific kinetic rate considerations. These offer two options to address charge balance, calculate and fix the imbalance, or adjust one of the ionic components to achieve charge balance. Also, EQ3/6 uses the later Harvie (1981) approximation, which is the one used in essentially all modern work involving Pitzer's equations, including the Harvie, Møller, and Weare (1984) model for the sea-salt system that forms the core of the FMT CHEMDAT database. The WIPP version of EQ3/6 is Version 8.0a. This is the version of the code package that would be recommended for geochemical modeling related to disposal of HLW in salt.

2.5.4 Coupled Reactive Transport Modeling

Nonisothermal, multiphase reactive transport modeling could be applied in understanding the evolution of a salt repository for HLW. The purpose would be to simulate composition of the gas phase, including water, oxygen, hydrogen, and CO_2. Because performance is sensitive to how the DRZ and crushed salt backfill consolidate and heal to encapsulate the waste/waste canisters, simulation of gas movement in the system, which involves thermal hydrology, could be beneficial. To confirm such a model using a field test, one would compare model predictions to gas-phase chemical and isotopic analyses. Traces of moisture, CO_2, and other gases with connate and modern origins would be driven off when the intact rock and the crushed salt backfill are heated. The initial off-gassing would decline with time, and one could attempt mass balance within the drift while also interpreting changes within and mass exchange with the intact host salt. Reactive transport simulations have limitations in application to repository problems related to complexity, accuracy, and extrapolation of time scales. Because there is not likely to be much water present in a salt repository, especially during the thermal period, the aqueous chemistry may not be very significant to performance. However, numerical reactive transport simulations are ideal tools for interpreting gas-phase movement in an in situ heater test. Existing simulators (e.g., TOUGHREACT) would be examined to determine how best to include required features (e.g., osmolality).

2.5.5 Radionuclide Transport

An understanding of the source term discussed in this section is desirable if there is a potential for radionuclide transport to the biosphere. In such cases, release scenarios would involve leaching materials into the available brine and movement of the brine to the biosphere. One appeal of a salt repository for HLW is that intact salt is essentially impermeable. This eliminates the diffusive transport pathway for a salt repository. Depending on the stratigraphy and location of the repository, advective transport pathways such as interbeds may exist. However, if contaminated brine from a salt repository finds an advective path to the regulatory boundary, some radionuclide sorption will occur, although not as much as expected in clay or shale. Typically, the efficacy of a salt repository does not rely on radionuclide sorption for significant retardation of radionuclides. Sorption capability is ranked very low in Table 2. In addition, the heat-generating nature of HLW has only minor influence on far-field processes like radionuclide transport and sorption. Modeling these processes for a HLW repository in salt, if required, would parallel modeling for an isothermal repository.

2.5.6 International Collaboration on Salt Repository Chemistry

An international collaboration on salt repository chemistry took place in September 2010. The collaboration is part of an ongoing effort bringing national and international researchers together for the advancement of salt repository science. Workshop topics include recent advances in geochemical experimental and modeling studies, the effect of microbes in the salt environment, and corrosion of package materials in brines. The outcome of the geochemistry workshop will integrate respective research goals with those described in this report.

3 PERFORMANCE ANALYSIS FOR HLW DISPOSAL IN SALT

The information presented in Section 2 summarizes an understanding of and expectations for the thermal, hydrologic, mechanical, and chemical behavior of salt as a disposal medium for HLW. This section discusses the development of a performance-based, directed research program using the PA methodology shown in Figure 9 as a tool.

The PA methodology shown in Figure 9 does not simply encompass demonstrations of repository performance and regulatory compliance, which is a more traditional definition of PA. In early stages of repository development, as disposal in a particular geologic medium or with a particular design concept is being considered, the methodology includes analyses that inform the decision maker about what is important for repository performance and what, if any, "data gaps" would need to be filled. Thus, this methodology is the basis for a directed science program that may lead to the development of a repository for HLW. These principles have been applied to several very different disposal concepts that advanced to licensing: WIPP, Yucca Mountain Project, and Greater Confinement Disposal (Cochran and Price 2006). Although these are dissimilar settings and have different controlling regulations, the performance assessment methodology integrates the same key elements.

The first step, *Performance Goals*, establishes overarching boundary conditions, which govern the framework for subsequent strategic choices (Figure 9). The boundary conditions include national and international law and regulatory requirements. The second step, *Characterize System*, develops the strategic choices that are intended to meet the performance goals. These include the geologic formation, the waste inventory and the concept of disposal. At the time of this report, regulatory performance goals specific to a salt repository for HLW are not available, but one can envision goals similar to those that exist for other repository programs, including the complete containment approach adopted by Germany (Rothfuchs et al. 2010). The second step becomes increasingly important as the repository project moves from concept to implementation and the performance of a particular system must be established. The third step, *Identify Scenarios for Analysis*, involves the systematic process of evaluating the FEPs associated with the particular site, the concept of operation, and the HLW waste inventory.

The next step, *Performance Assessment*, involves development and implementation of conceptual and mathematical models, and numerical models incorporated into simulation software. One can use the output from this step to inform decisions about compliance with performance goals (upper right hand side of Figure 9) or to inform decisions about a directed science program (lower left hand side of Figure 9). The latter is the objective of this section. Based on experience in the U.S. and collaborations with international peers (e.g., Belgium and Germany), the content of this section follows the process shown in Figure 9 at a very high level for the purpose of identifying what are the key elements of a directed science program addressing the possibility of HLW disposal in salt.

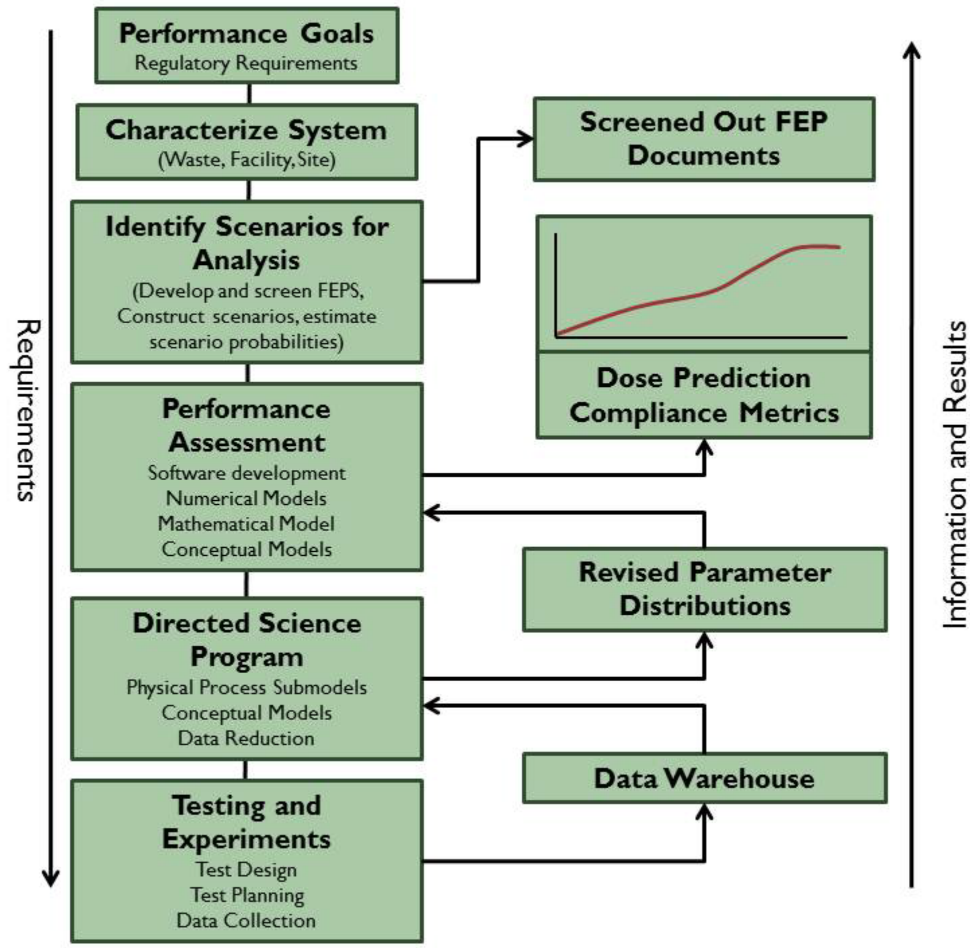


Figure 9. SNL long-term Performance Assessment methodology.

3.1 Identification of Relevant Features, Events, and Processes

To effectively use performance assessment to evaluate a disposal system, three questions must be answered:

- What can happen to the disposal system?
- What are the chances of it happening?
- What are the consequences if it happens?

The answers to these questions are derived from many sources, including field studies, laboratory evaluations, experiments, and, in the case of some features not amenable to direct characterization, professional judgment. The information used in performance assessment is described in terms *of features* of the disposal system that can be used to describe its isolation capability, *events* that can affect the disposal system and *processes* that are reasonably expected to act on the disposal system. These features, events, and processes (FEPs) are the cornerstone of any meaningful evaluation of performance of the disposal system.

3.1.1 Catalogs of FEPs

Well-developed catalogs of FEPs exist for the various repository programs around the world, although these lists are, by design, general in nature (Stenhouse, Chapman, and Sumerling 1993; Prij 1993; Guzowski and Newman 1993). This ensures that the list for a specific site is comprehensive and does not overlook FEPs that might be otherwise omitted based on the characteristics of a particular site. While the list of possible FEPs is derived independently of the disposal system, its screening should be based on a basic understanding of the geology, hydrology, and climatology of the region and the site. Other screening considerations include waste form and characteristics, disposal concept, and regulatory and performance standards. The screening process will result in a list of FEPs that should be represented in performance scenarios for the waste repository. In this way, FEPs that are relevant to the three questions posed above are included in the scientific analyses used in making performance predictions.

The process used for the development of a FEPs list is well documented (Cranwell et al 1982, DOE 1996a, DOE 1996b, Hansen et al. 2010) and could serve as a model for the development and screening of FEPs for a HLW repository in salt. For example, the WIPP FEPs list (see Appendix A) is divided into three primary categories: natural FEPs, human-initiated FEPs, and waste- and repository-related FEPs. Because the WIPP is situated in bedded salt, the natural FEPs used for the WIPP could be used for a HLW repository in bedded salt with minor changes.

Based on the analysis of the FEPs supporting the performance assessment and compliance certification for WIPP, the primary contributor to any possible release is human intrusion. Thus, the human-initiated FEPs are studied extensively. However, they are site specific, stemming largely from the drilling rate associated with existence of oil and potash resources in the region. A direct human borehole intrusion through a HLW repository could possibly drill through the entombed waste. The probability of that event is a function of the drilling rate and the resulting human exposure of that event depends on the location of the site. Thus, the human-initiated FEPs determined for a salt formation in southeastern New Mexico are not necessarily applicable to another HLW repository in salt.

The phenomena caused by heat from HLW would add some FEPs. In addition, the physical characteristics of HLW are likely to be appreciably different than the TRU waste that is being disposed in WIPP. Therefore, the waste-related and repository FEPs would need to be evaluated. Additionally, there could be differences in the disposal concept, container types, and performance period represented in the FEP list, underscoring the need to carefully review the appropriate FEPs for a HLW repository in salt.

3.2 Scenario Selection

Once the host rock has been characterized, the repository designed, and the waste characterized, a PA generally begins by identifying a list of FEPs potentially relevant to long-term performance of the disposal system. FEPs are then examined to determine if releases of radionuclides from the disposal system would be significantly affected by inclusion of the FEP; FEPs without significant effects may be omitted from the performance assessment. Retained FEPs are next grouped to construct scenarios for analysis of disposal system performance.

3.2.1 Scenario for an Isothermal "Cool" Salt Repository

The following is an example of a scenario developed from the screening of FEPs for the WIPP (DOE 2009). It is being presented as an example of a scenario in a "cool" salt repository.

After closure, the WIPP compliance models show rapid increase in repository pressure during the first 1,000 years that is caused by several factors: rapid initial creep closure of rooms, initial inflow of brine causing gas generation due to corrosion; and gas production by microbial consumption of cellulosics, plastics, and rubber in the waste inventory. Pressure generally approaches a steady-state value after 2,000 years as room closure ceases, brine inflow slows and cellulosics, plastics, and rubber materials gradually break down by microbial or abiotic processes. Gas pressure in the repository rooms may approach lithostatic pressure.

For WIPP performance assessment, cumulative releases from the repository consist almost entirely of direct releases to the surface resulting from an unintentional human intrusion by drilling. Direct releases comprise solids removed by the drill (cuttings), material eroded from the borehole walls by the drilling fluid (cavings), contaminated brine (direct brine releases), and pressure-driven releases of solids (spalling). Unless repository pressure exceeds hydrostatic, direct brine releases are zero; spalling releases are also zero unless repository pressure approaches lithostatic. Consequently, the volume of brine in the repository significantly affects releases from the repository through its effect on repository pressure.

3.2.2 Scenario for a Thermal "Hot" Salt Repository

Thus far, the modeled conditions for salt disposal room evolution for non-heat-generating waste, using WIPP as an example, have been described. Even when conservative models are used, there is no path for movement of radionuclides out of the isothermal salt repository except diffusion, which is extremely limited. The only potential releases are from human intrusion scenarios where flooding of the repository and/or pressure increases lead to releases to the surface through boreholes.

The expected isolation of HLW could be even more robust in a repository that is appropriately sited, constructed, and operated. Temperature effects on salt deformation are dramatic as shown by laboratory tests on natural salt specimens. Elevated temperature in a salt repository will enhance deformation upon placement of the waste in the rooms. Elevated temperatures and deviatoric stress states near the waste will enhance dry-out and promote encapsulation. Thermally induced salt plasticity is a constant-volume process. As stress equilibrium is re-established by accelerated salt creep, permeability will be eliminated.

It is likely that heat from disposed waste will initially drive moisture out of the near-field rock. It is well known that excavation of underground openings in salt induces stress gradients and assorted fractures. A DRZ forms around the opening. Brine flows down the stress gradient into the opening, which might comprise a drift or disposal room. Heat would further mobilize near-field moisture by vaporization. Thus, the DRZ and waste heat combine initially to form a dry halo around the waste. The moisture may be swept away completely by ventilation and possibly condensed elsewhere away from heat-generating waste, or it may be hygroscopically absorbed by the salt in a cooler area where the relative humidity exceeds 75%. As creep deformation of the salt proceeds with time, the near-field rock becomes impermeable to future invasion by brine or water vapor, as its properties approach those of intact salt.

After hot waste is placed in the salt, heat is conducted into the salt, setting up temperature gradients in the surrounding rock. It is possible that brine inclusions could migrate through intact salt, toward the heat source. However, in the early period when thermal gradients are steep, the migrating inclusions will encounter grain boundaries or microfractures, where they will move down the stress gradient toward the repository ventilation. Under these circumstances, a heat source placed within the salt would drive moisture away instead of attracting it.

A reasonable expectation of a heated disposal room evolution can be predicted from existing knowledge where

- The damaged zones around the disposal room release the accessible moisture by flow down the stress gradient and evacuation by the ventilation air.
- Room closure will be accelerated by thermal activation of crystal plasticity (flow without damage).
- If the room is backfilled with crushed salt, the granular material will reconsolidate.
- Stresses will drive toward equilibrium, which effectively heals damaged rock, and the waste is expected to be entombed in dry halite.
- Once the DRZ is healed, the permeability will be similar to that of undisturbed halite.

- Response of the modified system to future human-initiated borehole intrusion, is improved because there is less moisture available, and lower permeability around the emplaced waste.

Based on the logic presented above, an undisturbed salt repository containing hot waste may be even more robust than that certified for non-heat-generating waste.

3.2.3 Important FEPs for a "Hot" Salt Repository

The German approach to repository performance relies on complete isolation within the salt formation (called the isolation rock zone or IRZ). Complete isolation is predicated on the long-term integrity of the IRZ and proof of functional efficacy and robustness of the engineered barrier system. This concept is entirely consistent with the expectation of salt performance assessment for undisturbed cases, as discussed above.

As noted by Rothfuchs et al. (2010), the new approach for complete containment is an important development for repository safety assessments. Previous safety assessments emphasized release scenarios and compared results to regulatory performance objectives. The engineered barrier system played an important role in long-term safety of the repository system, particularly the seals in the shafts and connecting drifts, which are essential features to avoid intrusion of brine from overlying, water-bearing strata.

In the current IRZ concept, the shaft and drift seals are assumed to have finite lifetimes. This differs with the design philosophy for WIPP in which shaft seal system elements perform forever and are redundant. In the German concept, the long-term sealing function is taken over by compacting crushed salt backfill. The crushed salt backfill has essentially no barrier function in the early years. Permeability reduction is achieved as room closure reconsolidates the granular salt. Thus, in their concept FEPs that represent degraded function of the shaft and drift seals, such as FEPs describing the DRZ, become less important with time.

Scenario development for an HLW salt repository is one of the first activities to be pursued if a salt disposal option is selected for the U.S. Considerable uncertainty in the most important FEPs still exists, and the types of human intrusion scenarios to be considered for a HLW repository in salt might depend on the location of the repository and treatment dictated by regulatory requirements. Nevertheless, an understanding of the nature of scenario development for performance assessment clarifies which FEPs are currently deemed important based on the information summarized in this report.

Section 4 outlines a science-based approach to these data needs that begins with the current state of the art, identifies possible weaknesses, describes investigations that could address possible points of contention, and concurs with international perspectives and recommendations.

4 A PERFORMANCE-BASED DIRECTED RESEARCH PROGRAM

Much information has been collected in the past fifty years that supports development of a HLW repository in salt. The next step in establishing the case for HLW disposal in salt is to exploit the available information and develop a solid basis for modeling thermally driven coupled processes. This section evaluates what is presently known versus what information is still needed: a preliminary gap analysis. A stylized depiction of gap analysis is presented in Figure 10. Analyses of this type would be undertaken if there is a U.S. decision to investigate HLW disposal in salt, to provide a foundation for determining the scope of further work as the investigation proceeds.

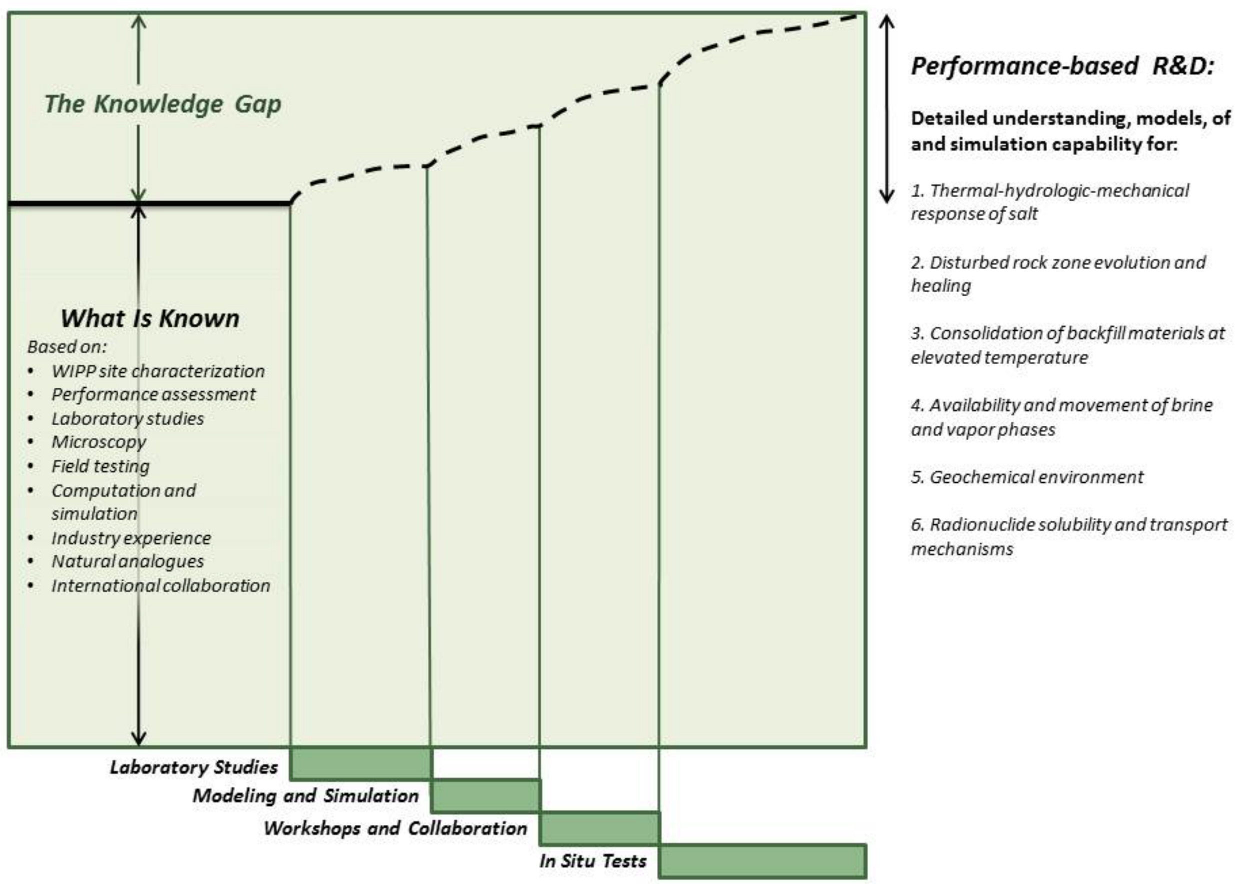


Figure 10. Gap analysis for a HLW repository in salt.

To demonstrate the performance of a salt repository based on technical information, one needs a detailed understanding of the important phenomena. That understanding must be translated into appropriate models with associated parameters and supporting data. Simulation capabilities are central to design, analysis and performance assessment. Six research areas listed on the right hand side of Figure 10 are examples deriving from Section 3. Each of these elements is compared to the technical information from Section 2, at a high level. With this type of analysis, proposed research and characterization activities can be prioritized into a performance-based directed science program. An identified data gap in an area that is not necessarily important to repository performance should not propel the program into a study of that technical area. In contrast, a small data gap in an area important to repository performance might justify directed science activities in that technical area.

The following sections discuss data gaps for the six FEP areas, to establish the framework for performance-based directed research and development should the U.S. decide to investigate HLW disposal in salt. In addition, Section 4.7 incorporates the findings of the U.S./German salt repository workshop held in May 2010. Results from the workshop are broader than the perspectives represented by the six FEP areas, but significant overlap exists. Thus the research and development activities recommended in the following sections are consistent with many of the primary goals of salt repository programs internationally.

4.1 Thermal-Hydrologic-Mechanical Response of Salt

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

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

4.2 DRZ Evolution and Healing

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

The DRZ is usually explicitly implemented in performance assessment process models used to predict future repository conditions and evaluate the possibility of brine flow to the accessible environment. The properties of the DRZ control a significant portion of the brine that is postulated to flow into waste rooms. The most important DRZ properties are the extent (or thickness) of the DRZ, its porosity, and its permeability as they are the three fundamental parameters used for analysis. Evidence suggests that the DRZ is much smaller in extent and has a lower permeability, thereby limiting the amount of brine that could flow into the disposal rooms.

The damage volumetric strain gives rise to high permeability. The evolution and healing processes are fundamental to seal system design considerations. Building on known information summarized in Section 2.4.1, several approaches would be used to study the DRZ, including laboratory testing, in situ testing, and analogues. These approaches are compatible with international research goals and objectives.

4.3 Consolidation of Backfill Materials at Elevated Temperature

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

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

4.4 Availability and Movement of Brine and Vapor Phases

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

The conceptual model for brine migration involves a fluid inclusion trapped within the crystal structure, which tends to migrate toward the heat source because of enhanced solubility on the "hot" end and relatively less solubility on the "cool" end. The fluid inclusion preferentially dissolves salt away from the hot end and deposits the dissolved salt on the cool end, thus the crystal void migrates toward the heat. The phenomenon of brine migration has been observed in the laboratory and in field experiments.

Introduction of heat into the salt formation will drive moisture movement. Schlich (1986) describes some relevant results obtained by computer simulation of water transport in the heater experiments conducted at the Asse mine. The main result was that an evaporation model with Knudsen-type vapor transport combined with fluid transport by thermal expansion of the adsorbed water layers in the non-evaporated zone showed the best agreement with experimental evidence. Based on his studies it appears that vapor transport processes dominate moisture movement.

Potentially, the hydraulic gradient between the far field host salt formation and the excavated room is initially large. If the permeability is high enough to allow brine flow, nearly all the brine contained in the DRZ can flow into the waste emplacement openings. These processes are observed in underground openings in salt. Stress differences occur immediately upon excavation, so the dewatering process begins quickly. Brine migrates down the stress gradient and evaporates into the ventilation air. Understanding the rate and extent of moisture removal by these processes is important for advanced modeling and PA.

Description of the evolution and movement of brine and water vapor in a hot salt repository requires multiphysics modeling for all three of the brine movement mechanisms described above.

4.5 Geochemical Environment

The importance of the geochemical environment near the waste or waste packages depends on thermal-hydrologic-mechanical coupled processes. If the repository is dry and the salt has consolidated around the waste, there is no dissolution mechanism for the waste package and/or waste and no mechanism for movement of contaminants away from the waste.

However, if evidence arises indicating that the near-field geochemical environment may have an impact on repository performance, or if it is of interest to a repository regulator, the primary interaction needing study is the interaction between the brine and waste package materials. This research area would address waste package corrosion rates and the corrosion products formed at elevated temperatures. Also of interest is clarification of the hypothesis that waste forms placed in salt will degrade sufficiently at elevated temperatures that the residue can be removed readily by a human drilling intrusion. Evidence of extensive waste form degradation does not exist and would need to be gathered to support a process model if one were required.

4.6 Radionuclide Solubility Controls and Transport Mechanisms

An underlying premise of waste form solubility is that there is plentiful brine in the repository setting. If there were ample brine to dissolve the waste package and to dissolve the waste, the salt formation would be poorly suited for repository purposes. The volume of brine potentially available in a repository depends on the proposed mechanism bringing brine into the repository. As understood from the compliance basis for the WIPP, for an undisturbed repository at low temperatures, brine can only come in contact with the waste by flowing through or from the DRZ. The permeability of undisturbed halite is too low to permit significant migration of brine. A thermally driven repository could respond differently, but in either setting, there is a strong possibility for complete healing of the damage zone.

Nonetheless, research may need to address radionuclide solubility if there is ample brine available during the thermal period. If this is the case, the data gaps include information on elevated temperature interactions between brine, waste package materials, and waste.

4.7 Findings of the U.S./German Workshop on Salt Repository Research, Design and Operation

The remaining uncertainties regarding disposal of HLW in salt are of national interest and also international interest, since other countries and particularly Germany are considering salt as a disposal medium for HLW. Recent resurgence of international collaboration has focused on the approach for resolving lingering uncertainties related to HLW disposal in salt. The following section discusses the findings of a U.S./German workshop held in May 2010. The workshop topic was the thermal, mechanical and hydrologic aspects of salt disposal for HLW. A second workshop held in September 2010 discussed the geochemical aspects of salt disposal for HLW. The findings from the first U.S./German workshop are presented here.

Recent developments in Germany and the U.S. have renewed efforts in salt repository investigations. Representatives of institutions in both countries conducted a workshop in Canton, Mississippi. The first workshop was hosted by Mississippi State University and Sandia National Laboratories (Sandia National Laboratories 2010). The purposes of the workshop were to coordinate a potential research agenda of mutual interest and to leverage collective efforts for the benefit of their respective programs. The following sections summarize the findings of the workshop and describe a series of investigations to advance the state of knowledge for repository applications.

4.7.1 Description of the Work

Invited key investigators in salt repository science and engineering presented past, present, and future directions in salt research applied to radioactive waste disposal. The goal was to identify a coordinated research agenda that participants can agree in principle to pursue, with the intent of maximizing resources available, for the mutual benefit of each program. By conducting this workshop, participants intend to reinitiate collaborative research activities and bring them to the level of cooperation enjoyed in the past, create a potential joint research agenda, and renew working relationships among institutions and individuals. This workshop basically refocused previous collaborative research activities that had been waning for about ten years.

The workshop presentations are posted on a website (Sandia National Laboratories 2010). Based on these and other materials, participants identified several potential coordinated research areas. An abbreviated list of research topics derived from the workshop is given here, and a more comprehensive summary has been published (Karlsruher Institut für Technologie 2010). Some collaboration topics are less *research* oriented, than they are recognized needs to review and summarize existing information to address technical issues, before embarking on research collaborations. In several instances, research topics for collaboration were clearly identified.

The primary attributes of salt disposal are known and have been demonstrated at an operational scale over many years. However, there remain issues that have either not been substantially investigated or have not been reviewed to the point of objective reconciliation. This section examines some of these issues identified at the workshop. It is noted that some statements of technical sufficiency, or a lack thereof, are technical judgments in the absence of supporting scientific evidence. However, in most cases, the questions arise from established research inquiries. For comprehensive pursuit of salt repository science, the investigators should evaluate the full range of these issues.

The following list from the U.S./German Workshop-Mississippi salt workshop gives the status of phenomena or processes, which may need to be incorporated into PA or supporting models, and may require research collaboration:

1. **Brine Migration**. Brine exists in bedded salt in three forms: fluid inclusions, hydrous minerals, and grain boundary water. Owing to the characteristics and environments of the brine in salt, its transport or migration occurs via three primary mechanisms: motion of the brine inclusions in a temperature gradient, vapor-phase transport along connected porosity, and liquid transport driven by the stress gradient.

2. **Vapor Transport**. One of the most important issues in a HLW repository is the presence and fate of any brine that may be present.

3. **Gas Generation and Pressure Buildup**. Hydrogen gas generation from anaerobic corrosion of steel container materials might inhibit rock convergence and consolidation of crushed rock backfill. The associated hydrogen volumes and rates require further quantification.

4. **Buoyancy**. Movement of canisters containing heat-generating wastes, buried in salt-derived materials, has been postulated in the past. The existence of buoyant forces due to density differences, and thermally activated deformation, suggests the possibility of thermally driven convection or flow resulting in canister movement.

5. **Heat Effects**. It is widely held that the heat load from HLW is detrimental to operations and long-term isolation in salt. This perception may be balanced by accounting for heat effects that are favorable to operations and long-term safety.

6. **Damage Induced Permeability**. Mechanically or hydraulically induced permeability is based on the same microphysical process of percolation flow along grain boundaries after exceeding a threshold. In both cases the induced permeability is created by removal of intergranular cohesion.

7. **Consolidation of Hot Granular Salt**. Crushed salt used as backfill may be an important element in a potential HLW repository. Relatively little elevated temperature mechanical testing has been conducted for crushed salt. The accelerating effect of moisture on consolidation needs further investigation. Modeling concerned with long-term, low-porosity, two-phase flow is likely required.

8. **Solubility and Transport**. The salt repository community continues to research radionuclide solubility as if there will be ample brine available within the salt to dissolve and transport the waste. There are at least two parts to this important issue: one concerns brine sources and volume, and the other concerns existence of a pressure gradient capable of driving the soluble radionuclides to the biosphere.

9. **Degradation**. This research area addresses the underlying hypothesis that waste forms placed in salt will degrade sufficiently that the residue can be removed readily by a human drilling intrusion.

10. **Radiolysis**. Radiation is known to liberate hydrogen but further data are needed on the effect of combining radiation and temperature on the waste materials, waste packages, and the salt.

11. **Climate Changes**. The radioactivity of nuclear waste will decay over a period of time (100,000 years or longer) in which major environmental changes are possible. Climate driven changes such as glaciation, permafrost, and changes in sea level could affect the subsurface environment of a salt formation and must therefore be considered in performance and safety assessments.

4.7.2 Future Direction

The topics given above pertain to specific phenomena, several of which could be incorporated into the next generation of repository performance assessment and supporting models. Future directions for research collaborations could be twofold: (1) exploring fundamental processes using laboratory investigations and (2) exercising powerful new computational tools.

Stone et al. (2010) have completed fully coupled, three-dimensional (3-D), thermal-mechanical simulations for a generic salt disposal scheme. These calculations demonstrate the available tools for coupled, multiphysics modeling and repository systems engineering. Several aspects of this nonlinear, thermal-mechanical analysis are especially important. Past analyses of salt creep and room closure have been constrained by the computational effort and complexity. The advanced suite of SIERRA Mechanics codes has been developed at Sandia to run on massively parallel computing hardware, to address these past limitations (Edwards 2002).

Hampel and coworkers (Hampel et al. 2010) recently summarized numerical simulations for the design and stability analysis of underground openings in rock salt. Several partners performed benchmark analyses using various constitutive models. Their benchmark calculations and comparisons of isothermal results from joint projects showed that the constitutive models captured deformational phenomena in rock salt below and above the dilatancy boundary.

Based on the developments at Sandia National Laboratories with SIERRA Mechanics and the developments described by several German salt researchers, it would appear that different teams have collected extensive experimental data and theoretical knowledge for simulating the mechanical deformation of rock salt. Several advanced constitutive models have also been developed and applied. The strong temperature dependence of salt deformation and the thermal influence on reconsolidation need to be reevaluated soon if the U.S. chooses to investigate the salt disposal option. For the calculation and assessment of the tightness of the geological barrier rock salt around a repository, further effort is also to be made in the investigation and modeling of salt damage healing and the corresponding reduction of permeability.

Coupled thermal-mechanical benchmark 3-D simulations could be performed in order to calculate the evolution of stresses, strains, dilatant volumetric strains, and damage around a potential repository for heat-generating radioactive wastes in rock salt. Useful outcomes would include advancing the technical baseline regarding the processes described in the U.S./German salt repository workshop, and performing appropriate code benchmark calculations, ultimately leading to an in situ test for model validation. U.S./German collaborations continue with a goal to hold an integrated salt repository workshop each year.

5 SUMMARY AND RECOMMENDATIONS

Deep geologic disposal of heat-generating nuclear waste (HLW) requires an explicitly stated methodology to link the various completed, ongoing, and proposed investigations to a meaningful examination of the suitability of a specific geologic medium. This review document on HLW disposal in salt is one of a series of SNL reports examining disposal of HLW in various geologic media. Brady et al. (2009) looked at disposal in very deep boreholes. Hansen et al. (2010) also looked at HLW disposal in clay or shale media.

The methodology for assessing repository viability includes clearly defining the objectives, boundary conditions, and safety strategies. A top-down approach helps define gaps in the technical basis that should be resolved if a salt HLW repository program is pursued as an option for the U.S. This document summarizes the information currently available to identify research activities needed to strengthen the basis for salt disposal. Future regulations could impose other, key requirements on characterization and research activities.

This report first documents that the U.S. has vast land areas with salt formations of sufficient thickness and lateral extent to accommodate a nuclear waste repository. Second, that international nuclear waste repository programs have advanced the engineering and science sufficiently to impart confidence that such a repository could be safely constructed, operated, and sealed. Third, that the performance function of a salt repository would readily satisfy expected regulatory criteria for the safety case. And fourth, that sophisticated multiphysics analysis techniques are poised to investigate features, events, and processes that determine salt repository performance.

5.1 Summary of Findings

Use of salt formations for nuclear waste disposal has been a widely embraced concept for more than 50 years. Salt is impermeable and deforms plastically around the waste. There is no natural water flow through a salt repository. Disposal of nuclear waste in salt remains a viable concept in the U.S., as has been successfully demonstrated by more than ten years of successful operations at the WIPP repository for TRU waste near Carlsbad, New Mexico. The suitability of salt as a medium for HLW has been recognized by national and international repository programs, which have developed advanced engineering, scientific, and operational concepts. A high-level review of this progress and of previous investigations of salt media is provided in Sections 1 and 2. From this publicly available

Key study findings

Thermal, hydrologic, and geochemical considerations suggest that radionuclides in a salt repository for HLW would not migrate from the disposal horizon.

Current knowledge of thermal effects supports a viable concept of repository operations.

Three-dimensional multiphysics capabilities offer advanced capabilities for performance assessment modeling and field test development.

The suitability of salt as a medium for HLW disposal has been recognized by national and international repository programs.

information, the framework for evaluating a generic salt repository for HLW in the U.S. is developed.

Current knowledge of thermal effects in salt is based on limited testing and experience but supports a viable concept of repository operations. Further evaluation of tunnel deformation and stability, and the effects of excavation and heating on long-term performance would require development and application of site-specific constitutive models for the salt. Three-dimensional multiphysics capabilities are now available which promise advanced capabilities for performance assessment modeling and field test development.

Thermal, hydrologic, and geochemical considerations suggest that radionuclides in a salt repository for HLW would not migrate from the disposal horizon. The majority of radionuclides in the current waste inventory will be thermodynamically stable as solids and will therefore resist migration. Much of the inventory will decay before human intrusion would occur. A formal performance assessment would be used to examine these assumptions for a specific salt formation or location. A refined evaluation of the isothermal FEPs list is one of the first research elements proposed, should the U.S. decide to investigate a salt repository for HLW.

Findings of the evaluations presented in this report are summarized as follows:

1. Many areas of the U.S. have salt formations possessing positive characteristics for hosting a geologic repository for HLW.

2. International repository programs have advanced repository science for salt media, and have much to offer if the U.S. resumes investigations for disposal in salt.

3. Radionuclide transport for salt disposal options is extremely limited because intact salt is impermeable and because of the healing characteristics of fractures.

4. Multiphysics modeling is poised to exploit massively parallel computational hardware for simulation of coupled thermal-hydrologic-mechanical processes in salt. The ability to predict coupled behavior over long time spans with new computational approaches adds confidence to any performance assessment.

5. Laboratory testing of intact and granular salt will provide data that will enhance phenomenological understanding and parameters for thermal-hydrologic-mechanical models.

6. Eventually, an appropriate field test will be needed to prove the principles of the disposal concept, and to validate the coupled process models.

7. A HLW repository in salt is expected to exhibit excellent performance compared to existing or future regulatory standards.

8. Experience with seal systems for the WIPP repository would provide significant support to design, construction, testing, and performance assessment for a HLW salt repository.

These findings lead to the conclusion that salt media are highly viable to host repositories for HLW.

The authors note that the iterative process of determining the suitability of salt as a disposal medium for HLW began over forty years ago with the initiation of field and laboratory studies in the 1960s. Ongoing investigations in the U.S. and internationally have provided important answers to questions regarding the suitability of salt formations for radioactive waste disposal. The vast amount of available data and clear indications of primary data needs make salt a leading candidate rock type for HLW waste disposal. From the summary presented in this report, we conclude that investigations of HLW disposal in salt should continue, and will benefit from the following recommendations.

5.2 Recommendations for Continued Research

Based on the information presented in this report including the U.S./German workshop on thermal, mechanical and hydrologic responses of salt, there is a continued need for research into the potential performance of a HLW repository in salt. A large portion of the information needed to fully develop the technical basis for modeling salt behavior for HLW disposal was grouped in the following list by participants of the U.S./German workshop:

1. Response of the DRZ to combined thermal and mechanical forces
2. Consolidation of backfill materials
3. Availability and movement of brine
4. Vapor phase transport mechanisms
5. Radionuclide solubility controls
6. Potential radionuclide transport mechanisms
7. Waste form and/or waste package degradation
8. Gas generation and pressure buildup
9. Buoyancy of waste package
10. Radiolysis of waste materials, waste packages, and salt
11. Climate change

Table 4 presents a general proposal for addressing data gaps listed above and others discussed in Section 4. The table lists the broad areas of interest, specific data needed, and potential assessment methods that can be used to obtain the information.

Table 4. Areas of interest and possible assessment methods

Area of Interest	Specific Data Need	Assessment Methods
Response of the DRZ to combined thermal and mechanical effects	• Validation of constitutive model • Permeability as a function of damage • Field demonstrations • Seal system design	• International collaborations • Laboratory testing • In situ testing • Analogue comparisons • Model development
Consolidation of backfill materials	• Thermal conductivity as a function of porosity • Consolidation constitutive model with temperature dependence	• Laboratory testing • In situ testing • Microscopy
Availability and movement of brine	• 3-D coupled analysis tools • Field test measurements and validation	• Code capability development • International collaboration • Literature review • Historic field measurements • In situ testing
Vapor phase transport mechanisms	• Further development of theory • Module development for coupled codes • Field test validation	• Viability of conceptual model workshop • Code capability development • International collaboration • Laboratory testing • In situ testing
Radionuclide solubility controls	• Establish viability of scenario for radionuclide solubility studies	• International collaboration • Laboratory testing
Potential radionuclide transport mechanisms	• Establish viability for transport mechanisms	• Theory development • International collaboration • In situ testing
Waste degradation	• Evolution of the disposal room • Source term	• Literature research • International collaboration • Analogue comparisons
Gas generation and pressure buildup	• Source term • Ensure seal system function	• International collaboration • Analogue comparisons
Buoyancy of waste packages	• Consensus from international peers	• Workshop with consensus report • Literature review
Radiolysis of waste materials, waste packages, and salt	• Establish the basis • Review application to HLW repository in salt	• Workshop with consensus report
Climate change	• Local climate scenarios • Coupled analysis tools for thermal-hydrologic-mechanical simulation of long-term processes • Numerical studies of long-term evolution	• Literature research • International collaboration • Analogue comparisons • Numerical site studies

This analysis only addresses general research needs as they are distinct from the information that is needed to actually site a repository. That information would be specific to a site and would encompass the detailed geotechnical description of the candidate salt site and overlying stratigraphy and the verification of codes predicting the thermal and mechanical response of the rock mass with site specific data.

The proposed research and development roadmap comprises four general elements: Laboratory Testing, Modeling and Simulations, Workshops and International Collaborations, and Field Testing. In a chronologic sense, some laboratory studies can be started in the immediate future and would begin by adding to the data bases accumulated when the U.S. supported salt repository research (before the amendments to the NWPA in 1987). The science-based testing would provide long-term benefit and could be scoped at an appropriate level of effort commensurate with national policy. Modeling and simulation would naturally progress as described in the main text: first a benchmark comparison of existing capabilities could be initiated with similarly motivated international colleagues. These benchmarks would illuminate existing capabilities as well as needed development. The third initiative for international collaborations includes components of laboratory testing and modeling, to be sure, but also supports a workshop environment for discussion, definition, and reconciliation of technical issues. Ultimately, based on advancements from laboratory testing, enhancement of model capability, and workshop deliberations, a proof-of-principle field test could be deployed. This roadmap will provide the science basis for HLW salt repository design and performance assessment.

5.3 Laboratory Studies

Laboratory Thermal and Mechanical Studies. Several information gaps have been identified in the realm of thermal-mechanical salt response, which can be addressed in laboratory studies. Collaborative work with international researchers could lay the foundation for laboratory experiments on both intact and granular salt that provide information to the constitutive models. Any field test proof-of-principle testing would require the latest models to facilitate deployment (see Section 5.4 below). Laboratory testing could readily inform remaining uncertainties in material phenomenology and process description, particularly mathematical description of granular salt reconsolidation under isostatic loading at elevated temperature. In related but separate investigations, thermal conductivity of crushed salt can be readily determined as a function of porosity and temperature, during reconsolidation. For thermal conductivity studies, an oedometer press could be manufactured to perform heated consolidation simultaneously with line-source radial conductivity testing. Preliminary hot, intact salt phenomenology and brine migration could be initiated. Consolidation is widely considered a key phenomenon for HLW disposal in salt, an evaluation that was reinforced by the consensus of the U.S./German workshop participants.

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

Laboratory Chemical and Material Studies. Most of the aspects of the geochemical model are best addressed in a laboratory because the expected repository conditions are ultimately anoxic. Geochemistry testing would include quantification of the corrosion rates of candidate waste-package and/or waste form materials in any brines that could potentially migrate to the waste package or that could otherwise enter the repository. It could also include development of molecular-dynamics simulations to evaluate the effects of water, chemistry, and system size on radiolysis defect production and provide a direct comparison between experimental and numerical results. Finally, laboratory studies can readily address the issue of solubility control for the radionuclides that are part of the HLW.

5.4 Modeling and Simulation

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

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

5.5 International Collaboration

International collaboration to advance salt repository sciences has already begun by way of the U.S./German workshop in Mississippi in May 2010 (Sandia National Laboratories 2010). The presentations by subject matter experts helped identify areas of concern with respect to HLW disposal in salt as discussed in Section 4.7 of this report. Formal and consistent collaboration with German researchers provides immediate and ongoing technical guidance to the U.S. program in salt repository science. Much of the historic salt research was performed by German scientists. Because a generation has passed since the U.S. considered any disposal concept for HLW other than Yucca Mountain, some reassessment of the state of the art is in order. International collaboration can occur in laboratory work, with computational platforms, and in the field. Most importantly, workshops and focus areas provide the opportunity to explore issues and develop appropriate responses.

5.6 Field Tests

In situ testing is valuable for proof-of-principle demonstrations. A field test provides the opportunity to observe anticipated phenomenology, validate modeling capabilities, and evaluate design concepts. A full-scale field test could be undertaken after the knowledge gaps that can be addressed in the laboratory are evaluated and preliminary modeling studies are complete. In situ testing helps confirm the predictive ability of repository models, provides a range of expected parameters, and involves possible size affects associated with rock mass response. Full-scale heater tests can determine the following, under repository relevant heated conditions: the extent and properties of the DRZ, fracture healing characteristics, permeability and porosity, the thermal-mechanical response of compacted crushed salt backfill, brine influx rates, water vapor pressure, and salt composition and structure as part of brine migration assessment.

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APPENDIX A: BASELINE FEATURES, EVENTS, AND PROCESSES (FEPs) LIST FOR SALT DISPOSAL

This appendix lists the features, events, and processes (FEPs) used in the certification and recertification of the Waste Isolation Pilot Plant, an isothermal repository for transuranic waste. This list provides a valuable resource as a starting point if the U.S. chooses a salt option for disposal of high-level nuclear waste.

The purpose of FEP screening is to identify those FEPs that should be accounted for in PA calculations and those FEPs that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusion, low probability (i.e., probability below the regulatory screening threshold), or consequence (i.e., consequences insignificant to overall results). Some FEPs screened out because of consequence are, in fact, potentially beneficial to subsystem performance (DOE 1996a). These are identified in this list as "Screened out based on low consequence–beneficial"; this screening decision is applied where there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation of a beneficial FEP would incur unreasonable difficulties.

All three criteria are derived from regulatory requirements. FEPs not screened out as on the basis of probability, consequence, or an explicit regulatory exclusion were retained for inclusion in PA calculations and are classified as either undisturbed performance or disturbed performance FEPs. Specific FEP screening criteria are stated in the current governing regulations for U.S. radioactive waste repository programs (40 CFR 197 and 10 CFR 63), and would be expected to be updated, as appropriate, if a new repository policy is enacted for the U.S.

In some cases, the effects of the particular event or process occurring, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be included in PA calculations implicitly, within the range of uncertainty associated with the included FEP. Although some FEPs could be eliminated from PA calculations on the basis of more than one criterion; the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence screening classification. FEPs that have not been screened out based on any of the three criteria were included in the PA.

FEPs classified in this table as "Included in undisturbed performance scenarios" were accounted for in WIPP PA calculations for undisturbed performance of the disposal system; i.e., the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. Undisturbed PA calculations are used to demonstrate compliance with the individual and groundwater protection requirements. The FEPs classified in this table as "Included in disturbed performance scenarios" are accounted for only in assessment calculations for disturbed performance of the disposal system. The disturbed performance FEPs that remain following the screening process relate to the disruptive effects of potential future drilling and mining events in the controlled area.

In the FEPs numbering scheme for WIPP, as shown in the following table, FEPs are categorized as "Natural FEPs," "Waste- and Repository-Induced FEPs," and "Human-Induced Events and Processes." ID numbers of Natural FEPs begin with *N* (e.g., N1, N2, etc.); IDs of Waste- and Repository-Induced FEPs begin with *W* (e.g., W1, W2, etc.); IDs of Human-Induced Events and Processes begin with *H* (e.g., H1, H2, etc.). The FEPs are also considered within time frames during which they may occur. Because of the regulatory requirements concerning human activities, two time periods were used when evaluating Human-Induced EPs. These time frames were defined as (1) Historical, Current, and Near-Future Human Activities and (2) Future Human Activities. In the table, they are annotated as "HCN" and "Future," respectively.

One of the first activities to be undertaken if a salt repository option were to be investigated as a disposal option for UNF and HLW would be consideration of the FEPs screening table given below. Introduction of new waste forms with attendant heat and radioactivity will likely, as suggested in this report, add some key FEPs to the performance assessment analyses.

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
N1—***Stratigraphy***—Disposition and properties of geological formations control system performance.	Included in undisturbed performance scenarios
N2—***Brine Reservoirs***—Pressurized brine reservoirs may be present in the Castile beneath the controlled area.	Included in disturbed performance scenarios
N3—***Changes in Regional Stress***—Tectonic activity on a regional scale may change levels of stress. N4—***Regional Tectonics***—Tectonic setting of the region governs current level of stress. N5—***Regional Uplift and Subsidence***—Tectonic activity on a regional scale could cause uplift and subsidence.	Screened out based on low consequence
N6—***Salt Deformation***—Salt formations may deform under gravity or other forces. N7—***Diapirism***—Buoyancy forces may cause salt to rise through denser rocks.	Screened out based on low probability
N8—***Formation of Fractures***—Changes in stress may cause new fracture sets to form.	Screened out based on low probability Included in undisturbed performance scenarios (near repository)
N9—***Changes in Fracture Properties***—Changes in the local stress field may change fracture properties such as aperture and asperity.	Screened out based on low consequence Included in undisturbed performance scenarios (near repository)
N10—***Formation of New Faults***—Tectonic activity on a regional scale could cause new faults to form. N11—***Fault Movement***—Movement along faults in the Rustler or in units below the Salado could affect the hydrogeology.	Screened out based on low probability
N12—***Seismic Activity***—Ground shaking may give rise to cracking at free surfaces such as the roof of the repository.	Included in undisturbed performance scenarios
N13—***Volcanic Activity***—Igneous material feeding volcanoes or surface flows could affect disposal system performance.	Screened out based on low probability
N14—***Magmatic Activity***—Subsurface intrusion of igneous rocks could affect disposal system performance.	Screened out based on low consequence
N15—***Metamorphic Activity***—High pressures and/or temperatures could cause solid-state recrystallization changes.	Screened out based on low probability
N16—***Shallow Dissolution***—Percolation of groundwater and dissolution in the Rustler may increase transmissivity.	Included in undisturbed performance scenarios
N18—***Deep Dissolution***—Dissolution cavities in the Castile or at the base of the Salado may propagate toward the surface.	Screened out based on low probability
N20—***Breccia Pipes (Solution Chimneys)***—Formations above deep dissolution cavities may fracture.	Screened out based on low probability
N21—***Collapse Breccias***—Dissolution may result in collapse of overlying units.	Screened out based on low probability
N22—***Fracture Infills***—Precipitation of minerals as fracture infills can reduce hydraulic conductivities.	Screened out based on low consequence—beneficial
N23—***Saturated Groundwater Flow***—Groundwater flow beneath the water table is important to disposal system performance.	Included in undisturbed performance scenarios
N24—***Unsaturated Groundwater Flow***—The presence of air or other gas phases may influence groundwater flow. N25—***Fracture Flow***—Groundwater may flow along fractures as well as through interconnected pore space.	Included in undisturbed performance scenarios

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
N27—***Effects of Preferential Pathways***—Groundwater flow may not be uniform and may occur along particular pathways.	
N26—***Density Effects on Groundwater Flow***—Spatial variability of groundwater density could affect flow directions.	Screened out based on low consequence
N28—***Thermal Effects on Groundwater Flow***—Natural temperature variability could cause convection or otherwise affect groundwater flow.	Screened out based on low consequence
N29—***Saline Intrusion [Hydrogeological Effects]***—The introduction of more saline water into the Rustler could affect groundwater flow.	Screened out based on low probability
N30—***Freshwater Intrusion [Hydrogeological Effects]***—The introduction of freshwater into the Rustler could affect groundwater flow.	Screened out based on low probability
N31—***Hydrological Response to Earthquakes***—Fault movement can affect groundwater flow directions, and pressure changes can affect groundwater levels and movement.	Screened out based on low consequence
N32—***Natural Gas Intrusion***—The introduction of natural gas from formations beneath the repository could affect groundwater flow.	Screened out based on low probability
N33—***Groundwater Geochemistry***—Groundwater geochemistry influences actinide retardation and colloid stability.	Included in undisturbed performance scenarios
N34—***Saline Intrusion (Geochemical Effects)***—The introduction of more saline water into the Rustler could affect actinide retardation and colloid stability. N38—***Effects of Dissolution***—Dissolution could affect groundwater chemistry and hence radionuclide transport.	Screened out based on low consequence
N35—***Freshwater Intrusion (Geochemical Effects)***—The introduction of freshwater into the Rustler could affect actinide retardation and colloid stability. N36—***Changes in Groundwater Eh***—Changes in oxidation potentials could affect radionuclide mobilization. N37—***Changes in Groundwater pH***—Changes in pH could affect colloid stability and the mobility of radionuclides.	Screened out based on low consequence
N39—***Physiography***—The physiography of the area is a control on the surface water hydrology.	Included in undisturbed performance scenarios
N40—***Impact of a Large Meteorite***—A large meteorite could fracture the rocks above the repository.	Screened out based on low probability
N41—***Mechanical Weathering***—Processes such as freeze-thaw affect the rate of erosion. N42—***Chemical Weathering***—Breakdown of minerals in the surface environment affects the rate of erosion.	Screened out based on low consequence
N43—***Aeolian Erosion***—The wind can erode poorly consolidated surface deposits. N44—***Fluvial Erosion***—Erosion by rivers and streams could affect surface drainage. N45—***Mass Wasting [Erosion]***—Gravitational processes can erode material on steep slopes.	Screened out based on low consequence
N46—***Aeolian Deposition***—Sand dunes and sheet sands may be deposited by the wind and affect surface drainage. N47—***Fluvial Deposition***—Rivers and streams can deposit material and affect surface drainage. N48—***Lacustrine Deposition***—Lakes may be infilled by sediment and change the drainage pattern.	Screened out based on low consequence

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
N49—***Mass Wasting [Deposition]***—Landslides could block valleys and change the drainage pattern.	
N50—***Soil Development***—Vegetation and surface water movement is affected by the types of soil present.	Screened out based on low consequence
N51—***Stream and River Flow***—The amount of flow in streams and rivers affects erosion and deposition.	Screened out based on low consequence
N52—***Surface Water Bodies***—The disposition of lakes is a control on the surface hydrology.	Screened out based on low consequence
N53—***Groundwater Discharge***—The amount of water leaving the groundwater system to rivers, springs, and seeps affects the groundwater hydrology. N54—***Groundwater Recharge***—The amount of water passing into the saturated zone affects the groundwater hydrology. N55—***Infiltration***—The amount of water entering the unsaturated zone controls groundwater recharge.	Included in undisturbed performance scenarios
N56—***Changes in Groundwater Recharge and Discharge***—Changes in climate and drainage pattern may affect the amount of water entering and leaving the groundwater system.	Included in undisturbed performance scenarios
N57—***Lake Formation***—Formation of new lakes will affect the surface hydrology. N58—***River Flooding***—Flooding will affect the area over which infiltration takes place.	Screened out based on low consequence
N59—***Precipitation (e.g., Rainfall)***—Rainfall is the source of water for infiltration and stream flow. N60—***Temperature***—The temperature influences how much precipitation evaporates before it reaches streams or enters the ground.	Included in undisturbed performance scenarios
N61—***Climate Change***—Temperature and precipitation will vary as natural changes in the climate take place.	Included in undisturbed performance scenarios
N62—***Glaciation***—Natural climate change could lead to the growth of glaciers and ice sheets. N63—***Permafrost***—The regions in front of advancing ice sheets will be subject to frozen ground preventing infiltration.	Screened out based on low probability
N64—***Seas and Oceans***—The volume and circulation patterns in seas and oceans would affect the distribution of radionuclides. N65—***Estuaries***—Water movement in estuaries would affect the distribution of radionuclides.	Screened out based on low consequence
N66—***Coastal Erosion***—Coastal erosion could affect the local groundwater system. N67—***Marine Sediment Transport and Deposition***—Transport and deposition could affect the distribution of radionuclides.	Screened out based on low consequence
N68—***Sea Level Changes***—Sea level change would affect coastal aquifers.	Screened out based on low consequence
N69—***Plants***—Plants play a role in the hydrological cycle by taking up water. N70—***Animals***—Burrowing animals can affect the structure of surface sediments.	Screened out based on low consequence
N71—***Microbes*** —Microbes can be important in soil development. Microbes in groundwater may sorb radionuclides.	Screened out based on low consequence (Included in undisturbed performance scenarios for colloidal effects and gas generation)
N72—***Natural Ecological Development***—Changes in climate may cause changes in the types of vegetation and animals present.	Screened out based on low consequence

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W1—***Disposal Geometry***—WIPP repository disposal geometry will influence flow and transport patterns.	Included in undisturbed performance scenarios
W2 —***Waste Inventory***—The quantity and type of radionuclides emplaced in the repository will dictate performance requirements.	Included in undisturbed performance scenarios
W3—***Heterogeneity of Waste Forms***—The distribution of radionuclides within the different waste types could affect release patterns.	Included in disturbed performance scenarios
W4—***Container Form***—The type and shape of waste container will affect heat dissipation and container strength.	Screened out based on low consequence—Beneficial
W5—***Container Material Inventory***—Steel and other materials will corrode and affect the amount of gas generated.	Included in undisturbed performance scenarios
W6—***Shaft Seal Geometry***—Size, location, and materials of shaft seals and panel and drift closures will affect flow patterns and transport pathways.	Included in undisturbed performance scenarios
W7—***Shaft Seal Physical Properties***—Porosity and permeability of seals will control flow rates.	
W109—***Panel Closure Geometry***—Size, location, and materials of panel closures will affect flow patterns and transport pathways.	
W110—***Panel Closure Physical Properties***—Porosity and permeability of panel closures will control flow rates.	
W8—***Shaft Seal Chemical Composition***—The chemistry of seal materials could affect actinide speciation and mobility.	Screened out based on low consequence—beneficial
W111—***Panel Closure Chemical Composition***—The chemistry of panel closures could affect actinide speciation and mobility.	
W9—***Backfill Physical Properties***—The amount and distribution of backfill could affect porosity and permeability in disposal rooms.	Screened out based on low consequence
W10—***Backfill Chemical Composition***—The chemical behavior of the backfill will affect actinide speciation and mobility.	Included in undisturbed performance scenarios
W11—***Post-Closure Monitoring***—Inappropriate monitoring after closure could affect performance.	Screened out based on low consequence
W12—***Radionuclide Decay and In-Growth***—Radioactive decay of waste will change and decrease the inventory with time.	Included in undisturbed performance scenarios
W13—***Heat from Radioactive Decay***—Radioactive decay of waste will generate heat in the repository.	Screened out based on low consequence
W14—***Nuclear Criticality: Heat***—A sustained fission reaction would generate heat.	Screened out based on low probability
W15—***Radiological Effects on Waste***—Radiation can change the physical properties of many materials.	Screened out based on low consequence
W16—***Radiological Effects on Containers***—Radiation can change the physical properties of many materials.	
W17—***Radiological Effects on Shaft Seals***—Radiation can change the physical properties of many materials.	
W112—***Radiological Effects on Panel Closures***—Radiation can change the physical properties of many materials.	
W18—***Disturbed Rock Zone (DRZ)***—Repository construction has led to fracturing of rock around the opening	Included in undisturbed performance scenarios
W19—***Excavation-Induced Changes in Stress***—Repository construction has led to changes in stress around the opening.	
W20—***Salt Creep***—Salt creep will consolidate seal components and close the disposal rooms thereby compacting the waste.	Included in undisturbed performance scenarios
W21—***Changes in the Stress Field***—Salt creep will affect the stress field around the repository opening.	

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W22—***Roof Falls***—Instability of the DRZ could lead to roof falls.	Included in undisturbed performance scenarios
W23—***Subsidence***—Salt creep and roof falls could lead to subsidence of horizons above the repository.	Screened out based on low consequence
W24—***Large-Scale Rock Fracturing***—Salt creep and roof falls could lead to fracturing between the repository and higher units or the surface.	Screened out based on low probability
W25—***Disruption Due to Gas Effects***—Increased gas pressures may lead to fracturing of Salado interbeds. W26—***Pressurization***—Increased gas pressures may slow the rate of salt creep.	Included in undisturbed performance scenarios
W27—***Gas Explosions***—Explosion of gas mixtures in the repository could affect the DRZ.	Included in undisturbed performance scenarios
W28—***Nuclear Explosions***—A critical mass of plutonium in the repository could explode if rapidly compressed.	Screened out based on low probability
W29—***Thermal Effects on Material Properties***—Temperature rises could lead to changes in porosity and permeability. W30—***Thermally Induced Stress Changes***—Elevated temperatures could change the local stress field and alter the rate of salt creep. W31—***Differing Thermal Expansion of Repository Components***—Stress distribution and strain changes can depend on differing rates of thermal expansion between adjacent materials. W72—***Exothermic Reactions***—Exothermic reactions, including concrete and backfill hydration, and aluminum corrosion, may raise the temperature of the disposal system. W73—***Concrete Hydration***—Hydration of concrete in seals will enhance rates of salt creep and may induce thermal cracking.	Screened out based on low consequence
W32—***Consolidation of Waste***—Salt creep and room closure will change waste permeability. W36—***Consolidation of Shaft Seals***—Salt creep will consolidate long-term seal components, reducing porosity and permeability. W37—***Mechanical Degradation of Shaft Seals***—Gas pressurization, clay swelling, and cracking of concrete could affect seal properties. W39—***Underground Boreholes–***Improperly sealed boreholes drilled from the repository could provide pathways to the interbeds. W113—***Consolidation of Panel Closures***—Salt creep will consolidate long-term panel closures components, reducing porosity and permeability. W114—***Mechanical Degradation of Panel Closures***—Gas pressurization, clay swelling, and cracking of concrete could affect panel closure properties.	Included in undisturbed performance scenarios
W33—***Movement of Containers***—Density differences or temperature rises could lead to movement of containers within the salt.	Screened out based on low consequence
W34—***Container Integrity***—Long-lived containers could delay dissolution of waste.	Screened out based on low consequence–Beneficial
W35—***Mechanical Effects of Backfill***—Backfill in disposal rooms will act to resist creep closure.	Screened out based on low consequence
W40—***Brine Inflow***—Brine will enter the disposal rooms through the interbeds, impure halite, and clay layers. W41—***Wicking***—Capillary rise is a mechanism for brine flow in unsaturated zones in the repository.	Included in undisturbed performance scenarios
W42—***Fluid Flow Due to Gas Production***—Increases in gas pressure could affect the rate of brine inflow.	Included in undisturbed performance scenarios

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W43—***Convection***—Temperature differentials in the repository could lead to convection cells.	Screened out based on low consequence
W44—***Degradation of Organic Material***—Microbial breakdown of cellulosic material in the waste will generate gas. W45—***Effects of Temperature on Microbial Gas Generation***—Temperature rises could affect the rate of microbial gas generation. W48—***Effects of Biofilms on Microbial Gas Generation***—Biofilms serve to maintain optimum conditions for microbial populations and affect gas generation rates.	Included in undisturbed performance scenarios
W46—***Effects of Pressure on Microbial Gas Generation***—Increases in gas pressure could affect microbial populations and gas generation rates.	Screened out based on low consequence
W47—***Effects of Radiation on Microbial Gas Generation***—Radiation could affect microbial populations and, therefore, gas generation rates.	Screened out based on low consequence
W49—***Gases from Metal Corrosion***—Anoxic corrosion of steel will produce hydrogen. W51—***Chemical Effects of Corrosion***—Corrosion reactions will lower the oxidation state of brines and affect gas generation rates.	Included in undisturbed performance scenarios
W50—***Galvanic Coupling (within the Repository)***—Potential gradients between metals could affect corrosion rates.	Screened out based on low consequence
W52—***Radiolysis of Brine***—Alpha particles from decay of plutonium can split water molecules to form hydrogen and oxygen.	Screened out based on low consequence
W53—***Radiolysis of Cellulose***—Alpha particles from decay of plutonium can split cellulose molecules and affect gas generation rates.	Screened out based on low consequence
W54—***Helium Gas Production***—Reduction of alpha particles emitted from the waste will form helium.	Screened out based on low consequence
W55—***Radioactive Gases***—Radon will form from decay of plutonium. Carbon dioxide and methane may contain radioactive ^{14}C.	Screened out based on low consequence
W56—***Speciation***—Speciation is the form in which elements occur under particular conditions. This form controls mobility and the reactions that are likely to occur.	Included in undisturbed performance scenarios in disposal rooms and Culebra Screened out based on low consequence (beneficial) in cementitious seals Screened out based on low consequence elsewhere
W57—***Kinetics of Speciation***—Reaction kinetics control the rate at which particular reactions occur thereby dictating which reactions are prevalent in nonequilibrium systems.	Screened out based on low consequence
W58—***Dissolution of Waste***—Dissolution of waste controls the concentrations of radionuclides in brines and groundwaters.	Included in undisturbed performance scenarios
W59—***Precipitation of Secondary Minerals***—Precipitation of secondary minerals could affect the concentrations of radionuclides in brines and groundwaters.	Screened out based on low consequence—Beneficial
W60—***Kinetics of Precipitation and Dissolution***—The rates of dissolution and precipitation reactions could affect radionuclide concentrations.	Screened out based on low consequence
W61—***Actinide Sorption***—Actinides may accumulate at the interface between a solid and a solution. This affects the rate of transport of actinides in brines and groundwaters.	Included in undisturbed performance scenarios in the Culebra and Dewey Lake Screened out based on low consequence (beneficial) in the disposal room, shaft seals, panel closures, and other geologic units

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W62—***Kinetics of Sorption***—The rate at which actinides are sorbed can affect radionuclide concentrations.	Included in undisturbed performance scenarios in the Culebra and Dewey Lake Screened out based on low consequence (beneficial) in the disposal room, shaft seals, panel closures, and other geologic units
W63—***Changes in Sorptive Surfaces***—Changes in mineralogy along fracture walls could change the extent of sorption.	Included in undisturbed performance scenarios
W64—***Effects of Metal Corrosion***—Metal corrosion will have an effect on chemical conditions in the repository by absorbing oxygen W66—***Reduction-Oxidation Kinetics***—Reduction-oxidation reactions may not be in thermodynamic equilibrium thereby affecting speciation.	Included in undisturbed performance scenarios
W65—***Reduction-Oxidation Fronts***—Redox fronts may affect the speciation and hence migration of radionuclides.	Screened out based on low probability
W67—***Localized Reducing Zones***—Localized reducing zones, bounded by reduction-oxidation fronts, may develop on metals undergoing corrosion.	Screened out based on low consequence
W68—***Organic Complexation***—Aqueous complexes between radionuclides and organic materials may enhance the total dissolved radionuclide load W69—***Organic Ligands***—Increased concentrations of organic ligands favor the formation of complexes	Included in undisturbed performance scenarios
W71—***Kinetics of Organic Complexation***—The rates of complex dissociation may affect radionuclide uptake and other reactions.	Screened out based on low consequence
W70—***Humic and Fulvic Acids***—High molecular weight organic ligands, including humic and fulvic acids, may be present in soil waste.	Included in undisturbed performance scenarios
W74—***Chemical Degradation of Shaft Seals***—Reaction of cement with brine and groundwater may affect seal permeability. W76—***Microbial Growth on Concrete***—Acids produced by microbes could accelerate concrete seal degradation. W115—***Chemical Degradation of Panel Closures***—Reaction of cement with brine and groundwater may affect closure permeability.	Included in undisturbed performance scenarios
W75—***Chemical Degradation of Backfill***—Reaction of the MgO backfill with CO_2 and brine may affect disposal room permeabilities.	Screened out based on low consequence
W77—***Solute Transport***—Radionuclides may be transported as dissolved species or solutes.	Included in undisturbed performance scenarios
W78—***Colloid Transport***—Colloid transport, with associated radionuclides, may occur at a different rate to dissolved species. W79—***Colloid Formation and Stability***—The formation and stability of colloids is dependent upon chemical conditions such as salinity. W80—***Colloid Filtration***—Colloids with associated radionuclides may be too large to pass through pore throats in some media. W81—***Colloid Sorption***—Colloids with associated radionuclides may be physically or chemically sorbed to the host rock.	Included in undisturbed performance scenarios
W82—***Suspensions of Particles***—Rapid brine flow could transport active particles in suspension.	Included in disturbed performance scenarios
W83—***Rinse***—Rapid brine flow could wash active particulates from waste surfaces.	Screened out based on low consequence
W84—***Cuttings***—Waste material intersected by a drill bit could be transported to the ground surface.	Included in disturbed performance scenarios
W85—***Cavings***—Waste material eroded from a borehole wall by drilling fluid could be transported to the ground surface.	Included in disturbed performance scenarios

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W86—***Spallings***—Waste material entering a borehole through repository depressurization could be transported to the ground surface.	Included in disturbed performance scenarios
W87—***Microbial Transport***—Radionuclides may be bound to or contained in microbes transported in groundwaters.	Included in undisturbed performance scenarios
W88—***Biofilms***—Biofilms may retard microbes and affect transport of radionuclides.	Screened out based on low consequence–Beneficial
W89—***Transport of Radioactive Gases***—Gas phase flow could transport radioactive gases.	Screened out based on low consequence
W90—***Advection***—Dissolved and solid material can be transported by a flowing fluid.	Included in undisturbed performance scenarios
W91—***Diffusion***—Dissolved and solid material can be transported in response to Brownian forces. W92—***Matrix Diffusion***—Dissolved and solid material may be transported transverse to the direction of advection in a fracture and into the rock matrix.	Included in undisturbed performance scenarios
W93—***Soret Effect***—There will be a solute flux proportional to any temperature gradient.	Screened out based on low consequence
W94—***Electrochemical Effects***—Potential gradients may exist as a result of electrochemical reactions and groundwater flow and affect radionuclide transport.	Screened out based on low consequence
W95—***Galvanic Coupling (outside the Repository)***—Potential gradients may be established between metal components of the waste and containers and affect radionuclide transport.	Screened out based on low probability
W96—***Electrophoresis***—Charged particles and colloids can be transported along electrical potential gradients.	Screened out based on low consequence
W97—***Chemical Gradients***—Chemical gradients will exist at interfaces between different parts of the disposal system and may cause enhanced diffusion.	Screened out based on low consequence
W98—***Osmotic Processes***—Osmosis may allow diffusion of solutes across a salinity interface	Screened out based on low consequence
W99—***Alpha Recoil***—Recoil of the daughter nuclide upon emission of an alpha particle during radioactive decay at the surface of a solid may eject the daughter into groundwater.	Screened out based on low consequence
W100—***Enhanced Diffusion***—Chemical gradients may locally enhance rates of diffusion.	Screened out based on low consequence
W101—***Plant Uptake***—Radionuclides released into the biosphere may be absorbed by plants. W102—***Animal Uptake***—Animals may eat or drink radionuclides released into the biosphere. W103—***Accumulation in Soils***—Radionuclides released into the biosphere may accumulate in soil.	Screened out by regulatory exclusion for section 191.13 Screened out based on low consequence for section 191.15
W104—***Ingestion***—Humans may receive a radiation dose from radionuclides in food or drink. W105—***Inhalation***—Humans may receive a radiation dose from air taken into the lungs. W106—***Irradiation***—Humans may receive a radiation dose from radionuclides external to the body. W107—***Dermal Sorption***—Humans may receive a radiation dose from radionuclides absorbed through the skin.	Screened out based on low consequence for section 191.15 Screened out by regulatory exclusion elsewhere

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
W108—***Injection***—Humans may receive a radiation dose from radionuclides injected beneath the skin.	
H1—***Oil and Gas Exploration***—Oil and gas exploration is a reason for drilling in the Delaware Basin. H2—***Potash Exploration***—Potash exploration is a reason for drilling in the Delaware Basin. H4—***Oil and Gas Exploitation***—Oil and gas exploitation is a reason for drilling in the Delaware Basin. H8—***Other Resources***—Exploration for other resources could be a reason for drilling in the Delaware Basin. H9—***Enhanced Oil and Gas Recovery***—Enhanced oil and gas recovery is a reason for drilling in the Delaware Basin.	Screened out based on low consequence (HCN) Included in disturbed performance scenarios (Future)
H3—***Water Resources Exploration***—Water resources exploration is a reason for drilling in the Delaware Basin. H5—***Groundwater Exploitation***—Groundwater exploitation is a reason for drilling in the Delaware Basin.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future)
H6—***Archaeological Investigations***—Archaeological investigations could be a reason for drilling in the Delaware Basin. H7—***Geothermal***—Geothermal energy could be a reason for drilling in the Delaware Basin. H10—***Liquid Waste Disposal***—Liquid waste disposal could be a reason for drilling in the Delaware Basin. H11—***Hydrocarbon Storage***—Hydrocarbon storage could be a reason for drilling in the Delaware Basin. H12—***Deliberate Drilling Intrusion***—Deliberate investigation of the repository could be a reason for drilling in the Delaware Basin.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H13—***Conventional Underground Potash Mining*** (formerly ***Potash Mining***)—Potash mining is a reason for excavations in the region around WIPP.	Included in undisturbed performance scenarios (HCN) Included in disturbed performance scenarios (Future)
H14—***Other Resources***—Mining of other resources could be a reason for excavations in the region around WIPP.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H15—***Tunneling***—Tunneling could be a reason for excavations in the region around WIPP. H16—***Construction of Underground Facilities (for Example Storage, Disposal, Accommodation)***—Construction of underground facilities could be a reason for excavations in the region around WIPP.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H17—***Archaeological Excavations***—Archaeological investigations could be a reason for excavations in the region around WIPP.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H18—***Deliberate Mining Intrusion*** —Deliberate investigation of the repository could be a reason for excavations in the region around WIPP.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H19—***Explosions for Resource Recovery***—Underground explosions could affect the geological characteristics of surrounding units.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H20—***Underground Nuclear Device Testing***—Underground nuclear device testing could affect the geological characteristics of surrounding units.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H21—***Drilling Fluid Flow***—Drilling within the controlled area could result in releases of radionuclides into the drilling fluid.	Screened out based on low consequence (HCN) Included in disturbed performance scenarios (Future)

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
H22—***Drilling Fluid Loss***—Borehole circulation fluid could be lost to thief zones encountered during drilling.	Screened out based on low consequence (HCN) Included in disturbed performance scenarios (Future)
H23—***Blowouts***—Fluid could flow from pressurized zones through the borehole to the land surface.	Screened out based on low consequence (HCN) Included in disturbed performance scenarios (Future)
H24—***Drilling-Induced Geochemical Changes***—Movement of brine from a pressurized zone through a borehole into potential thief zones such as the Salado interbeds or the Culebra could result in geochemical changes.	Included in undisturbed performance scenarios (HCN) Included in disturbed performance scenarios (Future)
H25—***Oil and Gas Extraction***—Extraction of oil and gas could alter fluid-flow patterns in the target horizons or in overlying units as a result of a failed borehole casing. Removal of confined fluids from oil- or gas-bearing units can cause compaction, potentially resulting in subvertical fracturing and surface subsidence. H26—***Groundwater Extraction***—Groundwater extraction from formations above the Salado could affect groundwater flow.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H27—***Liquid Waste Disposal–Outside Boundary (OB)***—Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. H28—***Enhanced Oil and Gas Production–OB*** —Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. H29—***Hydrocarbon Storage–OB*** —Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future)
H60—***Liquid Waste Disposal–Inside Boundary (IB)***—Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. H61—***Enhanced Oil and Gas Production–IB***—Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. H62—***Hydrocarbon Storage–IB***—Injection of fluids could alter fluid flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H30—***Fluid-Injection-Induced Geochemical Changes***—Injection of fluids through a leaking borehole could affect geochemical conditions in thief zones such as the Culebra or the Salado interbeds.	Included in undisturbed performance scenarios (HCN) Screened out by regulatory exclusion (Future)
H31—***Natural Borehole Fluid Flow***—Natural borehole flow through abandoned boreholes could alter fluid pressure distributions.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future) for holes not penetrating waste panels Included in disturbed performance scenarios (Future) for holes penetrating panels
H32—***Waste-Induced Borehole Flow***—Undetected boreholes that are inadequately sealed could provide pathways for radionuclide transport.	Screened out by regulatory exclusion (HCN) Included in disturbed performance scenarios (Future)

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
H34—***Borehole-Induced Solution and Subsidence***—Boreholes could provide pathways for surface-derived water or groundwater to percolate into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future)
H35—***Borehole-Induced Mineralization***—Fluid flow through a borehole between hydraulically conductive horizons could cause mineral precipitation to change permeabilities.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future)
H36—***Borehole-Induced Geochemical Changes***—Movement of fluids through abandoned boreholes could change the geochemistry of units such as the Salado interbeds or Culebra.	Included in undisturbed performance scenarios (HCN) Included in disturbed performance scenarios (Future) Screened out based on low consequence (for units other than the Culebra)
H37—***Changes in Groundwater Flow Due to Mining***—Fracturing and subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units.	Included in undisturbed performance scenarios (HCN) Included in disturbed performance scenarios (Future)
H38—***Changes in Geochemistry Due to Mining***—Fluid flow and dissolution associated with mining may change brine densities and geochemistry	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H39—***Changes in Groundwater Flow Due to Explosions***—Fracturing associated with explosions could affect groundwater flow patterns through increased hydraulic conductivity within and between units.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H40—***Land Use Changes***—Land use changes could have an effect upon the surface hydrology.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H41—***Surface Disruptions***—Surface disruptions could have an effect upon the surface hydrology	Included in undisturbed performance scenarios (HCN) Screened out based on low consequence (Future)
H42—***Damming of Streams or Rivers***—Damming of streams or rivers could have an effect upon the surface hydrology. H43—***Reservoirs***—Reservoirs could have an effect upon the surface hydrology. H44—***Irrigation***—Irrigation could have an effect upon the surface hydrology.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H45—***Lake Usage***—Lake usage could have an effect upon the surface hydrology.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H46—***Altered Soil or Surface Water Chemistry by Human Activities***—Surface activities associated with potash mining and oil fields could affect the movement of radionuclides in the surface environment.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H47—***Greenhouse Gas Effects***—Changes in climate resulting from increase in greenhouse gases could change the temperature and the amount of rainfall. H48—***Acid Rain***—Acid rain could change the behavior of radionuclides in the surface environment. H49—***Damage to the Ozone Layer*** —Damage to the ozone layer could affect the flora and fauna and their response to radioactivity.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H50—***Coastal Water Use***—Coastal water usage could affect the uptake of radionuclides by animals and humans. H51—***Sea Water Use***—Sea water usage could affect the uptake of radionuclides by animals and humans. H52—***Estuarine Water Use***—Estuarine water usage could affect the uptake of radionuclides by animals and humans.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)

WIPP FEP ID — ***FEP Name*** — Description	WIPP Screening Classification
H53—***Arable Farming***—Arable farming could have an effect upon the surface hydrology. H54—***Ranching***—Ranching could have an effect upon the surface hydrology. H55—***Fish Farming***—Fish farming could affect the uptake of radionuclides by animals and humans.	Screened out based on low consequence (HCN) Screened out by regulatory exclusion (Future)
H56—***Demographic Change and Urban Development***—Demographic change and urban development could have an effect upon the surface hydrology.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H57—***Loss of Records***—Loss of records could change the effectiveness of institutional controls.	Not Applicable (HCN) Included in disturbed performance scenarios (Future)
H58—***Solution Mining for Potash***—Solution mining could be a recovery method for potash.	Screened out by regulatory exclusion (HCN) Screened out by regulatory exclusion (Future)
H59—***Solution Mining for Other Resources***—Solution mining could be a recovery method for sulfur, halite, or other minerals.	Screened out based on low consequence (HCN) Screened out based on low consequence (Future)

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