Considerations of the Differences between Bedded and Domal Salt Pertaining to Disposal of Heat-Generating Nuclear Waste

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign

Francis D. Hansen,
Kristopher L. Kuhlman, and
Steve Sobolik
Sandia National Laboratories

July 7, 2016
FCRD-UFRD-2016-000441
SAND2016-6522R

SUMMARY

Salt formations hold promise for eternal removal of nuclear waste from our biosphere. Germany and the United States have ample salt formations for this purpose, ranging from flat-bedded formations to geologically mature dome structures. As both nations revisit nuclear waste disposal options, the choice between bedded, domal, or intermediate pillow formations is once again a contemporary issue.

For decades, favorable attributes of salt as a disposal medium have been extoled and evaluated, carefully and thoroughly. Yet, a sense of discovery continues as science and engineering interrogate naturally heterogeneous systems.

Salt formations are impermeable to fluids. Excavation-induced fractures heal as seal systems are placed or natural closure progresses toward equilibrium. Engineering required for nuclear waste disposal gains from mining and storage industries, as humans have been mining salt for millennia. This great intellectual warehouse has been honed and distilled, but not perfected, for all nuances of nuclear waste disposal. Nonetheless, nations are able and have already produced suitable license applications for radioactive waste disposal in salt. A remaining conundrum is site location.

Salt formations provide isolation and geotechnical barriers reestablish impermeability after waste is placed in the geology. Between excavation and closure, physical, mechanical, thermal, chemical, and hydrological processes ensue. Positive attributes for isolation in salt have many commonalities independent of the geologic setting. In some cases, specific details of the environment will affect the disposal concept and thereby define interaction of features, events and processes, while simultaneously influencing scenario development.

Here we identify and discuss high-level differences and similarities of bedded and domal salt formations. Positive geologic and engineering attributes for disposal purposes are more common among salt formations than are significant differences. Developing models, testing material, characterizing processes, and analyzing performance all have overlapping application regardless of the salt formation of interest.

ACKNOWLEDGMENTS

Laura Connolly applied diligence and skill while compiling this brief. Geoff Freeze brought his wide-ranging knowledge of repository science and expertise in features, events and processes to provide technical review. Thanks also to S. David Sevougian and Ed Matteo for discussion and insightful comments.

In addition to improvements made by these exceptional colleagues, several peers and contributors to salt repository research, design and operation have dissected these issues from numerous angles. Ongoing work on features, events and processes by S. David Sevougian, Geoff Freeze, Michael Gross, Jens Wolf, Jörg Mönig, and Dieter Buhmann adds a significant dimension to our comparisons of bedded and domal salt.

International collaborations and collaborators contribute immeasurably to advancement of salt repository science, engineering, operations, modeling, design, analysis, and performance assessment. This brief attempts to unveil the technical state of affairs for salt disposal and compare attributes over a range of scales as they become important. Collegial and professional relationships of extraordinary international scientists aid immensely toward this goal. Their ongoing contemplations of the differences and similarities of bedded and domal salt form much of the basis for the summary given here.

This endeavor in the national interest received support from the United States Department of Energy and fulfills the spirit of an overarching Memorandum of Understanding for such purposes signed with the Ministry of Germany in 2011. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

CONTENTS

FIGURES

TABLES

ACRONYMS

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BMU	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (German Federal Ministry for the Environment, Building, Nature Conservation, and Nuclear Safety)
BMWi	Federal Ministry for Economic Affairs and Energy (Germany)
CRZ	Containment-providing Rock Zone
DBE TEC	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe GmbH (The German Society for the construction and operation of waste repositories)
DOE	Department of Energy
EDZ	Excavation Damage Zone
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ERAM	Endlager für Radioaktive Abfälle Morsleben (Repository for RadioactiveWaste Morsleben)
FEP	Features, Events, and Processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit GmbH (Society for Plant and Reactor Safety)
HAW	High-Activity Waste
HLW	High-Level (Radioactive) Waste
IfG	Institut für Gebirgsmechanik GmbH (Institute for Geomechanics)
KIT	Karlsruher Institut für Technologie
KOSINA	Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits- und Nachweiskonzeptes (Concept development for a generic final repository for heat-generating wastes in flat-bedded salt layers in Germany as well as development and examination of a safety and verification concept)
NEA	Nuclear Energy Agency
OPERA	Onderzoeks Programma Eindberging Radioactief Afval
R&D	Research and Development
SIERRA	Sandia Integrated Environment for Robust Research Algorithms
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
TRU	Transuranic

US	United States
VSG	Vorläufige Sicherheitsanalyse für den Standort Gorleben (Preliminary Safety Analysis for the Gorleben Site)
WEIMOS	Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt)
WIPP	Waste Isolation Pilot Plant

1. INTRODUCTION

International repository programs are reinvestigating and reevaluating the utility of flat lying and domed salt formations for disposal of heat-generating nuclear waste. Both Germany and the United States (US) have repository program necessities to compare salt formations, and both countries possess relevant experience and extensive research applicable to this purpose. The Waste Isolation Pilot Plant (WIPP) is the operating US nuclear waste repository, situated in the Permian Basin, in the Salado bedded salt formation. The transuranic (TRU) waste currently disposed at WIPP does not emit heat, but many large-scale experiments including electric heaters were conducted there during the site characterization phase (1980s and 1990s). Similar repository investigations in Germany emphasized geologic domal formations, while flat-lying formations had not been considered in this context until recently. Germany completed a preliminary safety assessment for disposal in a salt dome at Gorleben. Each nation is once again considering options for mined geologic repositories, which creates a need – as well as an opportunity – to compare repository-relevant differentiating characteristics of bedded and domal salt. Distinguishing characteristics of these geologic formations manifest over an assortment of scales, become important over different periods, can affect concepts of operation and therefore analysis of features, events and processes (FEPs), and are applicable to design, analysis, performance assessment, and licensing.

Primary comparisons will encompass German and US practices; although Dutch initiatives are also applicable. Engagement of US and German studies related to salt repositories has been intermittent since Project Salt Vault in the Kansas portion of the Permian Basin (Bradshaw and McClain 1971). A majority of field investigations in the US have been in bedded salt. In Germany, salt repository operations and research have been undertaken at the Asse and Morsleben domes, which were production salt and potash mines before repository interests were undertaken. The US deliberated on several Gulf-coast domes for potential disposal sites in the earlier years of repository studies. Direct repository applications draw from the industrial experience of operating salt and potash mines and hydrocarbon storage caverns, largely in domal salt. A thorough comparison of bedded and domal salt would extract from experiences at numerous sites, and would be enormous in scope, far more than possible is this brief review. In the end, differentiating characteristics will become vital only when a site has been identified. Consequently, this overview focuses on desired characteristics of salt repository formations at various scales and elaborates slightly upon features that have the potential to differentiate in various contexts of a future repository-licensing portfolio.

A comparison of bedded and domal salt pertaining to disposal of heat–generating nuclear waste (including Spent Nuclear Fuel, High-Activity Waste (HAW), or High-Level (Radioactive) Waste (HLW) was a subject of great interest to collaborators attending the 6th US/German Workshop on Salt Repository Research, Design, and Operation in September 2015 (Hansen et al. 2016). German partners, along with Sandia National Laboratories (SNL or Sandia) as an associate partner, collaborate on research and development (R&D) in a project called KOSINA (a German acronym meaning: Development of a generic HLW repository concept in bedded salt including safety and safety demonstration concept). The objective of KOSINA is to develop both technical site-independent generic repository concepts and a safety concept for a bedded-salt repository for heat generating waste. As the KOSINA project moves forward, differences to the design and safety assessment for the Gorleben dome will likely be identified.

Participants at the 6th US/German Workshop discussed developing a joint compendium, which might be accomplished as collaborations continue and delivered as a major contribution to international salt repository R&D as sanctioned by the Nuclear Energy Agency (NEA) Salt Club. In addition to salt repository experience, both the US and Germany have extensive history of mining and salt exploitation for industrial purposes, which enrich the collective understanding of basic salt physical, mechanical, chemical, petrological, hydrological, and thermal behavior. These assets provide a supporting basis for such a salt-comparison compendium and compelling reasons to undertake this task are evident. At the 6th Workshop, principles for a comparison anthology were elicited and are used as guidance in this brief, which contains many of the elements that an international collaborative compendium may elaborate.

A short summary of the 6th Workshop recommendations is provided here. To begin, participants recommended the content provide a high-level summary without too much underlying detail. It was preferred that the compendium be globally available with a goal to revise and update approximately every 5 years as new information and knowledge become available or national policies change. A single document containing summary statements and references to supporting papers was favored. It should identify what knowledge for the safety case is required, available, or missing. It would not intend to determine preference for bedded or domal salt formations, as either is conceptually suitable. To accomplish a portion of these recommendations, substantial reliance is placed on the most pertinent salt repository experiences at the WIPP (bedded) and Gorleben (domal) sites. Programs concerned with these two sites developed safety assessments in response to applicable regulations. For example, the Gorleben safety assessment Vorläufige Sicherheitsanalyse für den Standort Gorleben (Preliminary Safety Analysis for the Gorleben Site or VSG) is based on the concept of a containment-providing rock zone (CRZ) and minor release from the CRZ, while the WIPP safety assessment is based on limited release, caused largely by human intrusion. Underlying the safety assessments are conceptual models, material constitutive models, numerical models with their boundary conditions and parameters, and evidence supporting appropriate model relevance (such as natural analogues). Material heterogeneity introduces other commonalities and differences with respect to repository design, which supports or limits concepts of operations, barrier strategy, and repository layout geometry, to name a few.

Additional statements and comments regarding the compendium included specific issues pertaining to geology, hydrogeology, safety, and geomechanics. For example, bedded salt typically contains more brine (water) than domal salt; salt domes have closer lateral boundaries and can contain anhydrite and clay inclusions at a range of orientations; bedded salt contains pervasive horizontal discontinuities; domes are often directly associated with hydrocarbons; the Salado Formation (WIPP) is not similar to German or European salt formations. These and other considerations require a line of sight between a comprehensive database of FEPs, differentiating physical characteristics, and practical choices for design and engineering of disposal concepts. Each safety case hinges around three prerequisites for development of FEPs, namely: 1) characteristics of the waste to be disposed, 2) the geologic medium, and 3) the safety and technical disposal concept. At present, a US salt repository for heat-generating nuclear waste and attendant safety case would have to be conceived without existing governing regulations, which may present challenges in determining which models and parameters need substantiation. Salt repository collaborators have had several discussions regarding development of a comparison document; they recognize the global international benefits to the Netherlands, Poland, Germany and the US, as members of the NEA Salt Club.

The body of work discussed here benefits from extensive international alliances with salt repository scientists and peers. The technical basis for a salt repository improves because of mutual national pursuits comparing bedded and domal salt characteristics related to repository applications. After an overview of repository guidelines and relative salt formation properties are provided, selected international collaborations describe how salt repository science is advancing. These enterprises are contemporary and ongoing such that interested readers can easily follow the research or possibly participate in certain venues.

The body of this brief discusses geologic characteristics and favorable attributes of bedded and domal salt as they pertain to nuclear waste disposal. Many previous salt programs investigated the subject matter contained here. Improvement in testing techniques, control, and evaluation coupled with massive escalation in computational hardware continue to increase understanding of salt properties and analysis applied to repositories. In this brief, information flows from larger to smaller scales. We finish with discussion of transferability and reflections on repository design.

2. GEOLOGIC CHARACTERISTICS

Bedded or domal salt formations provide prime candidates for disposal of heat-generating nuclear waste. Content of this brief that supports that statement evolves from extensive salt repository experience garnered by both the US and Germany in their respective R&D programs. Both countries have advanced salt repository science and engineering over several decades for the specific purpose of developing a safety case for salt disposal of radioactive waste. Largely, nuclear waste disposal in the US has concentrated on geologic bedded salt at WIPP while similar efforts in Germany emphasized geologic salt domes at Gorleben, Asse, and Morsleben. Each country also has extensive salt exploitation experience for industrial purposes, which enriches the collective understanding of basic salt physical, mechanical, chemical, petrological, hydrological, and thermal behavior. Differences and similarities exist for bedded and domal salt and they manifest at different scales when applied to nuclear waste disposal. Therefore, characteristics of the similarities or differences become relevant on the basis of scale from the large-scale (basin or geologic formation), to the mesoscale (meters), and down to the microscopic scale. At the formation scale structural geology, formation characteristics (i.e., layering, stratigraphy, petrography), flow paths, access ways, and therefore seal systems, concept of operations, and performance assessment numerical modeling (with required parameters and boundary conditions) come into play. At the mesoscale, the disposal concept, heterogeneity (i.e., interbeds and fabric), near-field phenomenology, damage and healing, creep constitutive models, far-field formation fluid accessibility, and corrosion potential may differ between bedded and domal salts. At the microscale, mineralogy, impurities, hydrous minerals, intergranular and intragranular fluid content, deformation mechanisms, healing processes, and decrepitation may depend on differences between and among grains.

In this brief we compare characteristics of bedded and domal salt, emphasizing reference to the WIPP and Gorleben sites, with additional information derived from secondary sites (e.g., Project Salt Vault bedded salt, Avery Island salt dome, Strategic Petroleum Reserve domes, and extensive commercial mining experience). The differences derive in part from the type of geologic deposit (bedded vs. domal), but also stem from peculiarities of each locale or investigation interval at an individual site. There can be significant variation among and within bedded salt sites or salt domes. While we attempt to discern apparently relevant differences from site peculiarities, one cannot completely disentangle their effects.

The extent to which bedded and domal salt formation types differ in characteristics important to HLW disposal is a somewhat unanswered question. Many properties of salt are similar regardless of origin. Neither domes nor bedded salt are completely comparable merely based setting, geologic history, and evolution. Flat-bedded salt formations include laterally extensive deposits of halite and other evaporates (e.g., anhydrite, polyhalite, and sylvite) layered sequentially as deposited and altered by diagenetic differentiation. Flat-bedded salt, such as the Salado Formation, has experienced no acute tectonic deformation since initial deposition. There are differences between bedded Zechstein salt formations in Germany/Europe and WIPP/Salado salt formation. Argillaceous salt layers are almost fully missing in German Zechstein, only at the base of z3 (Grauer Salzton) and z4 (Roter Salzton) and at the top of z3 (Tonmittelsalz) and z4 (Tonbrockensalz) there are relatively thin clay bearing layers (Hammer 2016). By contrast, the WIPP salt frequently contains significant amounts of polyhalite, which is rarely found in German Zechstein.

By contrast, domed salt such as in the Gulf Coast of the US and in the German northwest has been deformed extensively after the original bedded salt was deposited. Salt buried at great depth can rise via buoyancy through superincumbent sediments because salt is less dense and behaves plastically at the elevated temperatures and pressures associated with these depths. A diapir or salt dome can have a complex internal structure because of the extraordinary deformation accompanying its piercement through overlying layers. The center of the diapir contains the most deformed and deformable salt. Around the edges, the originally flat layers of non-deformable evaporates (e.g., anhydrite) are carried along upward and broken in the dome formation process.

2.1 Attributes for Geologic Disposal

Preliminary screening of potential sites can be guided by generally favorable attributes, which apply equally to various geologic media. These recommendations were applied to previous site evaluations and remain suitable for specific considerations of salt.

- **Depth –** The disposal horizon should be determined based on site-specific conditions. Geologic isolation is attained by ensuring significant separation between the repository and the biosphere, which would provide extensive zones for robust seal systems. Rock strength and overburden stress characteristics would also determine a practical and functional mining depth.

- **Thickness –** Maximal thickness of the isolation medium is desired to ensure radionuclide migration does not exceed regulatory criteria or boundaries. Various “minimal” thicknesses have been put forward, generally on the order of 100 m. However, the thickness of the formation is less important than its uniformity and structure.

- **Uniformity and Structure –** The potential repository interval and surrounding rock should be reasonably homogeneous both vertically and horizontally. The related benefits are simpler and more transparent characterization and performance assessments and safer repository mining and operations.

- **Seismicity –** Seismically quiescent regions favor repository design, operations, and long-term performance.

- **Hydrogeology –** Host rock should have acceptably low permeability to brine migration.
- **Self-sealing –** Salt exhibits plastic deformation characteristics, which assist in reestablishing an impermeable diffusion-dominated transport system.
- **Hydrogeochemistry –** Reducing chemical conditions minimize corrosion of engineered barriers and waste forms, reduce most radionuclide solubility, reduce transport of colloids, and improve sorption.

The contiguous forty-eight US states contain many salt formations that are likely to be technically suitable for deep geologic disposal of nuclear waste. Host salt formations would exhibit basic favorable physical dimensions, geologic stability, and low permeability. These general characteristics also apply to considerations of differing rock types, such as shale or granite.

Comparison of salt characteristics related to the salt safety case for nuclear waste disposal encompasses spatial and temporal differences and similarities of the media. For purposes of this brief, the nuclear waste will be heat-generating and specificity will be highlighted throughout the text as important distinctive thermally driven processes are considered as they impart differing effects between bedded and domal salt. The safety case is predicated on three prerequisites for development of FEPs: 1) characteristics of the waste to be disposed, 2) the medium into which the waste will be placed, and 3) the disposal concept. Additional detailed treatment of FEPs will integrate with the disposal concept inasmuch as differences can be identified for the types of salt formations. Discussion of similarities and differences is generic in large measure but effort is made to separate multiple differentiable characteristics as they pertain to the disposal safety case. Disposal concepts, design bases, and analyses may be dissimilar, which in turn would influence sealing strategy and time-wise evolution of the underground.

2.2 Salt Characteristics

The positive attributes of salt that make it an effective medium for disposal and isolation of hazardous, toxic, and radioactive materials have been recognized for over 50 years (National Academy of Science 1957). Each attribute will be briefly discussed below, and each is important to the isolation capability. Collectively, they provide the safety basis for isolation of material disposed within.

- **Salt can be mined easily.** Salt, an important mineral in human history, has been mined for millennia. A wealth of underground experience, including TRU waste disposal operations at WIPP, ensures that large-scale, safe mining can be conducted in salt.
- **Salt flows around the buried material and encapsulates it.** Salt will slowly deform to surround other materials, thus forming a geologic barrier that isolates waste from the environment. Creep or viscoplastic flow of salt has been well characterized for many applications. Research collaboration between Germany and the US has played a significant role in development of this technical understanding.
- **Salt is essentially impermeable.** The very existence of salt millions of years after deposition is proof that water has not flowed through the formation. The established values for permeability of intact salt come from many industry applications, such as the industrial large-scale storage of liquid and gas products in solution-mined salt caverns. The undisturbed formation permeability of salt is essentially too low to measure using

traditional hydrologic and reservoir engineering methods. In undisturbed and healed salt, brine cannot flow into or from emplaced waste at rates that would lead to significant radionuclide mobilization and transport.

- **Fractures in salt are self-healing**. In terms of disposal, one of the most important features of salt as an isolation medium is its ability to heal previously damaged areas. Damage recovery is often referred to as "healing" of fractures. The healing mechanisms include microfracture closure and bonding of fracture surfaces. Evidence for healing of fractures in salt has been obtained in laboratory experiments and through observations of natural analogs. Fracture healing can restore salt's ultralow permeability, as noted above.
- **Salt has a relatively high thermal conductivity**. Thermal conductivity of natural rock salt under ambient conditions is approximately 2 to 3 times higher than granite, clay, or tuff. A relatively high thermal conductivity is a positive attribute in a salt repository for heat-generating nuclear waste because the heat is dissipated via conduction into the surrounding formation rapidly, reducing thermal convection – an efficient method to transport radionuclides.
- **Suitable salt formations exist in wide geographic distributions.** There are many locations with stable geologic salt formations in the US and around the world.
- **Saline environments are biologically simple.** Few microorganisms have been found which can survive in salt formations (let alone thrive), reducing the need to study biological processes and biologically enhanced process in the repository environment.

In the US, a large number of potential salt site settings were characterized for disposal purposes. The first distinction among the salt settings related to domes and bedded salt. Although both bedded and domal geologic salt formations have halite as the host rock, the draft Environmental Impact Statement (EIS) (DOE 1984a) made the following statements regarding differences in properties of the two types of salt and the hydrologic framework.

> Bedded salt occurs as sedimentary layers of salt and interbed impurities and is typically bounded by aquifers above and below the salt units. Domes in the Gulf Coast of the United States are piercements of thick sedimentary clays, silts and sands. Domes are surrounded by aquifers at different depths. Thus, the geohydrology around domes is distinctly different from that of bedded salt.

Use of salt formations for nuclear waste disposal has been a widely embraced concept since the 1950s. Disposal of nuclear waste in salt remains a viable concept in the US, as demonstrated by licensing and operating the WIPP near Carlsbad in New Mexico. As shown in Figure 2-1, the conterminous US has many large salt formations, including bedded and domal salt. Four major regions of the US where salt formations are found include: 1) the Gulf Coast; 2) the Permian Basin; 3) the Michigan-Appalachian Region; and 4) the Williston Basin. Domal salts are found in the Gulf Coast region and Paradox Basin, and bedded salts are present in the remaining three major salt regions of the continental US, as well as in several other regions of smaller areal extent.

Screening of the entire US in the 1960s and 1970s identified large regions underlain by rock salt of sufficient depth and thickness to accommodate a repository as shown in Figure 2-1, modified from Johnson and Gonzales (1978).

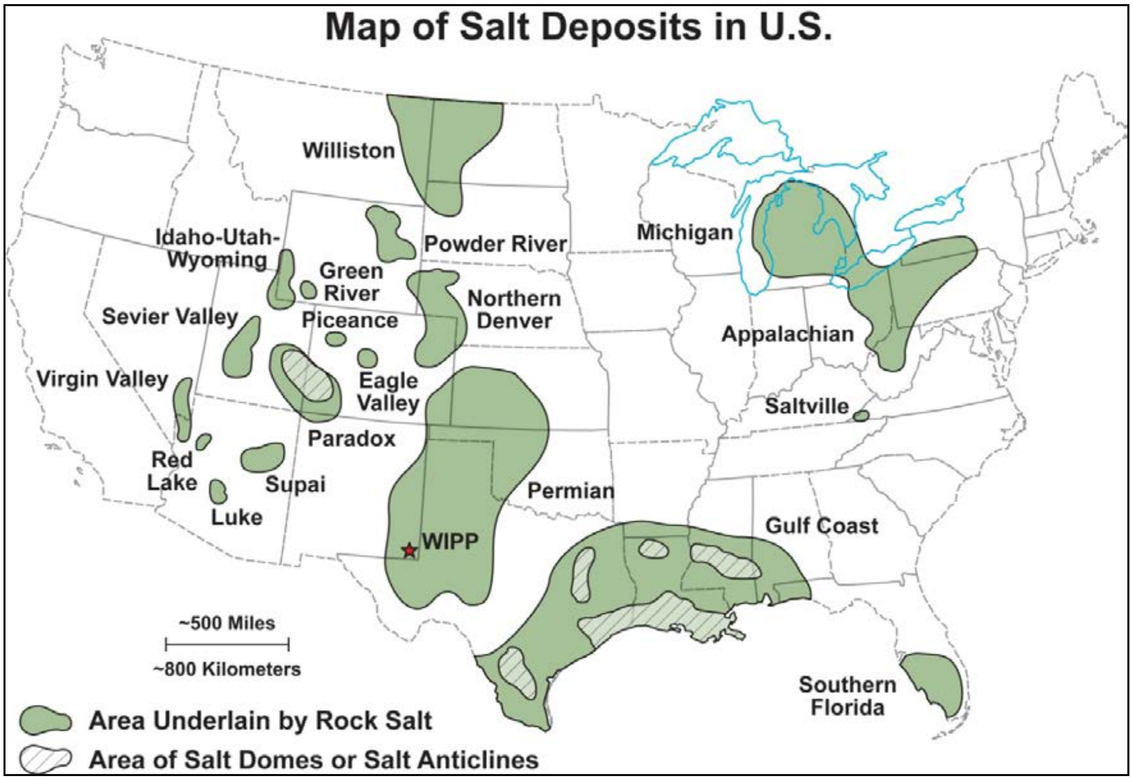


Figure 2-1. Map of salt deposits in the United States.

Salt domes in the Gulf Coast. The primary screening factors used to identify potentially favorable locations were the depth to the top of the dome and present use for gas storage or hydrocarbon production. Siting guidelines and the related evaluation reduced the list of over 500 salt domes to seven potential repository locations, with further screening resulting in the identification of the Cypress Creek, Richton, and Vacherie domes as potentially acceptable sites.

Bedded salt in Utah. The primary screening factors used to identify potentially favorable locations were the depth to the salt, the thickness of the salt, proximity to faults and boreholes, and proximity to the boundaries of the dedicated lands. The thickness of the salt, the thickness of the layers above and below the depth of a repository, and the minimum distance to salt-dissolution features were considered the most critical geologic discriminators. Davis Canyon and Lavender Canyon were identified as potentially acceptable sites.

Bedded salt in west Texas and southeastern New Mexico. The Permian bedded-salt deposits in the Texas Panhandle and western Oklahoma had been identified as potentially suitable for waste disposal. The primary screening factors were the depth to and the thickness of the salt, faults, seismic activity, salt dissolution, preexisting boreholes and underground mines, proximity to aquifers, mineral resources, and conflicting land uses, such as historical sites and state or national parks. All the evaluated sub-basins contain salt beds of adequate thickness and depth. Following considerable study, DOE decided to focus on locations in northeastern Deaf Smith and north-central Swisher counties in Texas.

In 1985, the Secretary of Energy nominated three salt sites among the five sites for further consideration: Deaf Smith County, Davis Canyon, and the Richton Dome sites. The President subsequently selected the Deaf Smith County site as one of the three sites to fully characterize prior to the 1987 enactment of the Nuclear Waste Policy Act Amendment.

The pathways and mechanisms by which radionuclides might reach the accessible environment are also quite different for bedded and dome salt because of their fundamental structural and stratigraphic differences. Salt domes originate from thick beds of deeply buried salt. When sediments were deposited on these salt beds and they were buried deep enough to significantly increase formation temperature and pressure, the salt migrated upward owing to buoyancy and tectonic evolution to form a dome structures. Salt within the dome experienced extreme deformation by virtue of plastically emerging over kilometer distances. Intrinsic brine from original deposition was squeezed out while the salt deformed. Consequently, salt domes contain less water than undeformed bedded salt, which retain remnants of formation brine in intragranular fluid inclusions.

The draft EIS (DOE 1984a) goes on to state the following generalizations of differences between the two types of salt rock:

- Because of its higher water content, bedded salt has a lower strength than dome salt
- Bedded salt has lower geothermal temperatures at equal depths of burial
- Bedded salt tends to have faster creep rate
- Bedded salt has a more variable chemical composition than domal salt
- Bedded salt has a simpler structure than domal salt.

These generalities are **not** likely to prove universal, as shown by examples given later in this brief. The varied nature of the Bryan Mound salt dome provides a good example of this. Parameters depend on comparison of specific sites and specific units within a given salt formation. In FEPs analyses in Section 3.3, factors affecting containment of wastes at salt sites take into account chemical composition and configuration of the host rock. On a case-by-case basis, dispersed hydrocarbons and pockets of methane gas have been observed in salt domes (NEA 2013). Inter-bedding in flat-lying salt can vary dramatically between different beds within a specific basin and between basins (Johnson and Gonzales 1978). Site suitability will invariably rely on the extremely low permeability of the salt formation to provide isolation from the biosphere.

Generic observations may be applicable across the spectrum of salt formations, and a portion will be site specific. The assessment of FEPs will necessitate evaluation of transferability between salt formation types. For example, results derived from disposal concept mock-up, confirmation testing, seal system construction and performance testing, and operational demonstrations are often transferable between or among salt sites. Transferability of experimental and analogue information forms a fundamental scientific tenet and has been used to establish peculiarities and similarities in salt repository programs for decades. Proposed research, development and demonstration can further add to the scientific basis for salt disposal, although some FEPs will unavoidably be site specific. As salt repository science moves forward and compares attributes of bedded and domal salt, an appreciation of generic and site-specific factors will be debated.

3. COLLABORATIONS

International salt repository partners have collaborated in several different venues, with key findings applicable to waste disposal in salt. Two projects currently underway pertain particularly to comparison of bedded and domal salt for repositories. One is named KOSINA, and one is named WEIMOS. In addition to these formal projects, international peers have been working on a comprehensive salt repository database. These efforts are described in this Section.

3.1 WEIMOS

The project name in German is: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (WEIMOS), which translates as: Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt. WEIMOS recently received approved from the German Ministry and continues a previous collaboration called the Joint Project, which concerned benchmarking and improvement of constitutive models in geomechanics simulations of field experiments conducted in bedded and domal salt, comprising WIPP/bedded formation in the US and Asse/dome formation in Germany.

Sandia has committed to supply German partners with additional WIPP salt core material for laboratory testing. A shipment comprising 4,489 lb. of 300mm diameter core left Albuquerque, New Mexico on June 27, 2016. In addition to German research centers performing tests on this bedded salt core, Sandia plans to perform its own experimental and theoretical work. The collaboration is particularly timely and relevant. Germany and the US undertake common applied research as a basis for comparison of bedded and domal salt options for HLW repository.

The search for a location of a repository for high-level radioactive waste in Germany is open again. In the US, there is a disposal facility in bedded salt at WIPP and a long history of site selection involving bedded and domal salt. In addition to salt repository applications, mining and cavern storage industries have characterized bedded and domal salt from many formations.

The WEIMOS project reflects the current stage of our respective repository programs, which includes consideration of bedded or domal salt as candidate host media. In recent years, extensive laboratory testing of intact WIPP samples, petrological studies, and consolidation of mine-run granular WIPP salt by German colleagues have extended the already substantial database. The theoretical work described in the WEIMOS project plan derives from a research agenda compiled by several collaborators (Popp et al. 2016). One measure of our collective ability to model salt deformation is matching models with observed measurements of room closure, which is a process that can potentially lead to a release of radionuclides from the repository. Within the scope of the long-term safety analysis, rock mechanical predictions covering periods up to 1 million years have to be made. The research agenda expounded upon by Popp et al. (2016) identified key testing regimes to enhance parameterization of constitutive model features:

- Shearing of inhomogeneities (e.g., clay seams)
- Tensile and extensile salt properties
- Damage and healing behavior
- Creep of salt at low deviatoric stress

As demonstrated in collaborative modeling of Rooms B & D at the WIPP, the phenomena encompassed in these testing regimes are applicable to bedded and domal salts, though shearing of inhomogeneities is more relevant to bedded salt. Despite being generally lithologically homogeneous, natural rock salt (domal and especially bedded salt formations) comprises natural bedding planes or mechanical discontinuities that could become mechanically and hydraulically weak when sheared. Underground observations and simulations at Sandia regarding WIPP (Rath and Argüello 2012) show that sliding along contact surfaces between halite and anhydrite or clay layers can significantly influence convergence behaviour of underground cavities. However, these properties are minimally constrained by the existing calculations.

Experimental deformation of rock salt performed to date focused primarily on the damage of rock salt due to compression. Extensile states of stress exist in the near perimeter of underground salt openings. Modeling approaches and constitutive laws need to be further developed for extensile and tensile behavior.

Seal construction leads to recovery of damage and restoration of integrity by way of crack closure, subsequent sealing, and healing. Field evidence and analogue examples support this contention; however, systematic experimental and microstructural investigations are needed for further development and validation of existing calculation approaches.

In situ observations indicate that the creep rates at room temperature and stress differences of less than three MPa approach 10^{-12}/s, several orders of magnitude higher than creep rates associated with assuming a constant stress exponent of $n \approx 5$. Figure 3-1a) illustrates an expansion of the classic Norton creep approach with $n = 4.9$ over a range with smaller deviatoric stresses with $n = 1$. In Figure 3-1 b) results of creep tests on WIPP rock salt at different temperatures are modeled according to the material approach by Günther and co-workers (Günther et al. 2014). Creep rates projected from the majority of test data acquired at stress differences from 5 to 20 MPa under-predict observed rates. This phenomenon represents deformation by mechanisms different from dislocation process represented at higher stresses and temperatures. Systematic experimental investigations have been identified for immediate future research.

Planned activities in the WEIMOS project are valid for both bedded and domal rock salt regardless of its location. Back-calculations of lab tests validate the tools and checks the transferability of calculation methods and results for rock salt from both types of deposits. The planned WEIMOS project has a close thematic relation to another contemporary effort called KOSINA sponsored by the German Federal Ministry for Economic Affairs and Energy (BMWi).

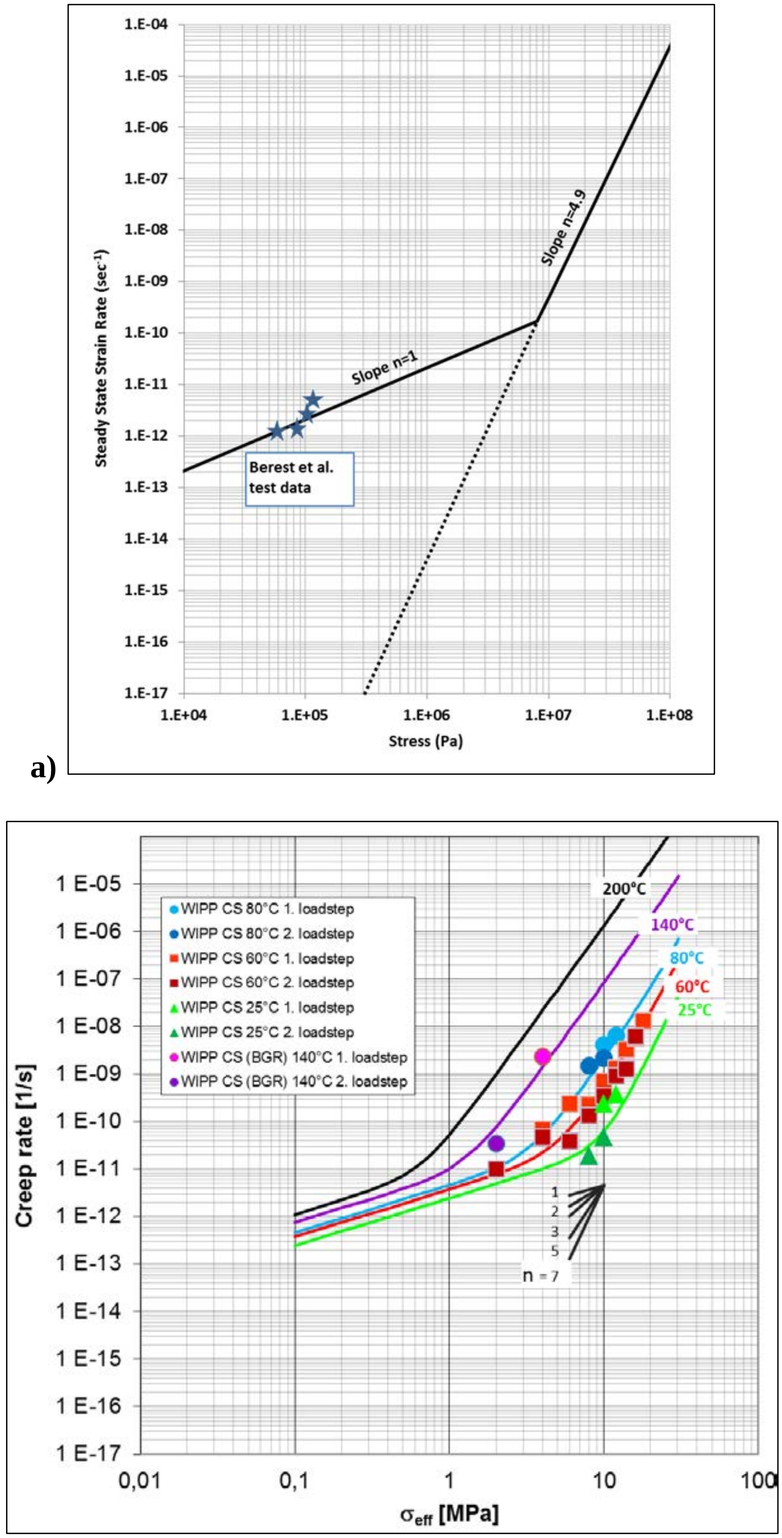


Figure 3-1. Creep of rock salt at low deviatoric stress.

3.2 KOSINA

The KOSINA project focuses on the analysis of integrity of the geological barrier for generic locations in bedded salt and salt pillows by means of geomechanical model calculations. There is no laboratory testing associated with the KOSINA project as there is in the WEIMOS project, which is further developing constitutive models and simulation procedures.

Partners in KOSINA include

- BGR – Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
- DBE TEC – Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe GmbH (The German Society for the construction and operation of waste repositories)
- GRS – Gesellschaft für Anlagen- und Reaktorsicherheit GmbH (Society for Plant and Reactor Safety)
- IfG – Institut für Gebirgsmechanik GmbH (Institute for Geomechanics)
- SNL – Sandia National Laboratories (Associate Partner)

In the past, bedded salt formations in Germany were not considered for HLW disposal even though bedded salt has been and still is used to host underground hazardous waste disposal facilities. Therefore, the KOSINA project was addressed in BMWi’s new research concept as an important issue to improve knowledge and perform investigations that clarify conceptual questions and to contribute to the technical-scientific basis for the safety-oriented evaluation of potential repository systems in host rocks available in Germany.

Since 1987, nuclear waste disposal in the US has concentrated on bedded salt while similar efforts in Germany emphasized geologic domal salt. The US is once again considering possible repository choices and therefore has parallel interests in relevant differentiating characteristics of bedded and domal salt. In Germany and the US rock salt remains one of the potential host rock formations. Consistent and close collaborations between German repository scientists and US peers have generated agreement that common goals of salt repository in bedded or domal salt provide an excellent opportunity for both countries. Each country has advanced salt repository science and engineering developed and applied over several decades for the specific purpose of providing the necessary expertise for developing a safety case for salt disposal. The KOSINA mission builds upon and uses this expertise.

Salt domes are distributed mainly in northwestern Germany; whereas central Germany contains flat or bedded salt formations and parts of north-east Germany contain salt pillow structures. The latter geologic formations are generically called bedded salt and have extensive lateral dimensions. The KOSINA R&D project has been initiated for a disposal concept and safety case development of a generic repository for heat-generating waste in such flat-lying salt formations in Germany.

Bedded salt formations differ from domal salt structures in many ways—lateral extent and vertical thickness are two of the most obvious geometric considerations. Bedded salt repository concepts have not been developed for heat-generating radioactive waste and spent fuel in Germany; however, these efforts embody many scientific intersections with the WIPP repository in the US. The WIPP site in New Mexico has been an operating repository for long-lived TRU waste of military origin. The facility resides at 650m depth in the bedded Salado Formation.

Long-term safety records and operational issues also profit from extensive experience accumulated from storage of chemical and toxic waste in flat-lying salt formations in Germany. This experience does not include the influence of heat, and therefore KOSINA undertakes a mission to specifically address heat-generating waste disposal in bedded salt.

Germany has advanced the VSG, which is the Preliminary Safety Analysis for the Gorleben salt dome. Disposal concepts considered included drift and borehole emplacement and direct disposal of transport and storage casks. Among multiple considerations, design of geotechnical barriers (plugs and seals) was developed accompanied by assembly of substantial technical database that was applied to these analyses. Here again we acknowledge an existing salt repository database comprising noteworthy background knowledge that can be applied to a repository in flat-lying formations.

3.3 Features, Events, and Processes

A long-term safety assessment for nuclear waste repositories conventionally includes an approach that evaluates future scenarios by combining FEPs relevant to evolution and performance. The FEPs screening process is performed to help ensure a critical feature (e.g., waste forms, drift seals, or the biosphere), physical process (e.g., thermal expansion of brine or creep closure), or event (e.g., earthquake or nuclear criticality) are not inadvertently left out of the safety case. A FEPs screening decision usually takes the form of either "include" or "exclude," denoting whether or not the FEP must be explicitly included in performance assessment models or scenario development.

In a separate but related effort, GRS and Sandia scientists are compiling a generic salt FEPs catalogue (Sevougian et al. 2015). To apply the FEPs process in detail, it is necessary to identify the waste inventory, the concept of disposal, and the geologic site. At that point, a systematic evaluation of interactions allows scenario development and differentiating salient characteristics can be related to repository applications. In this document, a few FEPs will be included as examples, which illustrate differences. Many of salt's favorable attributes apply without regard to the bedded or domed geologic formation. This Section provides FEP examples to illustrate depth and level of detail.

International collaborators are assembling a universal salt FEPs database report, which will serve as a resource for our nuclear waste repository programs, and as a reference document for future site selection and technical differentiation. An ambitious effort by GRS and Sandia personnel will eventually result in a compilation of a generic FEPs catalogue for bedded and domal salt. The essential document will also provide a road-map for FEPs considerations regarding other geologic formations such as granite and shale. This undertaking represents a long-term commitment consistent with the NEA Salt Club goals and advancement of national salt repository programs. The FEPs catalogue will be thorough and the collaboration has demonstrated exceptional success. For the purposes of this document, it is instructive to review a few representative FEPs from the generic catalogue as a gauge of differentiating characteristics of bedded and domal salt.

The concept of FEPs analysis and application has been implemented in repository programs and is a frequent topic of technical reports (e.g., NEA 2013; Freeze et al. 2010). Scenario development and performance assessment based on FEPs analysis is an important part of the repository long-term safety case. The practice has precedent in the preliminary safety assessment of the Gorleben salt dome and certification of WIPP. The existing body of FEPs work from Gorleben and WIPP is being developed into a generic assemblage of FEPS for salt, both bedded and domal (Sevougian et al. 2015). Through the FEPs analysis process, it may be possible to define scenarios in which repositories in bedded and domal salt evolve differently. Figure 3-2 below is extracted from Popp et al. (2016) and illustrates the order in which FEPs development follows the prerequisite descriptions of the waste to be disposed and the operational concept. Fundamental repository design and layout may be strongly influenced by the type of salt formation selected.

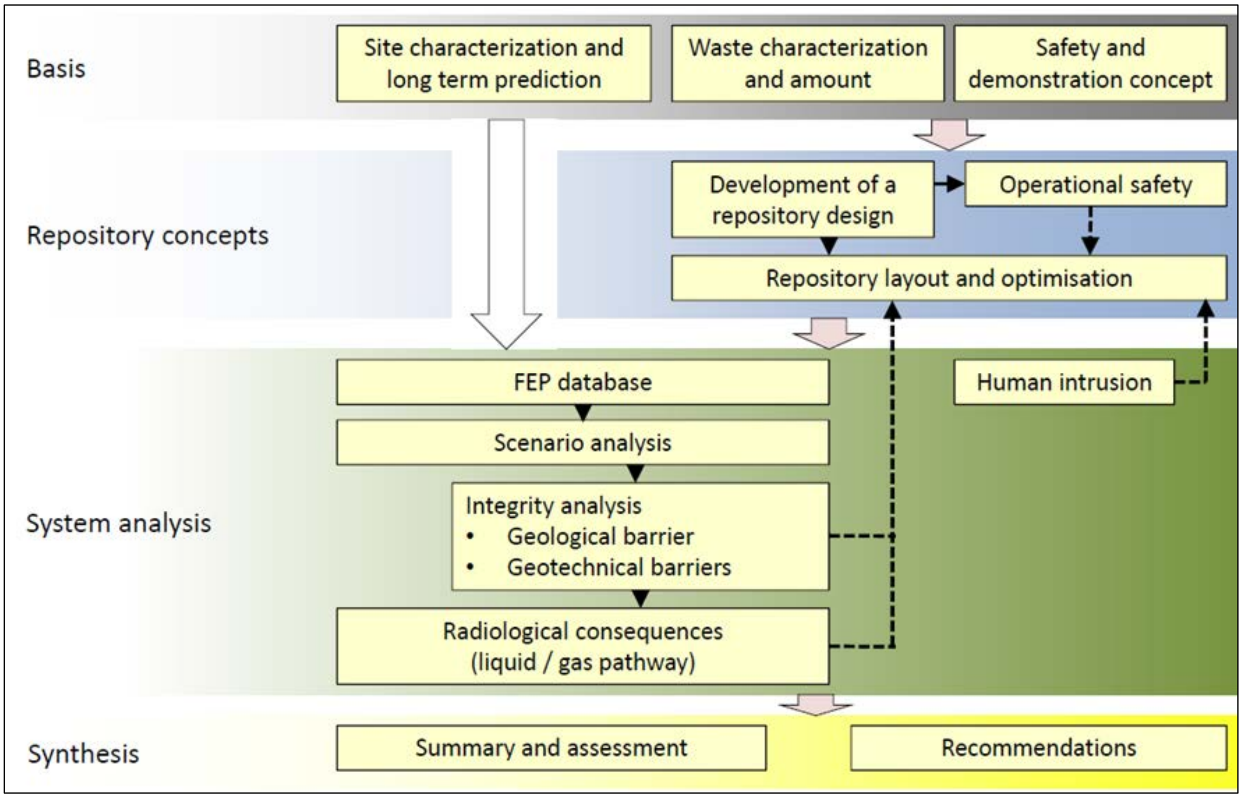


Figure 3-2. Scheme of the VSG safety demonstration.

Through several years of close international collaborations, a research agenda for generic salt studies has emerged. Concomitantly, international collaboration has recognized the mutual goal of a universal database for FEPs, which may identify further differentiating matters between domal and bedded salt. Three examples provided here are extracted from a comprehensive work in progress by a team of German and US salt experts (Sevougian et al. 2015). The comprehensive FEPs database assembled by Sevougian et al. (2015) pertains to a generic salt repository, but it contains a few salt-formation specific features and components that are used here to illustrate bedded or domal distinctions.

1. FEP **HR.01.CP.01** covers Stratigraphy and Properties of Bedded and Domal Salt. This is a new type of FEP, called a "characteristic" FEP, which defines the stratigraphic, physical and chemical properties of the host rock that are relevant to scenarios development and PA. Key associated processes include stability of

mined openings during operations and drift closure design and performance. Granular rock salt with or without additives is expected to be an integral part of drift closures. Research and engineering is currently studying consolidation and attendant properties that obtain as salt formation closes the drifts and impinges on the granular salt within. Drift closures of reconstituted salt will mimic the favorable characteristics of the host salt, which comprises a massive formation with potential inhomogeneities. Engineering of the underground openings would include assessment of creep closure and influence of local stratigraphy, which relate to another pair of FEPs screening arguments (HR.02.CP.01 Stratigraphy and Properties of the Disturbed Rock Zone in the Host Rock and HR.03.CP.01 Stratigraphy and Properties of Interbeds and Seams in the Host Rock).

The properties of host formation are important for long-term performance. Material properties and characteristics are well defined, but would vary depending on the salt site selected. Such parameters as salt density, *in situ* stress, elastic salt properties, constitutive models, strength of host and surrounding media, bulk compressibility, thermal properties, porosity and permeability are commonly evaluated in laboratory tests. In detail, other flow and transport properties such as residual brine saturation, residual gas saturation, pore distribution, and capillary pressure introduce a range of values. The properties of the host formation halite will be accounted for in the actual stratigraphic construct of the site and through advancing constitutive modeling. Therefore, screening this FEP is not possible until a specific site is selected.

2. FEP **HR.03.CP.01** applies specifically to Stratigraphy and Properties of Interbeds and Seams and therefore should be more differentiating than the one concerned singularly with the host rock (salt). The physical stratigraphy and characteristics of interbeds and seams can be appreciably diverse depending on geologic formation. As before, stability of underground operations, ground control, and drift closure are common, but fluid flow and transport of radionuclides through interbeds, seams, or other discontinuities in bedded salt may discriminate. Domal salt may also contain interbeds such as anhydrite encountered at Gorleben, where the uplift and folding processes have fractured it into discrete segments. The lateral extent of interbeds is a clear difference of these salt formations. Bedded salt in the US almost always contains horizontal beds of lithology other than halite. The hydrologic properties of interbeds would be important to long-term performance for a bedded salt formation and would be configured into model geometries.

3. FEP **HR.03.TT.01** takes the discussion of the influence of interbeds a step further. This FEP is called Advection of Dissolved Radionuclides in Interbeds and Seams and encompasses hydrologic, chemical, and transport processes relevant to advection of dissolved radionuclides in the interbeds and seams adjacent to the waste disposal areas. As noted in Sevougian et al. (2015), dissolved actinide transport focuses on fluid flow and transport in the advective porosity of the interbeds and seams of the host rock. If, as stated generally, bedded salt contains more brine than domal salt, greater volumes of brine would be available to flow into the waste room as the excavation damage zone (EDZ) evolves.

> Expulsion of contaminated brine is postulated to occur along seams and interbeds, where chemical environment would influence transport. Advection is deemed less important in domal salt because interbeds are not continuous and less formation brine is likely. The major open issue for this FEP is the site-specific information required to evaluate the role of advection through interbeds in a domal salt stratigraphy.

To be applied to the safety case, especially if it is intended to differentiate between bedded and domal salt, aspects considered in the FEPs analysis must be observable, measureable, and quantifiable to some degree. If a FEP parameter is found to have a strong correlation to a regulatory performance metric, it then becomes a primary candidate for performance confirmation monitoring, which by definition must be something that lends itself to observation. Toward this end, it is imperative to describe the FEP itself, demonstrate its relevance to the safety case, and identify quantitative and qualitative differences between bedded and domal salt.

International collaborations concerning HLW repositories in bedded or domal salt have expanded beyond Germany and the US to include Dutch and Polish scientists. Researchers in The Netherlands have had extensive interest in salt disposal. OPERA (Onderzoeks Programma Eindberging Radioactief Afval) is the Dutch research program on geological disposal of radioactive waste, including the possibility of Zechstein rock salt. Their nuclear waste policy includes interim storage for a period of at least 100 years. In OPERA an initial safety case will be developed to structure the research necessary for the eventual development of a repository in the Netherlands. The comprehensive salt FEP catalogue should prove to be a useful resource within the Dutch context.

4. SCALE

Concepts of operation will be engineered based on first-order geologic structures of the selected site. In this regard, bedded salt and domal salt are substantially different. A convenient means to discuss bedded and domal salt characteristics is size or scale. We implement this concept here, beginning at the formation scale and moving to the intermediate scale of rooms, drifts and disposal concepts, where most research has concentrated. In consideration of waste disposal, the concept of operation will be a design matter that obliges decisions on facility construction in the geological environment. As a potential site characterization proceeds, detail will be rendered for design and decisions made with knowledge of site-specific properties and conditions. To provide guidance and forethought, known differences and similarities identified today guide many aspects of disposal operations, licensing, closure, and performance assessment.

4.1 Large Scale Geology

Salt is an unusual geological material for many reasons. It has relatively low density, exhibits complete plasticity under many relevant stress and temperature conditions, and is highly soluble. Because salt is relatively lighter than overlying sediments, it has a natural tendency to buoy upward and can deform without fracture over enormous strains. Undisturbed bedded salt retains its depositional layering with diagenetic alterations. Domes and pillows result from salt movement activated by tectonics, décollement-type sliding, and gravity swells which provide the initiation of isostatic up-building. There is a geological continuum in the structural geology of salt ranging from layered bedded salt, perturbations such as salt pillows, and ultimately diapirs and domes.

The formation of the salt dome begins like bedded salt with the deposition of salt in a restricted marine basin. Over time, non-halite evaporites and terrestrial sediments cover the layers of salt. As more overburden is added, the overlying sediment will undergo compaction (unlike the salt), increasing its density. Salt with its relatively low density becomes more buoyant than the overlying compacting sediment. Salt ductility allows flow laterally and vertically. In certain settings and over geologic time, salt can pierce the superincumbent sedimentary layers and form domes, diapirs, and even surface glaciers. Domes can easily reach 10 km in diameter and perhaps 5 or more km in depth.

As shown in Figure 4-1, the Gorleben dome is 4 km wide and nearly 15 km long, which provides ample area for flexible disposal concepts. It is composed of different salt rock types of the Zechstein (Upper Permian) series and extends to a depth of more than 3 km. In the course of the dome formation, the salt was moved and uplifted several kilometers, resulting in an extensively folded and complex internal structure (Bornemann et al. 2011). During the uplift, anhydrite as a competent layer was broken to isolated blocks. In the core of the salt dome the Hauptsalz forms a homogeneous halite body with a volume of several cubic kilometers. Contemporary with the diapiric movement of the salt, the Hauptsalz became homogenized in the central part with no lithological or stratigraphic discontinuities, as displayed by bedded salt.

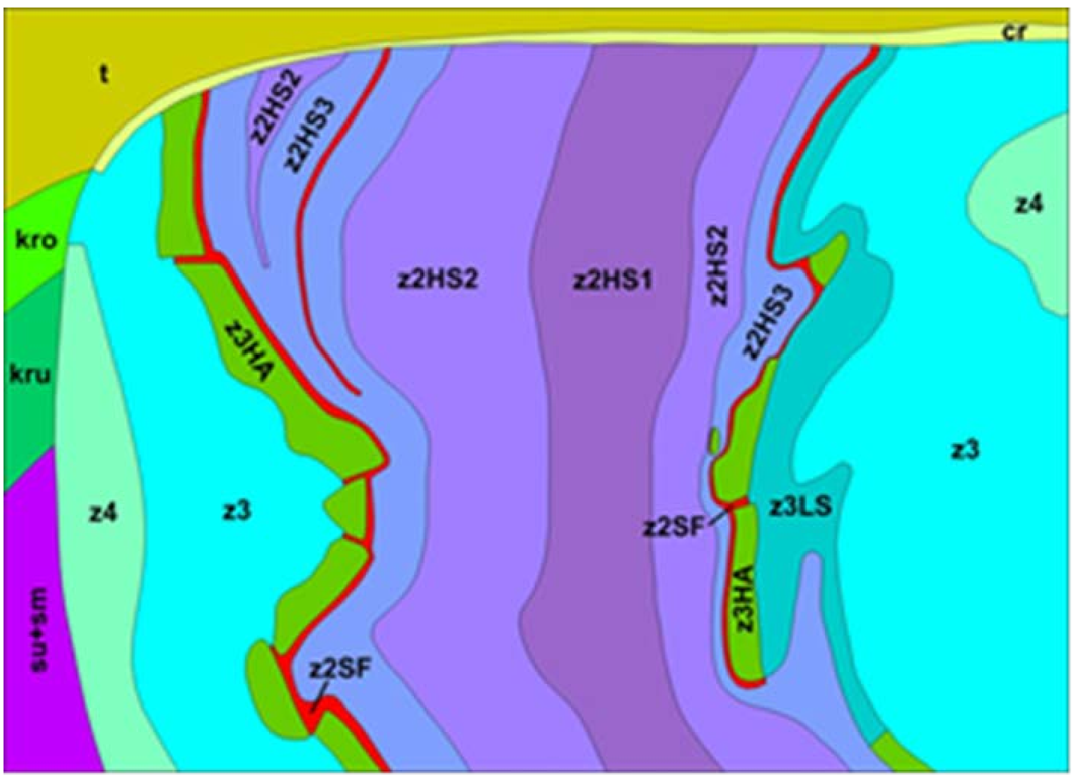


Figure 4-1. Simplified cross section of Gorleben salt dome.

The Hauptsalz contains small amounts of gaseous and liquid hydrocarbons in separated zones of decimeter to meter dimensions. Brine reservoirs with fluid volumes in the range of liters to hundreds of cubic meters exist in certain regions of this part of the salt dome. The average water content of the Hauptsalz is below 0.02 % by volume. Interconnected pores do not exist in the salt rock outside of fluid bearing or fractured areas rendering the salt rock impermeable.

The Salado Formation at the WIPP site contrasts strongly with dome structures such as Gorleben. Mapping of the WIPP Air Intake Shaft allowed an idealized Salado halite sequence to be constructed (Holt and Powers 1990). In their studies, Holt and Powers identified the complete Salado halite sequence and found no geologic evidence of naturally occurring late-stage fluid migration or alteration within Salado halite. A general cartoon at the one-kilometer scale of the WIPP setting is shown in Figure 4-2 top. Although vertical layering is evident, lateral extension in bedded-salt formations often persist for 100 kilometers or more, as shown in Figure 4-2 bottom.

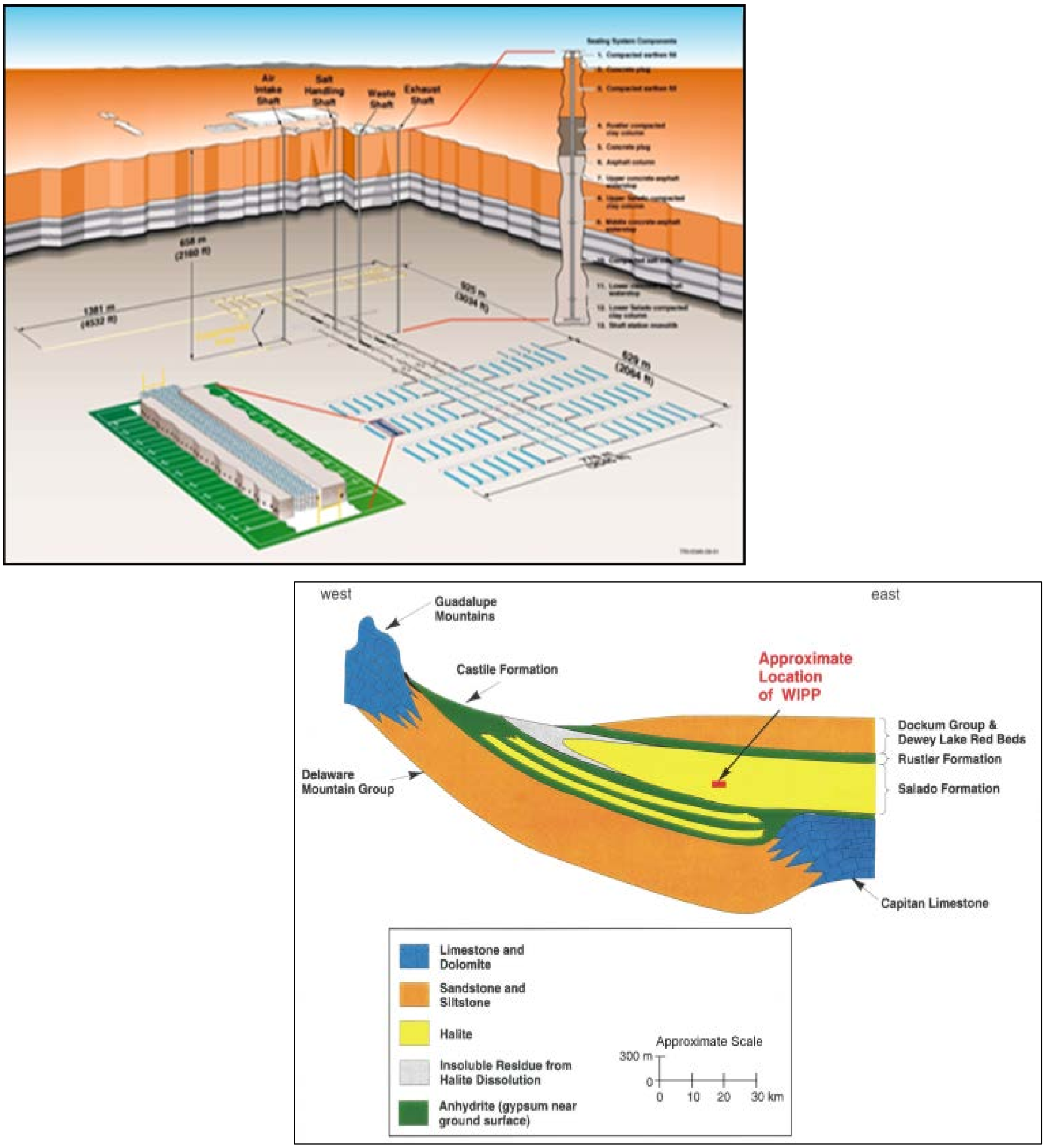


Figure 4-2. Local and regional flat-lying salt at WIPP.

4.1.1 Regional Groundwater Flow

At the formation scale structural geology, characteristics of layering and fabric, flow paths, access ways and seal systems, concept of operations, performance assessment modeling, and far-field boundary conditions come into play. Due to salt's high solubility, aquifers near the repository present a significant potential failure mechanism in salt. Potential for dissolution of the salt by circulating ground water, whether initiated by inadvertent human intrusion or by unexpected salt deformation, is a potential failure mechanism that differs significantly for bedded and dome salt in their respective geohydrologic environment. For example, at salt domes dissolution would occur along the flanks of the dome by ground water from overlying and pierced sedimentary strata. The dissolution of bedded salt could occur by laterally migrating dissolution fronts by inter-salt-bed sedimentary aquifers or by vertically circulating groundwater.

Ongoing collaboration between GRS and Sandia compares existing numerical groundwater flow and solute transport models to improve conceptualization and numerical implementation of regional groundwater flow simulations near repositories. GRS uses their flow and density-dependent solute-transport model d3f, while Sandia uses PFLOTRAN. The collaboration began by identifying key features missing from existing models. Several of these features have since been implemented, most notably solute concentration-dependent fluid density in PFLOTRAN.

Figure 4-3 shows the model grid and hydrogeologic conceptualization of the Delaware Basin near WIPP. This modeling is based on a previous study by Corbet (2000), and is currently being used as the basis for initial GRS/Sandia modeling comparison. Model domain is roughly 30×50 km in lateral extent, and includes all geologic units above the Salado Formation. Progress has been reported on at the US/German workshops, and advancements are being made by both Sandia and GRS. Once the WIPP basin-scale groundwater model stage is complete, comparisons will proceed to the hydrology surrounding a German salt dome, possibly Gorleben.

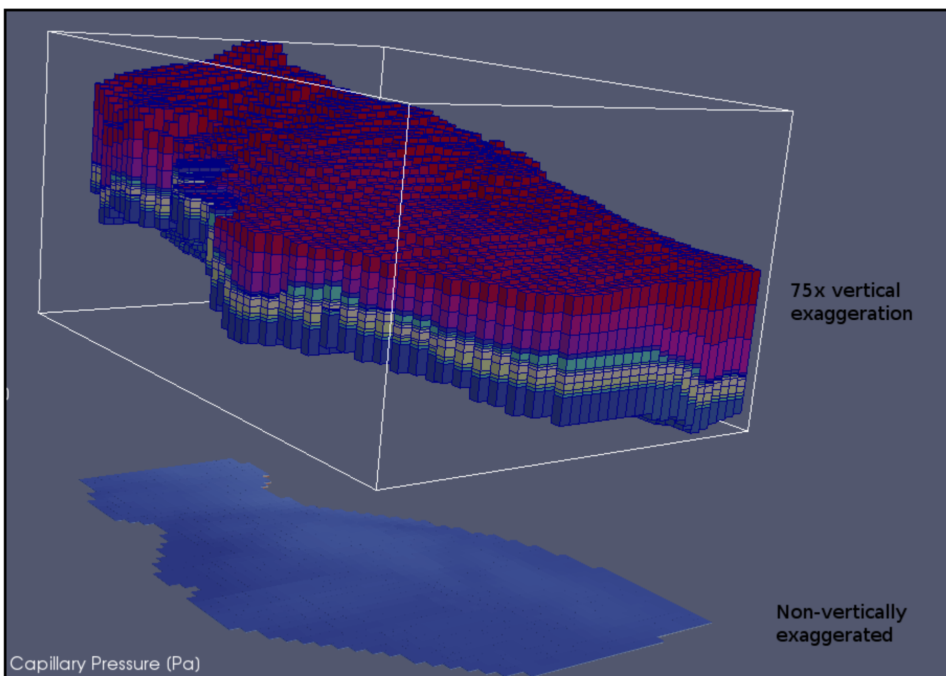


Figure 4-3. Basin-scale groundwater flow model of Delaware Basin (WIPP).

Complexity of the regional groundwater flow model is proportional to the geologic formation heterogeneity. At the basin scale, the differences between bedded and domal salt are significant, especially when considering regional groundwater flow patterns. Collaboration between GRS and Sandia has benefitted both parties because they have taken tools developed previously for applications associated with flow around bedded or domal salt, and demonstrated applicability in geologic settings not considered previously. In the case of PFLOTRAN, incorporation of additional physics into the model will potentially benefit all users of the model. The collaboration brings together modelers from different organizations to collaborate and share ideas on hydrologic modeling of bedded and domal salt repository settings.

In general, it is simple to create numerical flow modeling meshes for bedded formations because of the simple flat-lying geometry. Fewer stratigraphic control points are needed to constrain the geometry of the mesh, and the continuity of geologic layering. In domal salt, the shape of the salt dome is more complex, the flat-lying sedimentary layers are often distorted and broken up, and this complex geometry controls the flow around the salt dome. Proper constraint of the layering in the groundwater flow model requires significant stratigraphy data from boreholes and likely geophysical surveys.

When constructing regional groundwater flow, it is best to construct the boundaries of the model to coincide with hydrologic or geologic boundaries, rather than just cutting the model off and applying a possibly arbitrary boundary condition. In flat-lying sedimentary basins, where bedded salt would be found, this means the numerical flow model would need to include most or all of the relevant sedimentary basin (the example basin-scale groundwater model of WIPP did not include all of the Delaware Basin, but it did include a significant portion of it). The regional flow system surrounding a salt dome is often more complex, but may only involve groundwater flow in shallow aquifers near the top of the salt dome. Regardless of the geology, the same rules apply to salt domes as well. Ideally, we want to extend regional groundwater flow models to coincide with hydrologic or geologic boundaries.

4.1.2 Large-scale Geomechanical Modeling

Large-scale modeling central to safety arguments made for the Gorleben salt dome evaluation and has been reported in several venues. Easily obtainable summaries are included in Chapter 2 of the Proceedings of the 6th US/German Workshop on Salt Repository Research, Design. and Operation (Hansen et al. 2016) or Hansen and Popp (2015). The following is from the latter source.

In Germany, salt domes were identified as possible sites for a repository for heat-generating radioactive waste since the 1960s. As a candidate site, the Gorleben salt dome located in Northern Germany has been investigated since 1979, at first from the surface and since 1986 from underground when shaft sinking started (Bornemann et al. 2011). Investigations came to a halt between 2000 and 2010 based on an agreement between the German government and the electric utilities. In 2010 site investigations were resumed and the preliminary safety assessment for the VSG was undertaken.

Following the German safety requirements, released in 2010 by the Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (German Federal Ministry for the Environment, Building, Nature Conservation, and Nuclear Safety) (BMU 2010), a safety concept and a process for demonstrating long-term safety were developed, which became the basis for the design of the repository and the safety assessments performed in the Project VSG.

Based on the safety concept, specific requirements were derived concerning the site, the repository concept, the design of the repository openings, and the assessments to be performed within the Project VSG. Requirements concerning the site have to be fulfilled by the characteristic properties of the host rock and the overall geological situation. The main objective of the repository is to contain the radioactive waste inside a defined rock zone, called containment-providing rock zone. The radionuclides shall remain essentially at the emplacement site, and at the most, a small defined quantity of material shall be able to leave this rock zone. This shall be accomplished by the geological barrier and a technical barrier system, which is required to seal the inevitable penetration of the geological barrier by the construction of the mine.

The repository depth planned at Gorleben is 870 m and will have a maximum length of approximately 4 km and a width varying between 300 m and 700 m, according to the geology and depending on emplacement concept. An overview describing the technical design of the repository and the detailed design of the geotechnical barriers is given by Bollingerfehr et al. (2013).

Computer simulations were carried out on the geomechanical processes, which give rise to creation of micro-fractures caused by mechanical damage or fluid-pressure opening of grain boundaries. Large-scale, 2-D, and 3-D geomechanical models exposed relevant loading conditions at different scales, i.e., in the proximal emplacement zone (near field) including the drifts and emplacement containers, as well as the thermal effects on the salt dome as a whole (far field). In terms of this brief, there is a recognized overlap between large-scale geomechanics and the subject matter contained in 4.2.4 Applied Modeling.

Figure 4-4 illustrates the fundamental conclusion: thermally-induced stresses do not give rise to continuous migration paths. The highest thermomechanical stresses affecting the salt barrier occur within the first hundred years after sealing the geologic repository. Loss of barrier integrity becomes increasingly unlikely in the following period. Damage associated with the EDZ is local to underground openings and was found to be of secondary importance to overall integrity of the salt barrier. In terms of the dome structure, analyses showed that fluid could penetrate the formation from the cap rock, but even extreme scenarios would leave adequate barriers intact.

The integrity analysis clearly documents a high level of safety analysis based on geomechanical modeling, which demonstrates compliance with a one-million-year geological barrier for the site Gorleben. Additional studies on liquid and gaseous transport of radionuclides as presented by Kock et al. (2013) confirm that the compaction behavior of crushed salt backfill is one of the most relevant factors for the hydrodynamic evolution of the repository and the transport of contaminants.

Focusing on the geomechanical integrity, future safety analyses of salt domes should involve detailed investigations on the pressure-driven infiltration of fluids into bedding planes within salt rock masses or zones where the integrity criteria are not fulfilled. Coupled thermal-mechanical-hydrological calculations on fluid infiltration into the barriers require further development and coupling of appropriate numerical tools supplemented by a comprehensive experimental database that explores mechanical and hydrological properties of discontinuities.

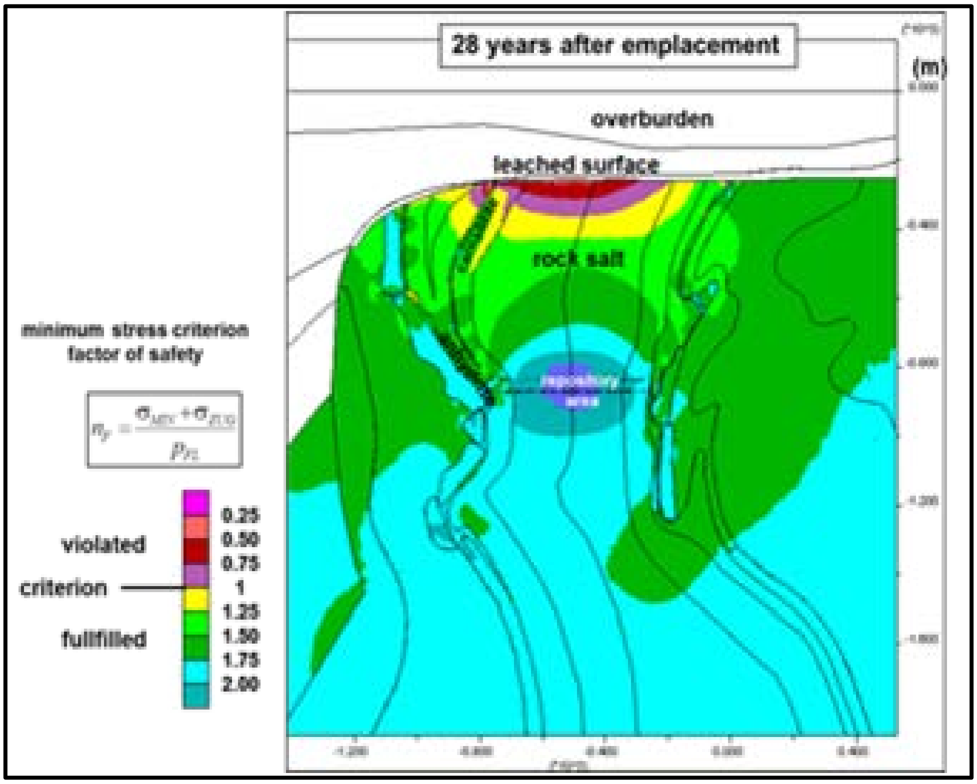


Figure 4-4. Evaluation of the minimum stress criterion 28 years after the start of emplacement. Note the criterion violation ($\eta_F < 1$) in the purple to red zone at the salt dome top.

4.2 Mesoscale

Salt formations have many favorable characteristics that combine to make them promising sites for permanent radioactive waste disposal. Some of the favorable characteristics are modified during the excavation process and continue to evolve during operations. Accounting for these fundamental structural and hydrologic changes is essential for establishing credible repository performance models needed to support waste disposal licensing activities.

Rapid significant changes in stress lead to an EDZ near the free surfaces, which provides increased porosity and inter-connected flow paths between the far-field salt formation and the mined opening. This phenomenon is common to both bedded and domal salt, although bedded salt nominally has greater overall brine content. Upon excavation, the previously impermeable formation near to the room or drift becomes an anisotropic, high-porosity and higher-permeability zone. Enhanced permeability helps liberate native brine, either in the vapor or liquid phase. Transient creep strain accumulates rapidly at the onset of excavation and although it is an important element of constitutive modeling, it is usually not measurable *in situ*. Evolutionary characteristics of salt are well known, and straightforward engineering measurements can be made to quantify early evolution. This knowledge is equally important for designing and predicting performance of sealing structures.

4.2.1 Thermal Effects

It is widely believed that the heat load from high-level waste is detrimental to operations and long-term isolation in salt. The US NRC (10CFR Part 51 2008) states: *Salt formations are being considered as hosts only for reprocessed nuclear material because heat-generating waste, like spent nuclear fuel, exacerbates a process by which salt can rapidly deform. This process could cause problems for keeping drifts stable and open during the operating period of a repository*. Equally problematic is the perception of detrimental effects due to available brine from bedded salt formations, which is often simply labeled *brine migration*. These perceptions are only part of the technical basis for disposal of heat generating waste in salt, which includes the broad spectrum of thermal effects in a salt medium.

Thermomechanical response of the underground is an engineering consideration that actually creates positive performance of salt. Thermally activated processes allow salt to deform without fracture at predictable rates that can be factored into improved performance of room closure and seal system evolution. In addition, heat is minor for a huge volume of our nation's old "cold" fuel. Isolation of waste from the biosphere is predicated on a surrounding impermeable salt formation and evolution of geotechnical barriers, which can be constructed far from the heat sources, if desired.

Elevated temperature dramatically speeds up salt deformation, crushed salt reconsolidation, and creep closure. Elevated temperature in a nuclear waste repository will enhance deformation upon placement of the heat-generating waste in the rooms. Elevated temperatures can increase brine inflow in bedded salt to excavations in the short term, due to reduced viscosity of brine, and thermal expansion of brine – especially in anhydrite or clay layers. Elevated temperatures in crushed salt backfill and in the EDZ can enhance dry-out of openings in bedded salt during the facility operational phase by promoting brine liberation and removal through mine ventilation systems. In addition to stress-induced fracture in the EDZ, significantly elevated temperature in the near-field environment could give rise to local decrepitation of brine inclusions (around 270 degrees C) and dehydration of hydrous minerals over 200 degrees C. It is possible that both phenomena could have positive effects in terms of long-term performance because of the liberation and removal of small amounts of brine in the native salt from the EDZ. Conceptually, the heat load can be engineered to bolster many of the positive attributes for salt disposal.

With regard to the advance of the thermal pulse and the perceived problems with engineering an appropriate disposal scheme because of the enhanced creep rate, the thermal pulse activates the crystal plasticity of the surrounding salt, which accelerates creep closure and encapsulation. Thermally induced salt plasticity is a constant-volume process. As stress equilibrium is re-established by the accelerated salt creep, permeability is eliminated. Under this evolution scenario the thermally hot waste remains dry.

4.2.2 Brine and Vapor Migration

Much conversation about *brine migration* in salt portrays it as a serious concern for heat generating nuclear waste. Brine exists in bedded salt in three forms: brine inclusions, hydrous minerals and grain boundary water. The Salado Salt Formation at the WIPP horizon contains a variable amount (nominally <1%) of water by weight and the vast majority is associated with clay minerals. Owing to the characteristics and environments of the brine in salt, its transport or migration occurs via three primary mechanisms: motion of the intragranular brine inclusions under a temperature gradient, vapor-phase transport along connected porosity and liquid transport driven by the stress gradient (Shefelbine 1982; Kuhlman and Malama 2013; Kuhlman 2014).

The conceptual model for brine-inclusion migration is based on a model of a trapped inclusion within the crystal structure. In a steep temperature gradient, a single-phase brine inclusion tends to migrate up the gradient (toward the heat) 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 inclusion migrates toward the heat. Two-phase brine inclusions (i.e., those with an air bubble) migrate down the temperature gradient, away from the heat source. These phenomena of brine-inclusion migration have been observed in the laboratory and in field experiments.

From Project Salt Vault (PSV) (Bradshaw and McClain, 1971) until the demise of the civilian radioactive waste US salt program, several studies of brine migration were conducted. The first observations of brine migration from PSV were perhaps somewhat unfortunate, because a significant component of the total brine release occurred when electrical power was shut down. Loss of power to the heaters in the experiment quickly reduced temperature gradients and the tangential compressive stress at the wall of the testing borehole, conditions which allowed the brine accumulated and stopped by the stress gradient to be released into the test hole. In disposal operations there would be no such power shut down and a reversal of the thermal gradient, but experience at PSV intrigued a number of scientists.

Petrofabric examinations of salt samples from a region adjacent to PSV Array Hole 2 in Room 1 were conducted by Holdoway (1974). This region was located in a direction outward from the periphery of the array of waste canisters. Evidence for brine migration within crystals was observed, but only a few trails crossed crystal boundaries, supporting the postulation that brine was trapped on grain boundaries.

In a real repository in natural salt, both intragranular and intergranular water will be mobilized when salt is subjected to a temperature gradient. The intragranular inclusion will eventually reach boundaries under the influence of the temperature gradient. The fate of the inclusions and the accompanying water at the grain-boundaries is not quite clear (Olander 1982). If the grain boundaries are tight, migration will be impeded by the grain-boundary tension. On the other hand, it is likely that the grain-boundaries in natural salt deposits will be weakened by mechanical actions (EDZ) with release of pressure on salt in close proximity to the openings. Grain boundaries are thus permeable and the intergranular brine may escape through the pores.

These observations were largely confirmed by Pigford (1981), whose studies were specifically on WIPP salt. He noted only relatively large inclusions (>0.01 cm) are predicted to migrate and these large inclusions represent a small fraction of the inclusions in WIPP halite. He concludes the large inclusions may still terminate their migration at the grain boundary or within the crystalline lattice if they fission into smaller inclusions. Thus, the preponderance of the observational evidence argues against brine migration for large-scale transport in polycrystalline salt.

Brine inclusions can only migrate under steep temperature gradients. The high thermal conductivity of salt means thermal gradients imposed in the laboratory would only be observed within centimeters of the heat source. After hot waste is placed in the salt, heat conducts outward and establishes temperature gradients deeper into the surrounding rock. It is possible that inclusions could migrate toward the heat source. However, in the early period when thermal gradients are steep, the migrating inclusion will encounter grain boundaries or microfractures. At that point, the brine (no longer an inclusion) moves down the stress gradient, heats into vapor, enters repository ventilation, and is removed from the system.

Heat from disposed waste will initially drive moisture out of the system. It is well known that creation of the underground opening in salt creates a stress gradient, which manifests in an assortment of fractures. A disturbed rock zone forms around the opening. Brine seeps down the stress gradient into the opening, say a drift or disposal room. A heat-generating source, such as disposed HLW, would further liberate accessible moisture by vaporization. Thus, the disturbed rock zone and disposed waste heat combine to dry a halo around the waste. The accessibility and transport of brine can be important to the near-field environment. Non-halite lithologies such as clay and anhydrite have potentially important impact in the near-field and are distinctly different between bedded and domal salt.

4.2.3 Mechanical Properties

Mechanical deformation of salt is comparable on the laboratory scale (mesoscale); short-term strength has been universally demonstrated to be a function of stress state and temperature. Laboratory evidence, as illustrated below, demonstrates similar pressure dependence and strength of natural salt. Short-term strength and the brittle-to-ductile transition are not distinctively different among generic, dominantly salt samples, on the scale of laboratory tests. Unconfined compressive strength of many natural salts as determined from laboratory samples averages 20 MPa, about the strength of sidewalk concrete. Uniaxial tensile strength is the same, on average, between bedded and domal salt. Here again, laboratory tests from an actual site would be necessary to reduce uncertainty, but mechanical properties are sufficiently well known to support generic design and analysis.

The EIS (DOE 1984a) generalized differences between the two types of salt rock noted earlier in Section 2.2 are not usually verified in detail. The EIS stated that bedded salt exhibited lower strength and faster creep than domal salt. A vast suite of laboratory tests recently completed on WIPP salt tends to modify this generalization. In fact, compressive strength of WIPP bedded salt and Speisesalz from the Asse dome are comparable, while the WIPP salt creeps a little faster (Salzer et al. 2015). Figure 4-5 illustrates strength and dilatancy boundary similarity of these two, well-characterized salts. Collaboration on the WEIMOS project will extend laboratory investigations to extensile stresses, shear deformation, low-deviatoric creep, and damage/recovery according to the defined research agenda.

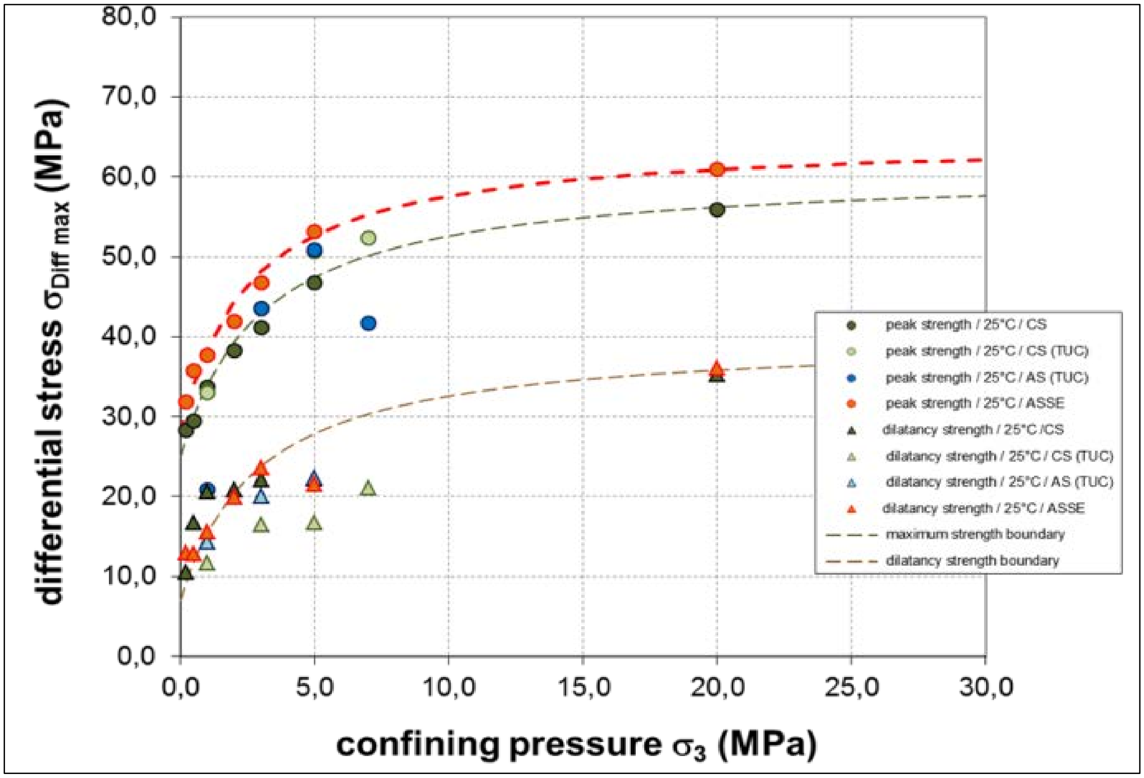


Figure 4-5. Comparison of ultimate and dilatant strength for Asse domal salt and WIPP bedded salt including both clean salt (CS) and argillaceous salt (AS).

As with the strength data, Strategic Petroleum Reserve (SPR) research at Sandia measures steady state strain rate on cores from many sites. A broad comparison of their findings is plotted in Figure 4-6 for a variety of stress differences at 60 C (Bauer and Broome 2010). Without critical examination, the trend shown by this data set is that of domal salt exhibiting lower creep rates than bedded salt. Be cautious. Salt creep behavior as evidenced by cavern volume closure can vary significantly across a single salt dome. For the case of the SPR West Hackberry salt dome, for which the salt is considered relatively homogeneous, cavern closure rates for caverns of similar depths, geometries and dimensions vary by a factor of approximately four (Sobolik 2016). For the SPR Bryan Mound salt dome, which contains multiple structural features including anhydrite and clay seams, different qualities of salt, and a significant fault structure, cavern closure rates for similar caverns vary by a factor of 10 (Sobolik 2014; Sobolik and Ehgartner 2009; 2012a; 2012b).

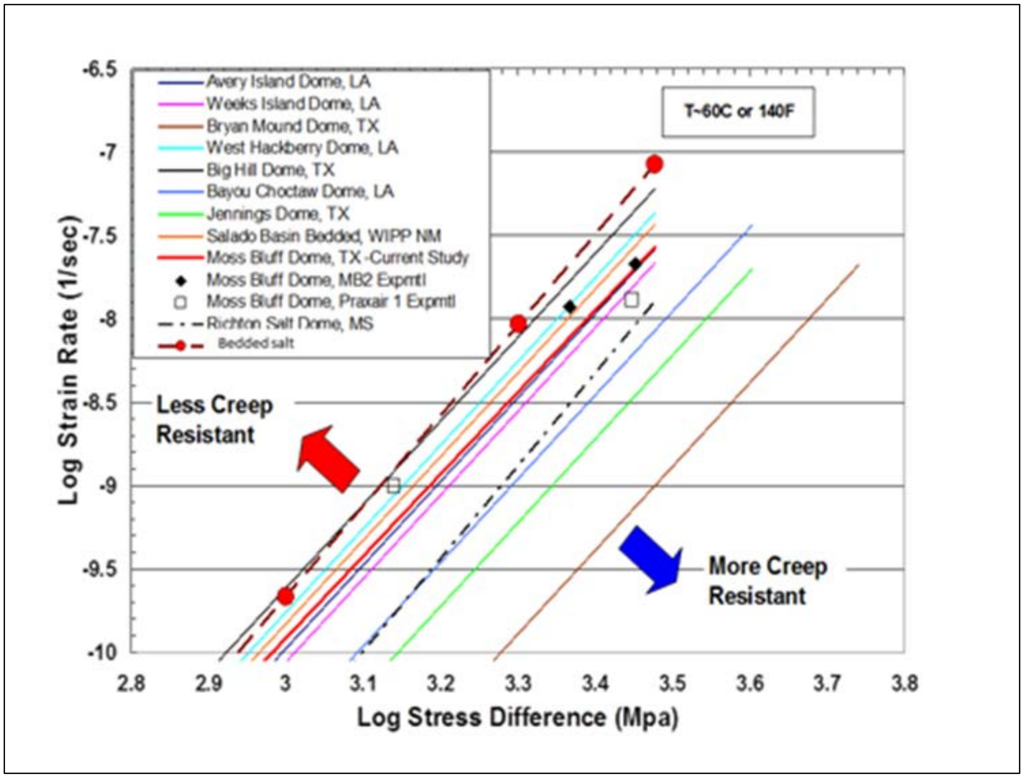


Figure 4-6. Broad comparison of salt creep rates.

Repository modeling might benefit from similar experience and applications to oil-storage caverns in domal salt. Salt cavern geomechanical modeling began as a tool to predict surface subsidence and cavern volume closure over periods of 20 years or more. Early analyses used a simple steady-state creep model with an elastic modulus reduced to simulate transient response. Simplified salt dome and cavern geometric models were thought to be sufficient for such analyses. Subsequently, more stringent cavern-specific and operational requirements were placed on the application of cavern modeling, such as identifying cavern geometries with high potential for dilatant cracking, evaluating effects on casings due to transient workover operations, and predicting the observed increased cavern creep response when adjacent caverns experience workovers. A workover operation requires the wellhead pressure drop to zero to allow for wellbore and cavern maintenance, such as logging and caliper instrumentation insertion. As a result, cavern modelers have upgraded creep models, mesh geometries, and material representations based on known features at each site. In addition, the heterogeneous nature of cavern volume closure at each site requires attempts to calibrate predicted cavern behavior by adjusting material parameters around individual caverns, using 35+ years of cavern volume closure and subsidence data. These practices have improved the applicability of cavern modeling to operational concerns, and have reduced uncertainty in predicted results. Large-magnitude, short-duration pressure changes experienced during workovers are not typically expected in a repository, but other processes such as cavern stability during emplacement and thermal-enhanced creep may also depend significantly on transient response of the salt.

Differences in geomechanical behavior likely depend more on chemistry than origin. In Germany argillaceous salt rocks from Rotliegend (Lower Permian) and Keuper (Upper Triassic) differ substantially in geomechanical behavior compared to clean halite rocks from salt domes (Hammer 2016). By comparison, WIPP salts with and without clay (clean and argillaceous salt) display similar mechanical and strength properties. In addition to stress differential and temperature, salt deformation accelerates appreciably if moisture is involved. Experiments have shown that creep rate is unchanged as long as the stress state is below the dilatancy boundary. When available, brine enhances creep deformation through grain boundary processes of pressure solution and re-deposition.

4.2.4 Applied Modeling

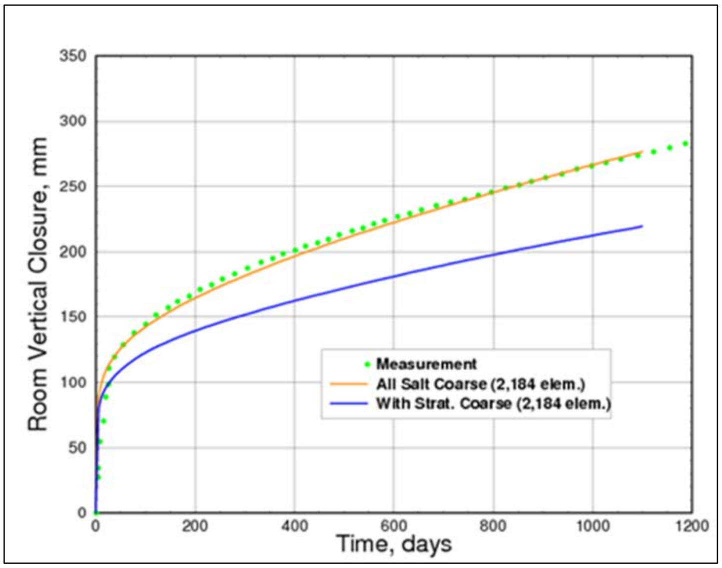
When physical processes of salt deformation are well understood, uncertainty in predictive capability is reduced. A viable constitutive model should therefore provide a reasonable approximation of laboratory results and reflect the physical processes that account for deformation. Laboratory studies facilitate measurement of generic mechanical, thermal, hydrological, and chemical salt properties in a controlled environment. A large body of laboratory data generated on salt deformation describes phenomenology of salt across a range of temperatures and stresses expected in a heat-generating waste disposal system. Microstructural studies help interpret input parameters for models that predict material behavior. Interpretation of mechanistic response continues today as international collaborators are testing bedded salt from the WIPP to better understand domains where physical processes are less well understood.

Laboratory and microscopic evaluations have been used to develop computer-based geomechanical modeling, which has been a component of the mineral industries for decades. Remarkable modeling capability exists today because computational hardware has advanced significantly over the last few decades. In salt repository application, modeling capability includes representation of thermal-mechanical behavior over long periods, appreciable variations of temperature, nonlinear large deformation (finite strain) and other phenomena associated with salt deformation in the repository setting. Integral to modeling studies are conventional issues of discretization, stability, and accuracy.

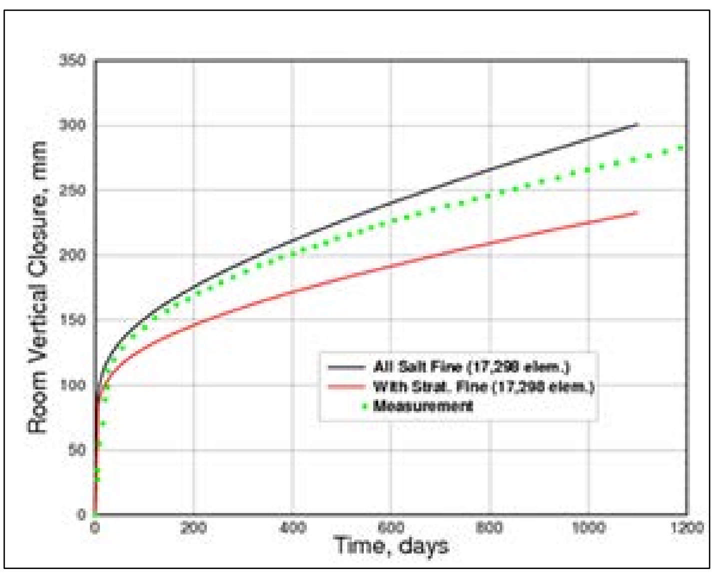
Contemporary effort is being put forward to identify best-in-class features of constitutive models, simulation architecture, and solution algorithms appropriate for analyzing performance of underground salt repositories. Modeling has included simulation of experiments conducted in the domal Asse salt mine. Recent simulations model bedded salt experiments in WIPP Rooms B and D. These full-scale rooms are of identical geometry and different thermal loading. Calculations include isothermal, thermal-mechanical uncoupled, and thermal-mechanical coupled conditions. Sandia uses a state-of-the-art Sandia Integrated Environment for Robust Research Algorithms (SIERRA) solid and thermal mechanics computer codes (Argüello 2014), while the German partners use their respective codes and models as described by Hampel and coworkers. (Collaborative Project I. 2004-2006). All calculations apply highly advanced constitutive laws that mathematically describe deformational processes intrinsic to those found in nuclear waste repository environment.

During site characterization of the WIPP, large thermomechanical *in situ* tests were conducted. Originally, the WIPP facility was designed for disposal of high-level, heat-generating defense waste as well as it current inventory. Even after a decision to eliminate HLW from the WIPP mission, these full-scale underground tests proceeded in support of the civilian program characterizing Palo Duro salt in the panhandle of Texas.

Models of WIPP large-scale experiments often matched the field data well (Munson 1989; 1990). Despite limited discretization, modeling symmetry assumptions, two-dimensional plane strain grids, field-test results could be reproduced by finite element models. An example of these benchmarking legacy calculations of WIPP Room D is shown in Figure 4-7 a) and Figure 4-7 b). In Figure 4-7 a) an all-salt idealization with relatively coarse mesh matched the vertical closure precisely, while a model with more detailed stratigraphy calculated closures below the measured values. By comparison, using a mesh about 8 times finer, Argüello (2014) obtains the results shown in Figure 4-7 b). As Argüello (2014) points out, an under-refined mesh is typically stiffer, but it would appear that parameters and features, such as the coefficient of friction of clay seams, were adjusted to match test results in legacy calculations. In lieu of testing, assumptions were made about the clay seam behavior in closure measurements associated with Rooms B and D. These are just examples of challenges addressed by the WEIMOS partners.



a)



b)

Figure 4-7. Benchmarking Room D deformation.

A large matrix of tests on WIPP salt conducted by German research laboratories adds appreciably to international collaboration on model benchmarking. In concert with benchmarking WIPP *in situ* experiments, German research groups are parameterizing their respective model variables through a series of special laboratory tests on WIPP salt. Their codes and models, which have been thoroughly calibrated against *in situ* experiments conducted in domal salt formations, will be appropriately parameterized for generic salt repository analysis with the inclusion of parameters representative of bedded salt. The benchmark problem extent, geometry, initial boundary conditions, and history are established from well-documented technical information from existing WIPP literature. Thus far, preliminary benchmark validation efforts suggest that additional characterization of non-salt elements such as anhydrite and clay seams would improve model fidelity. Results from independent calculations will be compared and critically reviewed to assess how well the respective modeling and simulations capture full-scale field response. Continued work on the leading-edge constitutive models will provide the next generation of modeling capability applied to salt repository design, operations, seal systems, *in situ* test prediction, and performance assessment for all salt formations.

Experiments at WIPP allow close examination of details and model adjustments. Understanding room closure is vital to operational concepts, safety, seal systems and performance assessment. The ability to model carefully orchestrated tests at WIPP is improving by further laboratory testing. By contrast to the detail available for room closure at WIPP, examples of cavern closure in domes provide real-world examples of analyses that are constrained by global measurements alone.

Two different SPR sites provide primary examples of the range of salt behaviors observed at oil storage facilities in domal salt. The West Hackberry site in southwestern Louisiana operates in a salt dome that is reasonably homogeneous and lacking in significant fault or shear structures. Although the salt is relatively homogeneous, volume closures for similar caverns vary by a factor of four. The Bryan Mound site near Freeport, Texas is in a salt dome that includes at least two regions of salt with significantly different creep properties, multiple faults and shear zones, multiple anhydrite and clay seams and impurities, and observed intrusion of gas from the salt and surrounding rock. These different domes illustrate difficulties in developing computational models that accurately depict behavior of caverns.

Figure 4-8 shows a comparison between measured and predicted cavern volume closure for several of the caverns at West Hackberry. The predictions were obtained using a fully implemented multi-mechanism deformation (M-D) creep model, and utilizing a single set of creep properties for the majority of the salt dome in addition to cavern-specific creep properties (Sobolik, 2016). The m-D model was chosen to evaluate the effect of large pressure changes in individual caverns on transient creep and the resulting cavern volume closure effects on the salt and wellbore casings. The cavern-specific properties in the modeling calculations were applied to an arbitrarily defined cylinder around the cavern of approximately twice the cavern’s diameter. The overall change in volume over 25 years is predicted reasonably well using these properties; however, the closure rates predicted during normal operations (the long periods of relatively constant slope) and the workover periods (the sudden increases in volume closure, typically over three months) are not matched as well. Current modeling of the relatively homogeneous site at West Hackberry shown in Figure 4-8 represents an improving capability to adjust creep model properties to fit measured data.

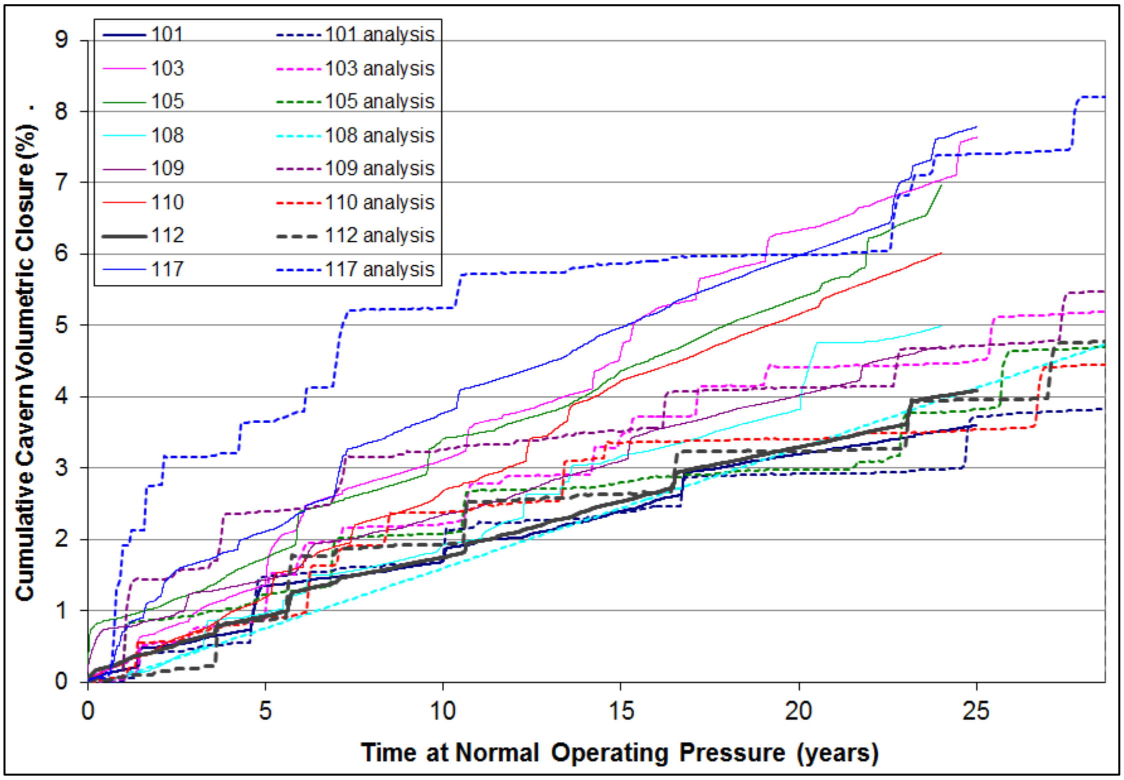


Figure 4-8. Broad comparison between measured, predicted cumulative cavern volume closure since 1/1/1990 for West Hackberry Phase 2 caverns, east side.

The difficulties apparent in the case of West Hackberry compound at Bryan Mound, which contains anhydrite and clay seams and regions of differing salt quality. Figure 4-9 shows the geometry of Bryan Mound Cavern 5, an enormous cavern whose unusual shape is attributable in part to the measured anhydrite content as a function of depth. Note that the neck region of the cavern coincides with one anhydrite spike at ~2780 ft depth. Analysis of this cavern encapsulates nearly all the operational issues geomechanical models are now required to address: accessibility to the oil in the lower lobe; salt falls from the neck region damaging the hanging string; emulsion issues when water is pumped into the cavern for oil recovery; gas intrusion issues; casing failures due to the large diameter of the roof; effect on stability of nearby caverns; and difficulty in modeling creep due to heterogeneous impurity content.

The purpose of these applied models is to point out that modeling is imperfect, even when exceptional detail is available. Further, the perception that domes are more homogeneous than flat lying salt is unwarranted. Improvement in the ability to model salt behavior is a quest in the industries and in repository applications.

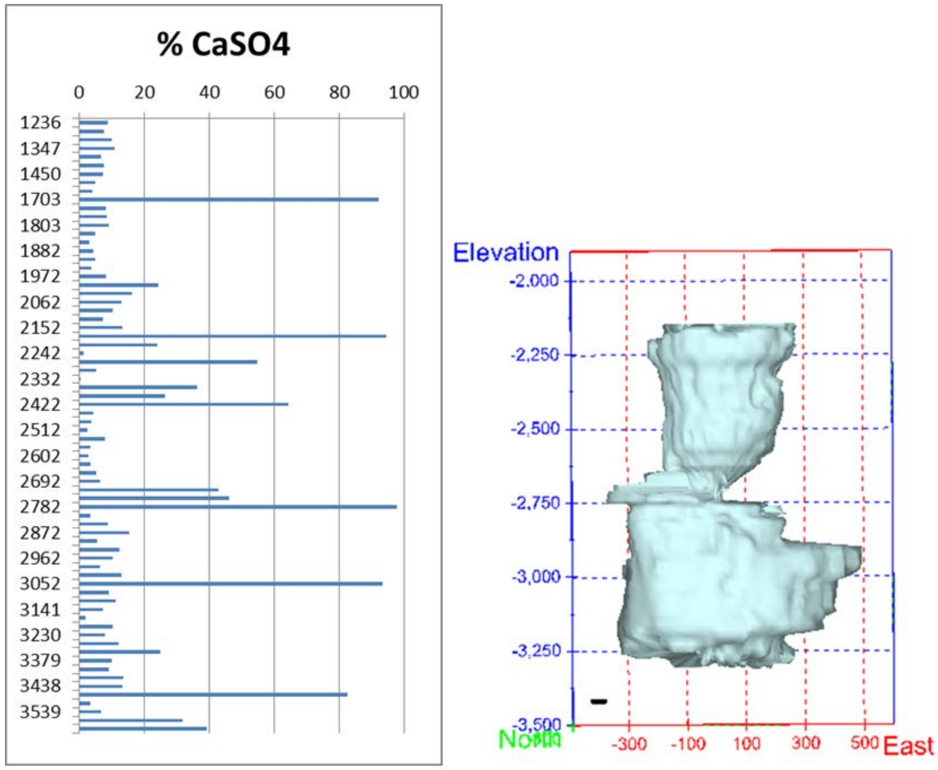


Figure 4-9. Bryan Mound Cavern 5 and its surrounding anhydrite content as function of depth.

4.2.5 Lithology

Proximal lithology influences decisions regarding disposal. For chemical reasons, disposal of heat-generating waste should avoid the presence of carnallite because of its water content. For mechanical and potential hydrological reasons anhydrite stringers can complicate concepts of operation and analysis. Bedded salt formations are typically interspersed with none-halite stringers. Bedded salt usually has anhydrite interbeds, clay layers and possibly other (horizontal) discontinuities arising from the initial geologic deposition processes and diagenesis. A salt repository would preferentially be located at a horizon (depth) that limits its hydrologic connection with anhydrite interbeds and clay layers. Their presence is often significant for long-term performance because local stratigraphy contributes to drift closure and because interbeds provide possible pathways for radionuclide transport. It follows that the properties of the halite itself as well as the location and properties of interbeds and clay layers in the halite are essential inputs to long-term performance of bedded salt disposal.

Although ascribed to be laterally continuous and predictable, bedded salt formations are variable. Stein (1985) described five lithologies within the Salado Formation distinguished in cores cut from 50-foot sections above and below the WIPP emplacement horizon: 1) clean halite, 2) polyhalitic halite 3) argillaceous halite, 4) mixed argillaceous-polyhalitic halite, and 5) clay seams and anhydrite beds. This is a typical depositional sequence seen in many bedded evaporites. The Lower San Andres Formation in the Palo Duro Basin of west Texas includes Unit 4, a depositional cycle proposed for potential HLW disposal (DOE 1984b). Unit 4 is an evaporite depositional cycle that includes approximately 50 meters of bedded salt in its upper portion. Unit 4 contains interbeds averaging 8% mudstone and 4% anhydrite. Anhydrite typically occurs as thin partings reminiscent of the Salado Salt shown in Figure 4-9. The Hutchinson salt in Kansas and the Salina salt in Michigan are similar, containing high percentages of thin anhydrite stringers.

At room temperature, salt with thin seams of anhydrite as shown in Figure 4-10 are stiffer and creep at a lower rate than salt with clay or clean domal salt (Hansen 1987). As witnessed in the photograph of deformed samples of Salina Basin bedded salt (Michigan), halite deforms plastically while anhydrite stringers pull apart in tension. Impurities of this type impede creep rates significantly at room temperature, an influence that decreases with increasing temperature. Contrary to the inference from Figure 4-6, this study demonstrated impure bedded salt far more creep resistant than clean domal salt from Avery Island.

Figure 4-10. Creep tests on bedded salt with anhydrite stringers.

Anhydrite stringers can be much thicker than those of the Salina Formation. Figure 4-11 contains photographs of Marker Bed 139, which underlies the repository horizon at WIPP. The material properties of anhydrite are substantially different from predominantly halite material. Anhydrite displays greater strength than halite, and is nearly elastic and brittle. With simplifying assumptions of elastic isotropy, the failure criterion for anhydrite is often described by conventional engineering mechanics formulations. Anhydrite of the thickness of Marker Bed 139 can influence design decisions. Because of its relatively brittle rheological response under repository conditions, anhydrite influences room closure and the proximal characteristics of the EDZ, as discussed in the next Section.

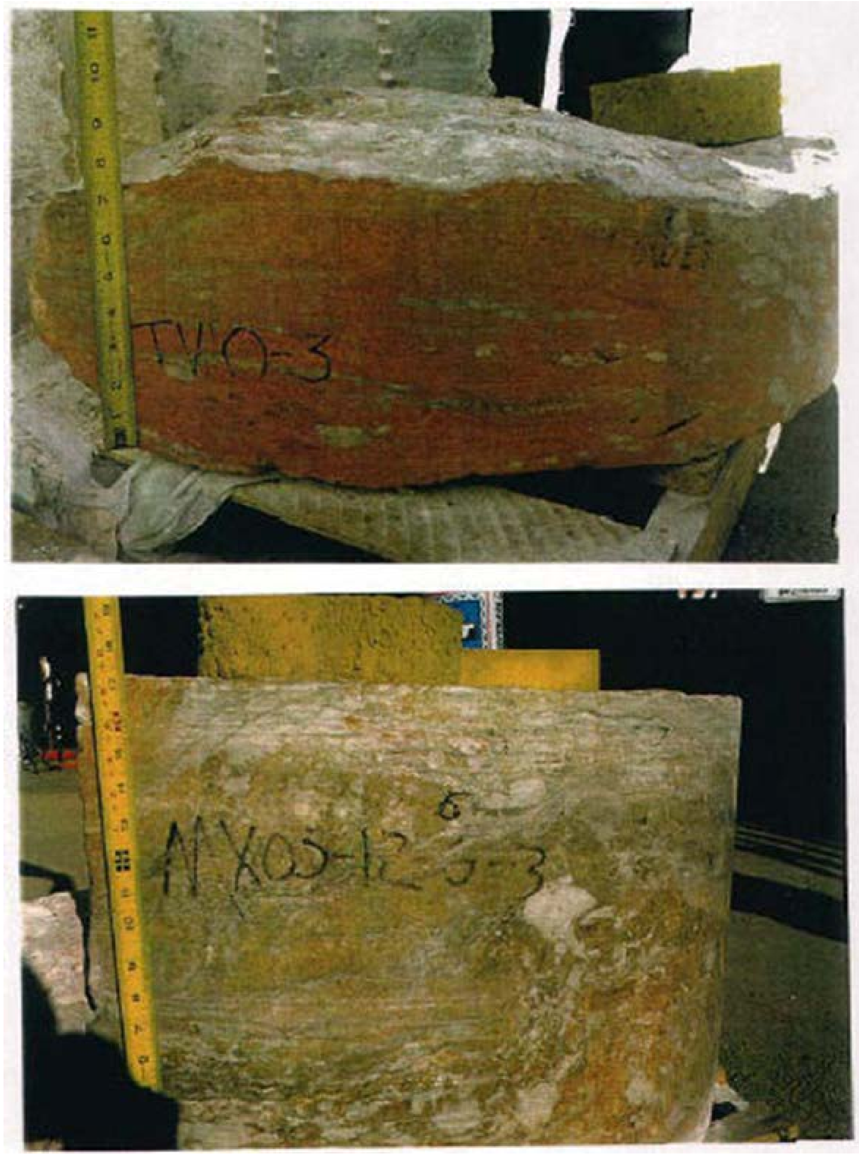


Figure 4-11. Anhydrite Marker Bed 139.

4.2.6 Excavation Damage Zone

The EDZ comprises the region near an excavation that experiences changes in hydrologic or mechanical properties. The three important properties of the EDZ that contribute to the amount and rate of brine flow into the repository are extent (thickness), porosity, and permeability. Properties that typically define a EDZ 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 EDZ 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.

Influence of bedded salt layering comprises an important difference between bedded and domal salt. In terms of a bedded salt repository, one of the most important features of salt as an isolation medium is its ability to heal previously damaged areas. The photographs in Figure 4-12 reveal the EDZ around the entry to WIPP disposal rooms. Fractures track shear stress trajectories around the opening as shown in Figure 4-12 a). Note the dramatic contribution of the anhydrite marker bed to floor heave in Figure 4-12 b). Anhydrite would not heal under the same circumstances as salt. Its contribution to EDZ evolution and engineering measures to mitigate its influence give rise to significant differences encountered in bedded and domal salt disposal schemes.

a)


b)


Figure 4-12. Excavation damage zone at WIPP.

Investigations of damage evolution remain international issues and are under investigation as part of the WEIMOS collaboration (Section 3.1). Evidence for salt healing has been obtained in laboratory experiments, small-scale tests at WIPP and through observations of analogues. German researchers report on a case study of an 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). Tests of *in situ* permeability were conducted on the 700-m sections of the drift and behind a steel liner placed in a drift during the 1920's. The extension and the hydraulic properties of the EDZ around a drift were investigated by means of gas and liquid injection testing. Healing the salt EDZ can restore low permeability to damaged salt.

The EDZ constitutes an important geomechanical element of salt behavior and is explicitly included in seal design and performance assessment. In the performance assessment methodology including FEPs, scenario development, and numerical modeling, the EDZ is among the most prominent concerns. Under repository relevant conditions anhydrite contributes significant mesoscale concerns with respect to the safety case.

Variable lithology influences the EDZ and therefore interaction between salt and nonsalt lithologies remains an important area of investigation. Quantification of the influence of inhomogeneities on mechanical response is essential for adequate comparison between bedded and domal salt. Inhomogeneities such as bedding planes and clay seams are thought to have first order effects on salt strength in repository environments. Currently, there are essentially no large-scale *in situ* measurements of shear strength of an interface in salt. The WIPP project (Munson and Matalucci 1983) proposed an *in situ* test with direct shear across a clay seam, but it was not executed. Some laboratory and computational investigations have evaluated slip along interfaces under several different stress environments. Minkley and Mühlbauer (2007) performed direct shear laboratory tests on carnallite and salt blocks under varying normal and shear loads and shear velocities, which serve as prototypes for laboratory and *in situ* tests proposed for future research.

4.2.7 Mineralogical Comparisons

Potential corrosion and degradation reactions with waste containers depend on brine composition. Brine content is an important discriminating factor for several reasons: decrepitation, fluid-aided deformational processes, corrosion, source term solubilities, and other performance assessment considerations. High temperatures and deviatoric stress states proximal to the waste will enhance dry-out of the underground opening by promoting brine liberation through the combined effects of heat and fracturing. In some extreme cases, elevated temperature in the near-field environment could give rise to local salt decrepitation in addition to stress-induced fracture. It is possible that both phenomena could have positive effects in terms of long-term performance because of the liberation and removal of brine in the native salt from the disturbed rock zone.

Brine content is a primary and well-recognized difference between bedded and domal salt and can be an important factor in the overall evolution of a salt repository. The WIPP long-term safety evaluations are highly dependent upon the availability of brine. Brine is essential to performance modeling to sustain corrosion of iron and other metals and to promote hypothetical microbial activity. In the absence of brine, a salt repository is extremely robust. There is a direct linkage between brine availability and the properties of the EDZ. Through application of engineering principles, the EDZ can be limited in extent and rapidly heal to a state approaching *in situ* permeability. Potentially, the hydraulic gradient between the far field and the excavated room is initially very high. If the permeability is high enough to allow brine flow, nearly all the brine contained in the EDZ can flow into the waste rooms. These processes are observed in underground openings at WIPP. Maximal stress differences occur immediately upon creating the opening, and therefore a near maximal extent of the EDZ is shaped, allowing the dewatering process of brine migrating down the stress gradient and evaporating into the ventilation air.

An extensive brine sampling and evaluation study was conducted in the WIPP underground for over a decade (Deal et al. 1995). The brine sampling and evaluation program adopted a mission 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. Soon after mining, geotechnical personnel noticed moist areas. Thus, it became apparent that not all brine was bound to hydrous minerals or sealed inside fluid inclusions. The clear or purer salt contained the least water by weight (0.3%), argillaceous salt contains somewhat more (1.5%) and clay by itself contains the most (>2.2%), according to Deal et al. (1995). Deal and co-workers concluded that near-field average water content for the bedded salt proximal to the WIPP disposal horizon is between 0.5 and 0.75 weight percent.

5. DISCUSSION

The goal of this write-up is to compare characteristics of bedded and domal salt as they pertain to disposal of heat-generating nuclear waste. If a nation should decide to use bedded, domal or pillow salt formations for disposal, some of the information contained here might be helpful as the site is characterized and operational schemes are evaluated against performance metrics. When science is discussed at a generic level, nagging questions of applicability remain. The question of transferability of information from different sites, widely varying tests, and analogues present interpretation challenges. Nonetheless, transferability is essential to salt science, and sound judgment will be required in site evaluations to come.

The differences between bedded and domal salt from a structural standpoint will limit design configurations and strategies, which also depend on the waste inventory. A short discussion of design attributes, including seal systems is included in this discussion section.

We close with a summary of the research agenda that applies to generic salt disposal. Laboratory methods have improved appreciably over the last 20-30 years. Primary test control parameters are exacting, providing more sophisticated data for analysis as well as the ability to probe stress space at virtually any Lode angle, to tightly control and vary temperature, and to adjust load rates or strain rates at high fidelity, all for extended periods. Constitutive model development continuously incorporates physical insights developed through testing. Close international cooperation in salt repository science has collectively identified the most valuable salt testing for immediate purposes and an overview of this research agenda is described in this section.

5.1 Transferability

Applicability of field test results between salt types is a major question. Field testing is difficult, expensive, and sometimes indeterminate because unanticipated things happen. While some results are site specific, generic observations pertain across the spectrum of salt formations. There has been a vast amount of field testing performed over the years, which helps to identify peculiar as well as similar attributes (site specific or generic).

Information derived from disposal concept mock-up, confirmation testing, seal system construction and performance testing, and operational demonstrations are transferable between salt sites. Transferability of experimental and analogue information forms a fundamental scientific tenet, and has been recognized in salt repository programs for decades. As summarized in Figure 5-1 from Kuhlman and Sevougian (2013), various field test programs at different times and places have been conducted and these shared results account for the substantial underpinning of salt properties over a wide range of applications. Proposed research, development and demonstration can further add to the scientific basis for salt disposal (e.g., see Sevougian et al. 2013; Sevougian and MacKinnon 2014), although some information will unavoidably be site specific.

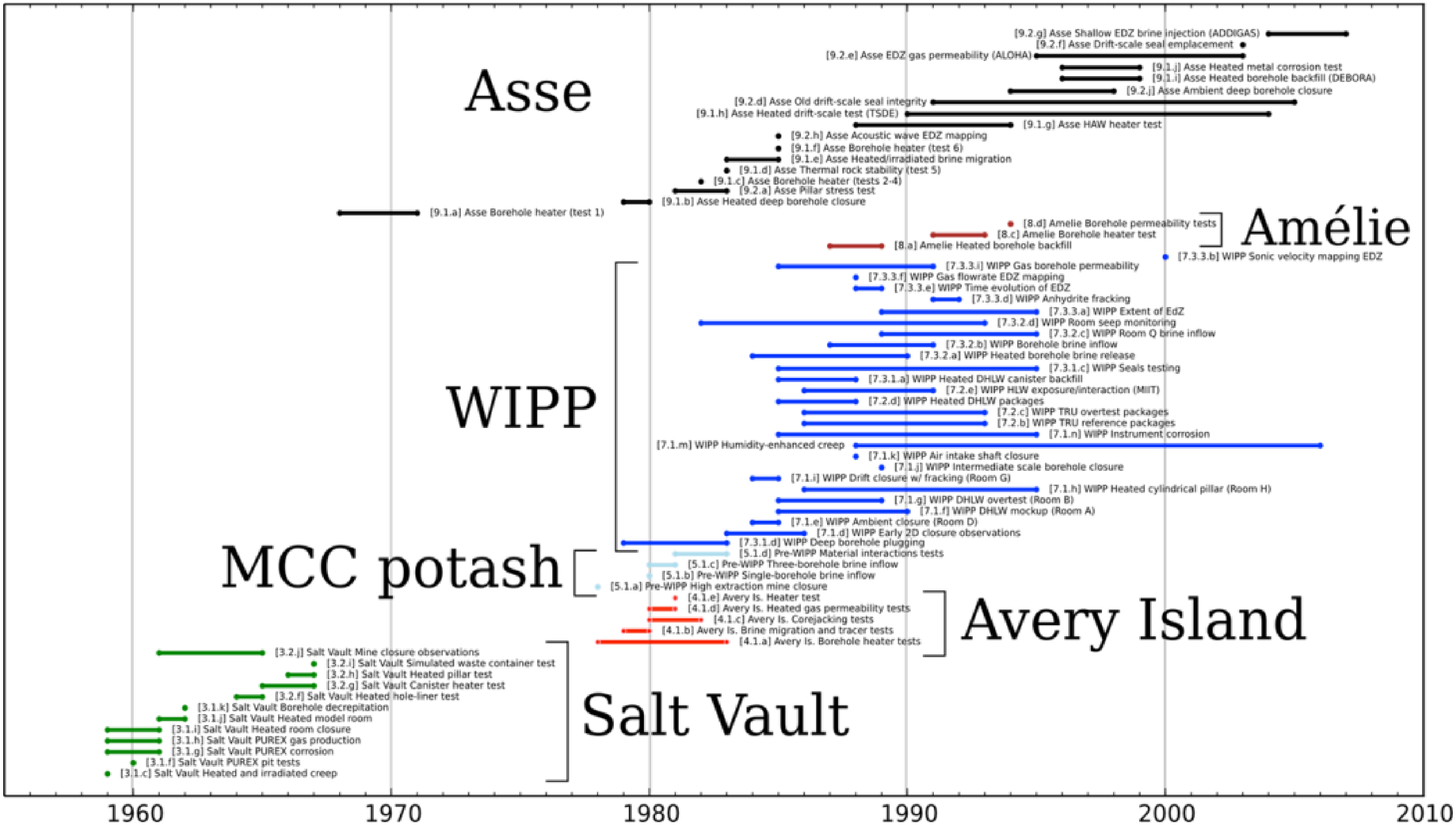


Figure 5-1. Summary of primary *in situ* salt tests.

Figure 5-1 highlights the history of in situ salt thermal tests both in the US and internationally since the 1960s. Salt repository programs have collaborated internationally for the purpose of understanding fundamental processes. Basic material properties, effects of stress and temperature, and phenomenology at a field scale are thought to be applicable and transferable between sites. The salt science community has been building the technical baseline collectively for decades, utilizing laboratory testing, code benchmarking, and field test results from many different sources.

The thermal tests at WIPP imparted a relatively modest temperature rise in a vertical borehole arrangement. These tests were primarily focused on thermomechanical response of the surrounding salt; and some of the results can be used to validate the next-generation high-performance codes over a portion of the multiphysics functionalities. Also, extensive geophysical testing of brine flow, brine chemistry, and material interactions was conducted on halite and interbeds.

Use of analogues for repository performance is predicated on transferability of information from one site to another. Analogues are used in all geologic repository programs, regardless of the geology. Considerable qualitative support for permanent isolation in salt derives from pertinent analogues. 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 Analogues over a wide range of conditions provide qualitative evidence that salt formations have the capacity to contain significant disturbance. This type of analogue information is commonly used in repository sciences and transferability of such observations is a fundamental part of the safety case.

In the end, room-scale testing in the field will include site-specific influences. Table 5-1 is a draft list of generic and site-specific issues, which hopefully will add to the dialogue.

Table 5-1. Potential generic vs. site specific issues

Generic factor	Site Specificity
Bedded and domal lithology	Bedded—heterogeneity-$CaSO_{4,}$ clay and other evaporite minerals
Mechanical behavior and deformational micromechanics	Discontinuities, bedding weakness, brittle material response
Brine	Quantity and accessibility
Disturbed rock zone creation and mitigation	Depth, size, shape and arrangement of openings Local stratigraphic controls noted for bedded salt
Seal system	Specialty concrete Mine-run salt placement with additives Other materials
Constitutive models	Thermomechanical flow-law parameters calibrated for specific site
Disposal concept	Mining dimensions with depth and lithology considerations
Geomechanics modeling—coupling	Local stratigraphic controls

5.2 Design Attributes

Based on what we know today, there is little doubt that either bedded or domal salt could function well as a nuclear waste repository. Both geologic settings provide ample area for lateral expansion, and either setting could accommodate vertical dimensionality, such as borehole disposal or multiple levels. Some characteristics of a chosen site will be unique, but can be readily evaluated against a wealth of existing information. Tools and techniques are equipped for site characterization, operational concept design, analysis, and performance evaluation.

The historically demonstrated difficulty with consent-based siting suggests it may be reasonable to consider a single, large repository for the US. In consideration of this particular option, bedded salt provides advantages that promote safety by design while substantial mining experience aids in configuring the architecture for operational concepts.

Bedded salt formations in the US exist in enormous dimensions, as illustrated in Figure 5-1. Many well-known salt repository investigations, such as Project Salt Vault in Kansas, the Civilian Waste Program created by the Nuclear Waste Policy Act of 1982 in the Pala Duro Basin in the Texas Panhandle, and the WIPP itself in the Delaware Basin are situated in the greater Permian Basin, which measures 800 kilometers east-west and 1600 kilometers north-south. Thickness of the Permian salt is considerable, amounting to 600 meters in the area of WIPP and a similarly functional thickness in the Palo Duro Basin, some 400 kilometers distant. Lateral dimensions of a salt repository would be an infinitesimally small portion of such vast dimensions. The point is, lateral dimensions of a salt formation allow operational areal design to extend outwardly.

Salt domes provide impressive areal expressions combined with great vertical dimensions often comprising relatively pure salt compared to bedded formations. Construction and disposal concepts can be considered at multiple levels in a dome. Borehole disposal, for example, might be more predictable in a dome than a similar strategy in bedded salt because of its clay and anhydrite layering.

Immense lateral dimensions of many bedded salt formations open the consideration of a single, long-term repository. The possibility of modular build and close (Gadbury and Hansen 2016) would allow individual sections of the mega-repository to be licensed and closed. Once closed, individual modules would no longer be accessible by workers, no maintenance would be required, and electricity and ventilation would be discontinued.

The geologic setting of domes is notably more complicated than flat-lying salt formations. Large-scale modeling would require detail and characterization of the geology surrounding domes, which is less challenging (perhaps) for bedded formations because of horizontal layering at shallow dip and continuity over large horizontal dimensions. Gridding, modeling, and boundary conditions are simpler for bedded salt and introduce less uncertainty than experienced with the 3-dimensionality of domal structures.

In either bedded or domal salt repositories, the most important consideration after the geologic formation itself is the sealing system. In this respect, both formations have equally high possibilities for geotechnical barriers made of crushed salt that can be engineered to become impermeable during the operational period of a repository. There is persuasive evidence that granular salt reconsolidation can be enhanced by improved construction techniques and use of additives. These developments have significant implications for future salt repository operations and licensing. The EDZ may affect the isolation properties of seal systems. In investigating the evolution of the EDZ and its impact on the post-closure safety it is recommended to focus on enhancement of the understanding of the influence of the EDZ on seal systems.

5.3 Closing Remarks

A cross-section of the geomechanics issues has evolved and comprises the most valuable future direction for salt R&D. Material parameters need to be known sufficiently for implementing the model-based theoretical approaches. An approach combining salt testing and constitutive modeling was developed during international benchmark modeling of WIPP Rooms B & D. Extending these models forward requires basic understanding of safety-relevant impacts and processes as well as their description captured in constitutive relations. The forward-looking project called WEIMOS (Section 3.1) implements a repository research agenda generally applicable to any salt formation.

Model calculations are performed in all stages of repository development, starting with dimensioning of underground openings for the concept of disposal. Planning and construction require an ability to evaluate stability during operations as well as to guide seal system construction. Finally, modeling is necessary to provide a persuasive of long-term integrity against a release into the biosphere. Reliable long-term predictions require well-vetted constitutive models and computer-based simulation procedures.

International collaboration has identified conditions for further testing. To date, German research centers have performed more than 140 tests on WIPP bedded salt, which augment the previous database developed for the Compliance Certification Application. In addition, test results are compared to extensive databases developed for Asse and Gorleben domal salts. The research agenda specifically addresses tests under low deviatoric states of stress, tests that evaluate damage and healing, tensile deformation and behaviour of inhomogeneities. This research agenda has received approval of the German ministry. A large shipment of WIPP core has been sent to Germany for these tests.

The search for a location of a repository for high-level radioactive waste in Germany is open again. Flat-bedded deposits of salt occur in sufficient thickness in regions of Germany to be considered as a repository site. A firm understanding of the approach to develop a safety case helps focus salt repository research to the most vital activities. Within the framework of the already existing US/German cooperation, FEP databases for rock salt are being enlarged to differentiate between salt domes and bedded salt formations. Salt repository investigations comparing disposal options are progressing positively by virtue of international collaborations. By combining international know-how on several venues (NEA Salt Club, US/German Workshops, KOSINA, WEIMOS, and many informal efforts) the involved nations multiply benefits at cost advantage, while ensuring research is conducted on the most important questions.

A repository for heat-generating nuclear waste provides an engineering challenge beyond general experience. Long-term evolution of repository performance is precluded from direct observation or measurement. Therefore, analogues and long-term predictions are necessary to establish enduring safety functions. Accurate prediction of salt repository response is enhanced by a thorough understanding of the mechanistic processes and application of valid models. In the instance of a salt formation providing the host medium, the scientific community has made progress toward formulating and using models that capture observed physical phenomena in computational mechanics applications.

This brief has presented a cross-sectional comparison of bedded and domal salt in the context of HLW disposal. Salt has many positive attributes for disposal and these characteristics are common among salt formations. Salt repository R&D builds on industry practices and operating facilities in both bedded and domal salt—including WIPP, Morsleben, Asse, Herfe-Nerode, and others. Ongoing collaboration has shaped the research agenda to which several entities lend their expertise. If and when a consent-based site is identified, the technical basis for a salt repository stands ready—regardless of whether the formation is bedded or domal.

6. REFERENCES

Argüello, J. G. 2014. *Results from the US-German Benchmark Initiative for FY14*. SAND2014-18272 R. Sandia National Laboratories, Albuquerque NM.

Bauer, S.J. and S.T. Broome. 2010. *Revised Results for Geomechanical Testing of MRIG-9 Core for the Potential SPR Siting at the Richton Salt Dome*. SAND2010-0658. Sandia National Laboratories, Albuquerque NM.

BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit). 2010. *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste*. Federal Ministry for the Environment. Nature Conservation and Nuclear Safety (BMU, now BMUB). Bonn, Germany.

Bollingerfehr, W., W. Filbert, C. Lerch, P. Herold, N. Müller-Hoeppe, F. Charlier, and R. Kilger. 2013. *Technical Design and Optimization of a HLW-Repository in the Gorleben Salt Dome including Detailed Design of the Sealing System*. WM2013 Proceedings. Phoenix, AZ.

Bornemann, O., J. Behlau, R. Fischbeck, J. Hammer, W. Jaritz, S. Keller, G. Mingerzahn, and M. Schramm. 2011. *Description of the Gorleben Site. Part 3: Results of the Geological Surface and Underground Exploration of the Salt Formation*. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), ISBN 978-3-9813373-6-5, Hannover, Germany.

Bracke, G. and K. Fischer-Appelt. 2013. *Overview on the Preliminary Safety Analysis of the Gorleben Site.* WM2013 Proceedings. Phoenix AZ USA.

Bradshaw, R.L. and W.C. McClain. 1971. *Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Waste in Underground Salt Mines*. Oak Ridge National Laboratory Report 4555.

Corbet, T.F. 2000. *A Groundwater-basin Approach to Conceptualize and Simulate Post-Pleistocene Subsurface Flow in a Semi-arid Region, Southeastern New Mexico and Western Texas, USA*. Hydrogeology Journal 8.3: 310-327.

Collaborative Project I. 2004-2006. *The Modeling of the Mechanical Behavior of Rock Salt: Comparison of Current Material Laws and Practices.* FKZ 02C1004 to 1054. Collaborative project II. 2007-2010. *Comparison of Current Material Laws and Practices Based on 3D Model Calculations for Long-Term Mechanical Behavior of Real Underground Structures in Rock Salt*. FKZ 02C1577 to 1617. The current Joint Project III. 2010-2016. *Compare Current Constitutive Models and Practices Based on Model Calculations for Thermo-Mechanical Behavior and the Healing of Rock Salt.* Collaboration of the project partners Dr. Hampel, TU Clausthal, IfG Leipzig, KIT Karlsruhe, University of Hannover, TU Braunschweig (FKZ 02E10810 02E10860 up) and Sandia National Laboratories (USA).

Deal D.E., R.J. Abitz, D.S. Belski, J.B. Case, M.E. Crawley, C.A. Givens, P.P. James Lipponer, D.J. Milligan, J. Myers, D.W. Powers and M.A. Valdivia. 1995. *Brine Sampling and Evaluation Program 1992-1993 Report and Summary of BSEP Data since 1982*. DOE-WIPP 94-011. et al 1995

Department of Energy. 1984a. *Draft Environmental Impact Statement*. DOE-800401-B9.

Department of Energy. 1984b. *Identification of Sites within the Palo Duro Basin: Volume 1—Palo Duro Location A.* DOE/CH-10(1).

Freeze, G., P. Mariner, J. Houseworth, and J.C. Cunnane. 2010. *Used Fuel Disposition Campaign Features, Events, and Processes (FEPs): FY10 Progress Report.* SAND2010-5902. Sandia National Laboratories, Albuquerque, NM.

Gadbury, C., and F. D. Hansen. 2016. *Reconsolidated Salt as a Geotechnical Barrier*. Waste Management 2016 Conference. Phoenix, AZ. SAND2015-9936C. Sandia National Laboratories, Albuquerque, NM.

Günther, R.-M., K. Salzer, T. Popp, and C. Lüdeling. 2014. *Steady State Creep of Rock Salt - Improved Approaches for Lab Determination and Modeling to Describe Transient, Stationary and Accelerated Creep, Dilatancy and Healing.* 48th U.S. Rock Mechanics Symposium Proceedings. Minneapolis MN USA.

Hammer, J. 2016. *Personal Communication*. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany.

Hansen, F.D. 1987. *Physical and Mechanical Variability of Natural Salt*. Bulletin of the Association of Engineering Geologists. Vol. XXIV, No. 2.

Hansen, F.D., W. Steininger, and W. Bollingerfehr. 2016. *6th US/German Workshop on Salt Repository Research, Design and Operation. Chapter 2: Salt Repository Research Agenda* by T. Popp, W. Minkley, S. Fahland, J. Hammer, A. Hampel, K.-H. Lux, N. Müller-Hoeppe, J. Stahlmann, C. Missal, K. Wieczorek and F. Hansen. SAND2016-0194. Sandia National Laboratories, Albuquerque, NM.

Hansen, F.D. and T. Popp. 2015. *Geomechanics Issues Regarding Heat-Generating Waste Disposal in Salt*. 49th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA. SAND2015-1234C. Sandia National Laboratories, Albuquerque, NM.

Holdoway, K. 1974. *Behavior of Fluid Inclusions in Salt during Heating and Irradiation.* Fourth International Symposium on Salt—Northern Ohio Geological Society.

Holt R.M. and D.W. Powers. 1990. *Geologic Mapping of the Air Intake Shaft at the Waste Isolation Pilot Plant.* DOE/WIPP 90-051.

Johnson, K., and S. Gonzales. 1978. *Salt Deposits in the United States and Regional Geologic Characteristics Important for Storage of Radioactive Waste*. Y/OWI/SUB—7414/1.

Kock, I., J. Larue, H. Fischer, G. Frieling, M. Navarro and H. Seher. 2013. *Results from One- and Two- Phase Fluid Flow Calculations within the Preliminary Safety Analysis of the Gorleben Site*. WM2013 Proceedings. Phoenix, AZ. WM-13310.20

Kuhlman, K.L. and B. Malama, 2013. *Brine Flow in Heated Geologic Salt*, SAND2013–1944. Sandia National Laboratories, Albuquerque, NM.

Kuhlman, K.L. and S.D. Sevougian, 2013. *Establishing the Technical Basis for Disposal of Heat-Generating Waste in Salt*. FCRD-UFD-2013–000233, SAND2013–6212P. Albuquerque, NM: US Department of Energy, Used Nuclear Fuel Disposition Campaign.

Kuhlman, K.L. 2014. *Summary Results for Brine Migration Modeling Performed by LANL, LBNL, and SNL for the Used Fuel Disposition Program*, FCRD-UFD-2014–000071, SAND2014–18217R. Albuquerque, NM: US Department of Energy, Used Nuclear Fuel Disposition Campaign.

Minkley, W. and J. Mühlbauer. 2007. *Constitutive Models to Describe the Mechanical Behavior of Salt Rocks and the Imbedded Weakened Planes. The Mechanical Behavior of Salt: Understanding of THMC Processes in Salt.* Wallner, M., K-H Lux, W. Minkley, H.R. Hardy, editors. Taylor and Franics/Balkema, Leiden, The Netherlands.

Munson, D.E., A.F. Fossum, and P.E. Senseny. 1989. *Advances in Resolution of Discrepancies between Predicted and Measured in situ WIPP Room Closures*. SAND88-2948, Sandia National Laboratories, Albuquerque, NM.

Munson, D.E., K.L. DeVries, and G.D. Callahan. 1990. *Comparison of Calculations and in situ Results for a Large, Heated Test Room at the Waste Isolation Pilot Plant (WIPP)*. In Rock Mechanics Contributions and Challenges, Proceedings of the 31st U. S. Symposium on Rock Mechanics, eds. Hustrulid & Johnson, 389-396, Rotterdam: Balkema.

National Academy of Science. 1957. *Disposal of Radioactive Waste on Land*. Publication 519.

NEA. 2013. *Natural Analogues for Safety Cases of Repositories in Rock Salt*. Salt Club Workshop Proceedings. Braunschweig, Germany. NEA/RWM/R (2014)10.

US NRC. 2008. *10CFR Part 51 Federal Register***.** Vol. 73, No. 197. Proposed Rules page 59555**.**

Olander, D.R. 1982. *A Model for Brine Migration and Water Transport in Rock Salt Supporting a Temperature Gradient*. Nuclear Technology.Vol: 58:2.

Pigford, T. H. 1981. *Migration of Brine inclusions in Salt*. Radioactive Waste Management Nuclear Technology, Vol. 56.

Popp T. W. Minkley, S. Fahland, J. Hammer, A. Hampel, K.-H. Lux, N. Müller-Hoeppe, J. Stahlmann, C. Missal, K. Wieczorek, and F. Hansen. 2016. *Salt Repository Research Agenda*. (US/German Workshop website: http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/usgerman-workshop-on-salt-repository-research-design-and-operation/.

Rath, J. S. and J. G. Argüello. 2012. *Revisiting Historic Numerical Analyses of the Waste Isolation Pilot Plant (WIPP) Room B and D in situ Experiments Regarding Thermal and Structural Response*. SAND2012-7525. Sandia National Laboratories, Albuquerque, New Mexico.

Salzer, K., R.-M. Günther, W. Minkley, D. Naumann, T. Popp, A. Hampel, K.-H. Lux, K. Herchen, U.,Düsterloh, J. G. Argüello, and F. D. Hansen. 2015. *Joint Project III on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt - II. Extensive Laboratory Test Program with Clean Salt from WIPP*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Sevougian, S. D. and R. J. MacKinnon. 2014. *A Decision Methodology for Prioritizing R&D Supporting Geologic Disposal of SNF/HLW in Salt – 14030*, Proceedings of the WM2014 Conference, Phoenix, Arizona USA.

Sevougian, S. D., R. J. MacKinnon, B. A. Robinson, C. D. Leigh, and D. J. Weaver. 2013. *RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes*, FCRD-UFD-2013-000161, Rev. 0, SAND2013-4386P, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C.

Sevougian S.D., G. Freeze, M. Gross, J. Wolf, J. Mönig, and D. Buhmann. 2015. *Generic Salt FEPs Catalogue, Volume II*. Sandia National Laboratories, Waste Isolation Pilot Plant.

Shefelbine, H.C. 1982. *Brine Migration: A Summary Report*. SAND82-0152. Sandia National Laboratories, Albuquerque, NM.

Sobolik, S.R. 2014. *Case Study of the Impact of Prior Cavern Abandonment on Long-Term Oil Storage at a Strategic Petroleum Reserve Site*. In Proceedings of the 48th U.S. Rock Mechanics Symposium, ARMA 14-7002, Minneapolis, Minnesota.

Sobolik, S.R. 2016. *Implementation of a Full-Dome, Sonar-Based Finite Element Geomechanical Model to Analyze Cavern and Well Stability at the West Hackberry SPR Site*. In Proceedings of the 50th U.S. Rock Mechanics Symposium, ARMA 16-320, Houston, Texas.

Sobolik, S.R. and B.L. Ehgartner. 2009. *Analysis of Cavern Stability at the Bryan Mound SPR Site*, SAND2009-1986. Sandia National Laboratories, Albuquerque, New Mexico.

Sobolik, S.R. and B.L. Ehgartner. 2012a. *Analysis of the Stability of Cavern 3 at the Bryan Mound SPR Site*, SAND2012-1953. Sandia National Laboratories, Albuquerque, New Mexico.

Sobolik, S.R. and B.L. Ehgartner. 2012b. *Structural Integrity of Oil Storage Caverns at a Strategic Petroleum Reserve Site with Highly Heterogeneous Salt and Caprock*. In Proceedings of the 46th U.S. Rock Mechanics Symposium, ARMA 12-189. Chicago, Illinois.

Stein, C.L. 1985. *Mineralogy in the Waste Isolation Pilot Plant (WIPP) Facility Stratigraphic Horizon*. SAND85-0321. Sandia National Laboratories, Albuquerque, New Mexco.

Weizorek K. and Zimmer, U. 1999. *Hydraulic Behavior of the Excavation Disturbed Zone around Openings in Rock Salt.* Proceedings: Seventh International Conference on Radioactive Waste Management and Environmental Remediation. ICEM. Nagoya, Japan.