

564594



Operated for the U.S. Department of Energy by the  
**Sandia Corporation**  
Defense Waste Management Programs  
4100 National Parks Highway  
Carlsbad, New Mexico 88220

Date: August 24, 2015

To: WIPP Records Center

From: F. D. Hansen, 6910

A handwritten signature in black ink that reads "F. D. Hansen".

*Technical Review:* Courtney Herrick

*QA Review:* Shelly Nielsen

*Management Review:* Christi Leigh

Subject: **Milestone INT-15-02: A Synthesis of Salt Reconsolidation Analogues**

### Abstract

Use of nature's laboratory for scientific analysis of complex systems provides a resource to understand long-term disposal of nuclear waste in salt. Salt as a geologic medium has several attributes favorable to long-term isolation of material placed in mined openings. Salt formations are largely impermeable and induced fractures heal. Permanent isolation also depends on our ability to construct geotechnical barriers that achieve high-performance characteristics attributed to the native salt formation. Crushed salt is commonly used as backfill in operating mines for structural and sealing purposes. In a similar fashion, salt repository seal concepts have often included elements of reconstituted granular salt. Recent studies of run-of-mine crushed salt performance characteristics have revealed significant enhancement by judicious use of additives. A lingering uncertainty with geotechnical barriers constructed of granular salt pertains mostly to the limits involved with testing over extended time periods and at an appropriately large scale. To strengthen the technical basis for salt seal systems, natural and anthropogenic analogues can be used to illustrate cases where salt reconstitutes itself into an impermeable medium. Invoking analogue examples provides an independent line of reasoning to safety case performance arguments.

Scientific aspects of salt reconsolidation have been studied extensively. Highlights of the state of knowledge are summarized here to add to the synthesis of reconsolidation analogues as well as to introduce forward-looking applications for salt repository science. Geotechnical barrier performance is strengthened by recent experimental findings and analogue comparisons. Our current knowledge and expected outcome of research can be assimilated with lessons learned to put forward designs and operational concepts for the next generation of salt repository considerations. Mined salt repositories have the potential to isolate permanently vast inventories of radioactive wastes. Advantage can be realized by these developments, leading to innovative operational concepts that embody safety-by-design.

WIPP: 4.4.2.4.1:TD: QA-L: 564593

**Information Only**

## 1.0 Introduction

This report draws in analogues of salt consolidation as part of a safety case for salt disposal of radioactive waste. Multiple lines of reasoning are typically used to establish safety case arguments with the regulatory agency in a framework of governing licensing criteria. Information put forward in this document pertains to geotechnical seal systems of which the primary seal function is achieved by reconsolidating crushed salt, with or without additives. Salt reconsolidation is integral to performance assessment of the Waste Isolation Pilot Plant by its function in the shaft seal system. Now that WIPP panel closures include run-of-mine salt components, reconsolidation of granular salt is an important consideration in horizontal configurations as well. International salt repository programs have exerted long-term research efforts to understand and quantify reconsolidation and attendant permeability characteristics. In addition to specific research and development efforts, industrial mining practice often involves backfilling, which provides large-scale response analogous to repository applications. Natural geologic and anthropogenic settings also provide relevant analogues for assessment of permeability reduction as a function of granular salt consolidation.

*Why are we still studying granular salt consolidation?* There is overwhelming evidence from laboratory tests and natural analogues demonstrating that disaggregated salt readily consolidates into an impermeable solid under a wide range of modest stress and temperature conditions. However, a key uncertainty in the otherwise strong empirical evidence is the lack of controlled intermediate-scale tests and demonstrations at the size of operational drifts. Without functional demonstrations at appropriate scale and under controlled or known state variables, we are left with calculations of performance objectives using models. Though modeling serves many practical purposes, the nature of prediction inherently introduces an element of uncertainty. In the regulatory environment, solid experimental demonstration of performance is more persuasive and convincing to stakeholders than prediction of performance at some far-off future date. Therefore, an active area of international research in salt repository programs in Europe and the United States (USA) is enhanced performance of operational period seal systems. Residual uncertainty can be significantly reduced and perhaps overcome if geotechnical functionality can be achieved during the operational period. Enhanced performance during operations could allow systematic geotechnical measurements as part of a performance confirmation program to further improve the salt repository technical basis. Analogues provide an additional avenue to approach safety case arguments for salt consolidation.

Generally, analogues are imperfectly matched to safety case circumstances, thus critical review and evaluation are required to ensure proper application. Analogue processes occur over a range of spatial and temporal scales, which must be objectively interpreted to discern pertinent information. Analogues come in different varieties, such as industrial, operational, natural, anthropogenic and negative analogues (where aggressive conditions remove archaeological evidence). Analogues often involve an “end product” where characteristics such as density, permeability, and porosity have evolved through time and under conditions that may have departed from expected repository environments. In this synthesis, analogue information regarding crushed salt consolidation is intended to bolster existing technical bases for evolving characteristics of room backfill and performance of plugs and seals.

This synthesis will be laid out in a sequence that starts with a general discussion of how crushed salt is used in practice and in a repository (2.0 Applications). The subsequent section (3.0

Consolidation Processes) explains the mechanisms by which granular salt reconsolidates. Section 4 (Analogues) describes analogue examples that have relevance to the salt repository performance. Section 5 (Future Directions) recommends a research agenda that will explore some of the issues described in the main body and concludes with a description of how this body of knowledge can be leveraged to develop salt repositories of enormous potential.

## 2.0 Applications

Elimination of radionuclide release includes interplay of the geological formation and geotechnical barriers. Radionuclide release scenarios are almost always modeled by discretizing and assigning parameters to the host formation and the geotechnical barrier, and incorporating a flow-and-transport model. Aspects of the host rock can be engineered to a certain extent by controlling the size and shape of the room, for example, or mitigating damaged zones before the geotechnical barrier is built. By contrast, the engineering barrier, as its name implies, can feature significant engineering to achieve performance specifications. Functional improvement of barriers containing crushed salt remains an active research and development (R&D) goal in salt repository programs. Some of the discussion of analogues in this paper illustrates how characteristics of an engineered barrier can be strikingly improved. One of the recognized “best practices” in repository safety cases is based on use of multiple lines of reasoning (NEA 2014). Therefore, in addition to models, an important line of reasoning for improving repository system understanding is the use of natural or anthropogenic analogues.

After the formation itself, seal systems are the most important design element for prevention of migration of disposed nuclear waste to the accessible environment. Design, analysis and performance assessment of potential salt repositories for heat-generating nuclear waste require knowledge of thermal, mechanical, and fluid transport properties of reconsolidating granular salt. Reconsolidation of granular salt has long been recognized as a fundamental element of seal systems and backfilling of salt repositories. In addition to mechanical and thermal properties, the most essential phenomena pertain to permeability as a function of porosity. The fact that disaggregated salt can be reconstituted to characteristics nearly equivalent to native salt has been widely demonstrated. However, for repository applications, the overriding concerns are how soon, under variable conditions, does reconsolidating salt attain desirable performance characteristics. Here we will emphasize reconsolidation in the sense of seal system performance; however, slurry placement of room backfill is another analogue application.

There are many analogues for geotechnical barriers, which include materials other than reconsolidating granular salt (Noseck & Wolf 2013). In addition to barriers containing a salt element, several other systems have been designed and tested. Stahlmann et al. (2015), Mauke (2013), Bollingerfehr et al. (2013), and others discuss and demonstrate geotechnical barriers comprising clay, salt concrete, Mg concrete, salt blocks, bitumen, and other promising engineering materials. An elaboration of salt repository sealing options would be a worthy compendium to assemble as a collaboration report between the USA and European salt communities. Such international outreach could serve as a resource document for years to come, perhaps published under the auspices of the Nuclear Energy Agency (NEA) Salt Club and other international venues. However, the full spectrum of geotechnical barriers is beyond the scope and intent of this report, which emphasizes analogue evidence for salt reconsolidation applied to salt repository seals.

Reconsolidation of granular salt is of high interest in the USA and Germany, countries actively collaborating in salt repository research, design, and operation (Hansen et al. 2015). The realm of salt consolidation for heat-generating nuclear waste disposal includes routine room backfill for structural stability, engineered systems to affect low-permeability seal capability relatively quickly, and higher-temperature environments near waste canisters. In almost all applications using crushed salt in the field, the most important characteristics are those that obtain at low porosity and attendant low permeability.

Crushed or granular salt reconsolidation will play an important role if a salt formation is selected for permanent isolation of heat-generating nuclear waste. In the salt disposal concept, crushed salt is naturally the most suitable backfill material. Crushed salt is readily compacted and reconsolidated. Through appropriate construction techniques, granular salt can be placed in a condition favorable to evolving thermal, mechanical, and hydrological properties approaching those of the undisturbed surrounding rock salt. Reuse of mined salt in the underground facility provides operational efficiency, reduces hoisting, and optimizes material transport logistics. Depending on the closure concept of the respective repository, the main functions of reconsolidating salt as backfill and seals are

- Restrict groundwater flow
- Limit hazardous constituent release pathways via drifts and shafts
- Conduct heat generated from the waste to the host rock
- Protect structural integrity of repository excavations
- Provide low permeability and/or diffusivity and/or long-term retardation.

Other considerations include availability of construction material and mechanical and chemical compatibility with the host salt formation.

Arguments from analogue studies can be important to support statements that the hydraulic resistance of geotechnical barriers is high enough for the required time frame to avoid water flow into a salt repository. Additionally, analogues demonstrating compaction of crushed salt leading to low porosities and permeabilities are of high relevance for the safety case (Noseck & Wolf 2013). Understanding and predicting reconsolidation behavior of granular crushed salt is essential to backfilling or sealing nuclear waste repositories in salt. Significant research efforts have addressed this recognized need for many years resulting in a long history of crushed salt backfill testing for salt repository applications. A preponderance of these studies focused on room temperature experiments, with only a few tests conducted at elevated temperatures.

Applications emphasized here pertain to seal systems and backfill within salt repositories for nuclear waste, which embody large-scale construction and long-term performance. Analogues provide useful long-term, full-scale anecdotal information, which confirm reconstitution of granular salt or slurry to mechanically viable solids that can attain characteristics of low porosity and low permeability. In repository applications, understanding and quantifying attainment of performance specifications are vital to demonstrate regulatory compliance.

### 3.0 Consolidation Processes

*How does salt reconsolidate?* To assist in evaluation of analogues, it is useful to review the basics of this question. Disaggregated granular material such as crushed salt contains 35-40% porosity. Quasi-static consolidation processes at high porosity involve cataclastic flow, translational sliding, rigid body rotation, and grain breakage. These predominantly mechanical processes remove void space by grain rearrangement. As porosity decreases, mechanical compaction no longer effectively reduces void space as grain-to-grain contact area increases. Further consolidation is enabled by grain boundary processes and by dislocation motion, which accounts for crystal shape changes.

For purposes of salt repository applications and related industrial functions, micromechanical mechanisms during late stages of consolidation are the most relevant. It is well understood that brittle consolidation processes usually accompany construction practices. Dynamic compaction, for example, tends to pulverize grains during construction. A desired outcome of construction is to place geotechnical barrier material at an initial condition of low porosity, which minimizes the time between placement and functionality.

Salt reconsolidation mechanics have been investigated by means of several experimental procedures over time, with increasing sophistication and test parameter control. Improvements in laboratory techniques as well as test-to-test comparisons have enabled a more complete analysis of test data and understanding of the consolidation processes than possible earlier. Interpretation of the effects of temperature, stress, moisture, and test techniques is basic to decipher laboratory results to repository-relevant applications. This section presents information and microphotographs of consolidation mechanisms, illustrates effects of engineering additives, and lays the ground work for evaluating analogues.

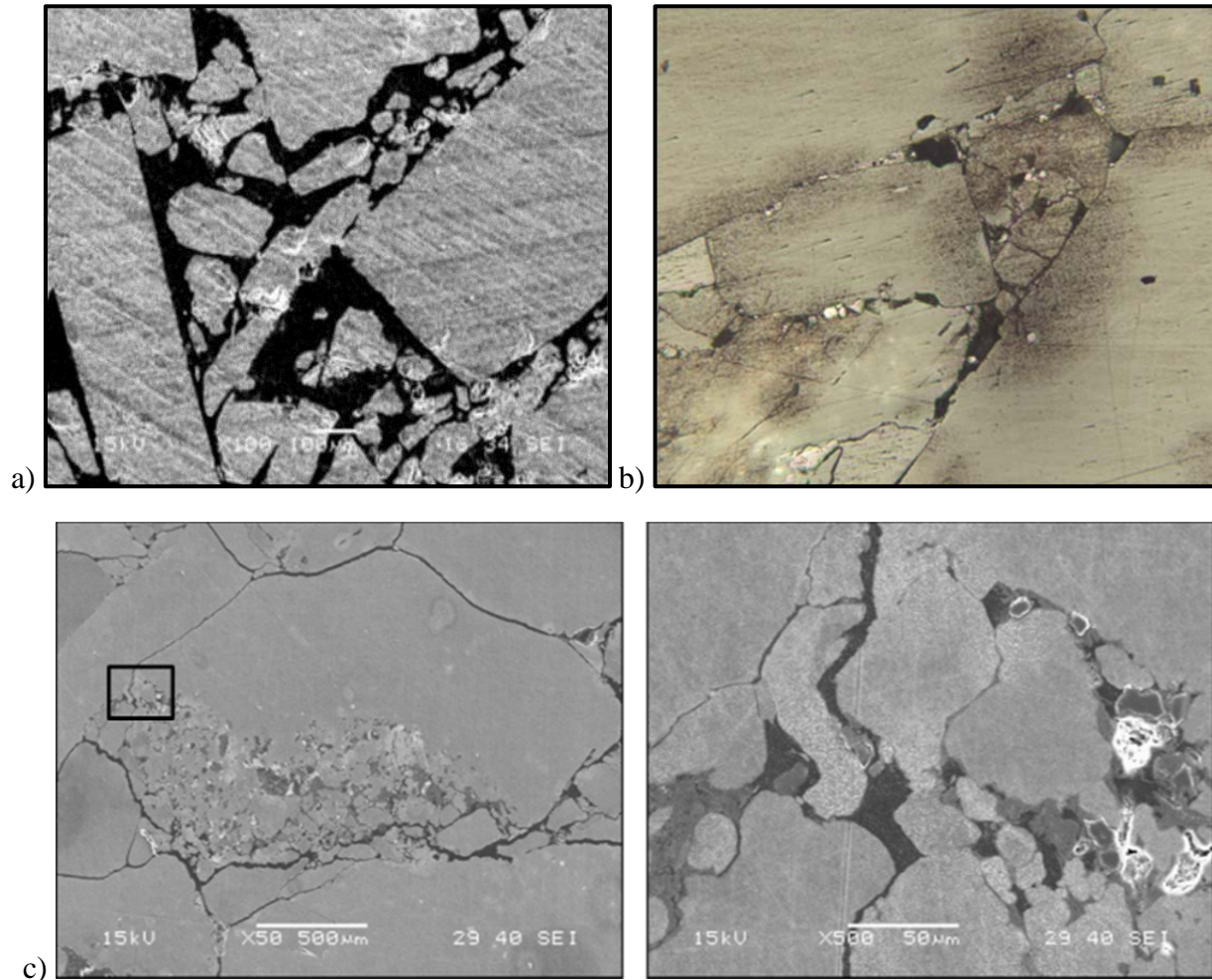
#### 3.1 Observational Techniques

Reconsolidation processes are determined by microscopic observations. Samples from many sources, including analogue sites and laboratory consolidation are cut, polished, and conditioned to facilitate microscopic examination. A variety of subsamples can be prepared for observational work, such as polished 5-mm thick petrographic sections, etched cleavage chips, and freshly broken surfaces. Substructure can be highlighted by etching techniques whereby the sample is agitated in a solution of methanol saturated with  $\text{PbCl}_2$  for a few seconds and stopped by submersion in butanol. Identification and documentation of consolidation processes are inferred from optical and scanning electron microstructural observations.

Examples in Figure 1 include representative stages of progressive consolidation processes from high porosity to low porosity (Hansen et al. 2015). Figure 1a is taken from the large-scale BAMBUS II field test (Bechthold et al. 2004) and depicts brittle cleavage fracture and translational sliding at 25% porosity. In practice, this substructure represents a relatively early stage of reconsolidation of granular salt that was placed in situ by pneumatic stowing. Figure 1b is another analogue sample from a room that was back-filled with salt slurry. The cubic habit exemplifies brittle cleavage fracture; fine particles result from pulverization along grain boundaries; well meshed grain boundaries are achieved through pressure solution. Figure 1c is taken from a thin-sectioned laboratory sample that was consolidated at 250°C to a normalized



density of 0.93. It exemplifies well sutured grain boundaries in the larger view (left) and extensive plastic deformation of individual grains at higher magnification (right).

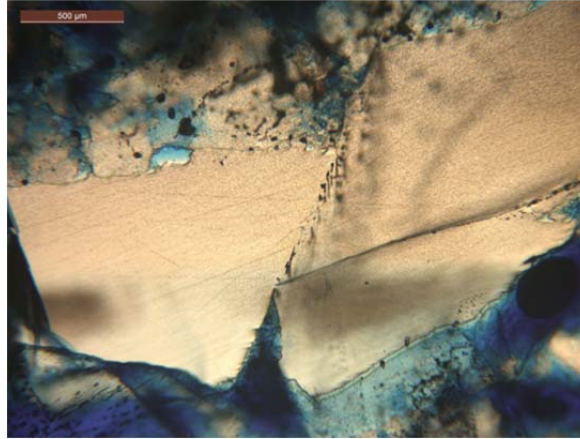


**Figure 1. Examples of consolidation processes from high (a) to low (c) porosity.**

### 3.2 Moisture Effects

Consolidation processes depend on both external and internal conditions. Variables include stress state, instantaneous porosity, deformation rate, temperature, water content, and other potential additives. In the setting of a salt geotechnical barrier, stress conditions are imparted by creep closure of the surrounding formation. In repository applications, most granular salt reconsolidation will occur at ambient temperature, although thermal effects will become important in some disposal situations, such as annulus backfilling around heat-generating waste canisters. As porosity diminishes, an increasing number of grain surfaces are brought into contact. Spiers & Brzesowsky (1993) described effects of moisture on the contact surface under these conditions as grain boundary diffusional pressure solution and plasticity-coupled pressure solution set up by a diffusive flux of solutes from the contact area to the free pore surface. Figure 2 is an example of dislocation creep operating in concert with pressure solution processes. This photomicrograph was taken from a 5mm-thin sectioned sample, which was consolidated in the laboratory to a fractional density of 97%. The horizontal, undulatory grain boundary on the left

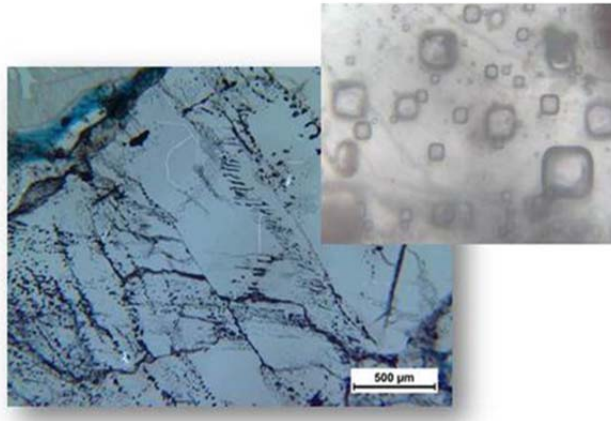
side of the micrograph exhibits pressure-solution and re-deposition. In the center, crystal plasticity shapes the grain such that the tip molds into the grain boundary intersection; this deformation couples with pressure solution that moves mass along the boundaries as the grains fuse together. The grain boundary is decorated with fluid inclusions. In addition, the tightly sutured grain boundary on the lower right benefits from alignment between grains and pressure solution transport outward to the right as the boundary heals. Note the last vestiges of cubic inclusions along the healing boundaries.



**Figure 2. Grain boundary pressure solution processes.**

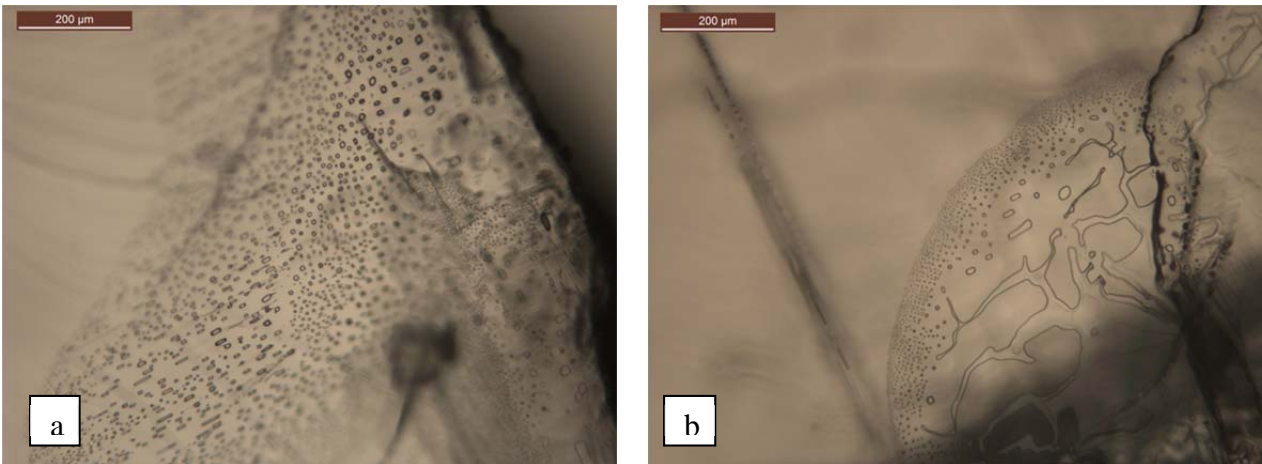
Grain distortion provides evidence of extensive dislocation creep (Hansen et al. 2015). Individual grains exhibit internal plastic deformation, including small subgrain sizes, consistent with high stress levels. In experiments using run-of-mine salt from a bedded formation, it appears crystal plasticity facilitates movement of internal fluid inclusions to grain boundaries whereupon pressure solution re-deposition processes actively consume smaller grains. Micromechanical processes are likely to be influenced by temperature, confining pressure, and impurities, but are most strongly dependent on the presence of sufficient water at grain boundaries to enable solution-precipitation phenomena. Therefore, a key question regarding consolidation concerns the availability of brine on grain boundaries.

The deformed crystal in Figure 3 captures motion of internal fluid inclusions on  $\{110\}$  planes and tightly closed grain boundaries. The blue hue is caused by epoxy impregnation from sectioning process. Fluid inclusions tend to collect along tight grain boundaries, as might be expected as the fluid itself promotes healing. The high degree of mobility of the inclusions can be witnessed in the lower left micrograph by the dark lineations at an angle to the grain boundaries (presumably along  $\{110\}$  planes). The upper insert is a generic photograph of fluid inclusions in native bedded salt. Observations such as documented in Figure 3 suggest that fluid inclusions can migrate to grain boundaries by virtue of glide and translational distortion of the crystalline structure.



**Figure 3. Trails of fluid inclusions in deformed grain (insert of undeformed inclusions).**

Run-of-mine bedded salt from WIPP contains ample moisture to support densification processes at the grain boundaries. Domal salt is also considered viable for nuclear waste disposal. It is therefore informative to compare domal salt internal water content. Because of diapiric rise and multiple episodes of recrystallization domal salt has fewer impurities and much less brine in the crystal structure; however, domal salt does contain brine along many grain boundaries. In Figure 4a and b below, we show images of grain-boundary fluid in salt from Avery Island salt dome. The total amount of fluid is minute, but brine-aided mechanisms require minuscule quantities.



**Figure 4a, b. Grain boundary fluid in Avery Island Salt.**

The photomicrographs in Figure 4 are taken from cleavage chips, which are nominally 2-3 mm thick. The microscope can scan through the single crystal and focus at selected depths. Therefore, some of the image appears out-of-focus. In Figure 4a cubic inclusions inhabit a healed volume within a single crystal. Termination of fluid inclusion zones can be seen in both micrographs. Figure 4b displays vestige elongate inclusions decorating linear and non-linear healing features. Figure 4b also illuminates dendritic channels where grain-boundary moisture resided.

Reconsolidation processes have been documented in laboratory experiments on natural and artificial salt aggregates, large-scale tests, and natural analogues. Empirical evidence indicates



that fluid-aided processes will be operative in typical bedded salt as porosity reduces below 10%, even if no moisture is added. Bedded salt contains adequate moisture in the form of fluid inclusions, grain-boundary fluid, and hydrous minerals to sustain fluid-assisted processes. Nominally, domal salt contains much less moisture than bedded salt, but as confirmed in the micrographs in Figure 4 above, it would appear that fluid film is largely present on grain boundaries, especially in zones of incipient healing.

#### **4.0 Analogues**

The purpose of accumulating scientific evidence for salt consolidation is to support a license application for disposal. The next generation of salt repositories should make use of scientific advances and operational lessons learned. Technical lessons are legion, but include specific operational efficiencies gained by experience at WIPP, closure construction at Morsleben, and geotechnical issues pertaining to the Asse mine. Taking the state of the practice as a whole, including analogues, we can put forward a robust concept for future salt repositories. This synopsis of analogues points to ongoing and useful research and applications that portend extraordinary possibilities for future salt repositories.

Analogue arguments will be necessary to establish safety functions inherent in the licensing process. Although analogues are imperfect renditions of salt repository seal elements, long-term processes and properties of underground workings can be related to the functionality of salt repository seal systems. The licensing process involves presentation of scientific, engineering, and experimental evidence to a regulatory body. Conveyance of rigorous technical information is often made clearer by using full-scale, long-term analogues. Time and geometric scales are recurring criticisms of applying laboratory reconsolidation test results to a nuclear waste repository in salt. Uncertainty of extrapolating experimental data obtained from laboratory test research arises because small-scale phenomena may only be representative of limited size, relatively short test duration, and would not be able to capture interplay of geophysical phenomena at larger scales. Field observations and analogues can help connect laboratory results to full repository-scale applications. At the same time, micro-mechanical observations can be used to demonstrate that the same micromechanical processes operate at the laboratory and field-scale.

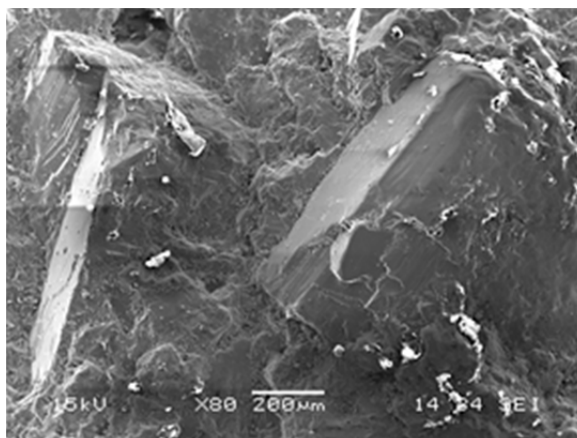
The BAMBUS and BAMBUS II projects (Bechthold et al. 2004) provide the best available full-scale, long-term, thermomechanical information on granular salt reconsolidation at in situ conditions. The principal scientific objective of the project was to extend the basis for optimizing salt repository design and construction and for predicting long-term performance of barriers, including reconsolidation of crushed-salt backfill. In situ investigations were conducted in the Asse salt mine subsequent to completion of the large-scale Thermal Simulation of Drift Emplacement (TSDE). The TSDE (also discussed in Bechtold et al. 2004) involved an emplacement drift that was electrically heated to between 170 and 200°C for more than 8 years. The photograph in Figure 5 is the BAMBUS II setting as the test room was reentered. The large heater is surrounded by partially reconsolidated granular salt, which had various porosities depending upon location. Most porosity measurements ranged from 20 to 25 percent. Initial

porosity from pneumatic stowing was approximately 35 percent in 1990. After 10 years of in situ reconsolidation, porosity was reduced by 10 to 15 percent and the closure rate had leveled off at 0.5 percent per year. An additional 20 years or more under these conditions would be required to reduce the porosity sufficiently to produce a low-permeability medium.



**Figure 5. Photograph of the BAMBUS II re-excavation.**

Structural stability is often achieved in the salt and potash industry by backfilling excavations. Backfilling is performed for operational efficiencies and the physical or mechanical properties of the backfill are seldom measured. Two forensic examinations are presented here, recognizing that further anthropogenic analogue studies are strongly desired. On a technical visit to the German mine Sigmundshall, a sample of reconsolidated slurry was obtained from the mine workings where excavations on the flank of the mine were backfilled with salt slurry. The Sigmundshall sample exhibited nearly complete reconsolidation. This sample had a porosity of only 1.4 % (Bechthold et al. 2004). Figure 6 is a scanning electron micrograph of the Sigmundshall backfill. Sutured intergranular structures are ubiquitous, facilitated by the introduction of large amounts of water when the slurry was placed. This analogue demonstrates that slurry will reconsolidate to near-intact conditions within the working life of a mine.



**Figure 6. Reconsolidated backfill from Sigmundshall.**

Samples of a younger slurry backfill operation were obtained from the Canadian K2 Mine. The reconsolidated K2 salt was originally deposited by slurry from the surface in 1988 (Kaskiw et al. 1989). The slurry was approximately 30 percent solids consisting of salt tailings. Rooms were filled completely with slurry and excess brine decanted by gravity. Room closure rate was measured at 1–2 inches per year in rooms 25 feet wide and 12 feet tall. Intact cubes measuring approximately 4 inches on a side were obtained for optical microscopy to evaluate the reconsolidation process. In this particular case between 20 and 40 percent of the void space has been removed. A photograph of this sample was included previously in Figure 1 b. Reconsolidation of granular salt, such as at the K2 Mine, has practical structural and production implications in salt mines. In repository applications, permeability would be the primary attribute of concern. In these field examples we note that grain boundaries mesh extremely well and would be impermeable at that boundary. As natural creep closes the room, remaining water is expelled as pressure solution re-deposition removes the void space.

Ancient salt mines provide anthropogenic analogues, dating back thousands of years. Archeological evidence includes preserved artifacts and evidence of impermeability. Further confirmation of long-term salt encapsulation via aperture closure and healing is evidenced in prehistoric sections of the Hallstatt salt mine: preserved holdings date from the Late Iron Age, including an unfortunate Celtic miner whose *corpse was well maintained by the conserving effect of the salt*. Other examples of integrity and tightness of salt barriers over geological timescales have been published by Minkley et al. (2015) who present evidence of a large volume of gas injected into a salt formation in Germany by volcanic activity 20 million years ago. This natural analogue and others cited by Minkley et al. (2015) demonstrate the long-term barrier integrity of salt formations, where highly compressed fluids were preserved for millions of years.

Natural geologic deposits themselves provide evidence that high-porosity evaporite crystals solidify readily into salt rock with negligible porosity. Processes of evaporite rock formation at low temperatures and pressures display pervasive early loss of porosity from more than 50 percent near the surface to essentially zero by 100–m depth (Warren 20056). For instance, Casas & Lowenstein (1989) reported that Quaternary halite layers only 10 m below the land surface have typical porosities of <10 percent and that layers at depths below 45 m (and proportionally low stresses) are cemented without visible porosity. By 100 m of burial, almost all halite units were tight and impervious. Porosity loss was attributed to early post depositional diagenetic

cementation by clear halite. All salt formations were formed originally by evaporation of highly saline brine. The process of reconsolidating salt is analogous to the process by which bedded salt became an impermeable formation in the first place.

## 5.0 Future Directions

This summary has been compiled to examine the strong case for granular salt consolidation, to draw analogues into the conversation, to identify a few focused research areas that can quantify certain properties and based on his body of information, to advocate for future salt repositories that include safety-by-design in a modular build-and-close concept.

### 5.1 Research Agenda

Collaboration has helped define a research agenda and concurrence of primary researchers on this topic can be found in the recent literature (Hansen et al. 2015), which is recapitulated here. The licensing process, as noted previously, involves several different lines of reasoning in presentation of performance arguments. Technical information needs to be conveyed to stakeholders and regulators in a manner that simultaneously demonstrates the supporting information and convinces a nontechnical audience. Whereas some technical experts believe phenomena associated with crushed-salt reconsolidation are well constrained and supported by analogue examples, this view may not be held by other experts and informed lay personnel. The perception that salt reconsolidation processes and associated phenomena are imperfectly known is crucial to a license application for a salt repository. A regulatory authority will ultimately weigh various lines of evidence and decide the merit of performance arguments. By virtue of extensive international collaborative research, a few areas warranting further examination are:

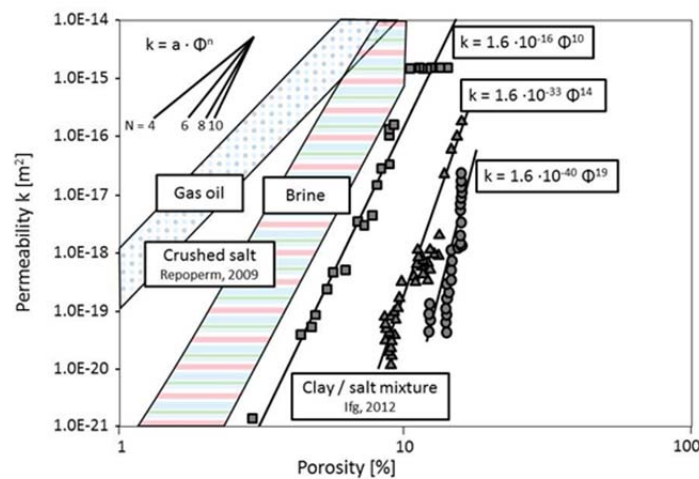
- Test scale: Testing time and space scales need to be reconciled with repository applications. Laboratory tests comprising the bulk of empirical evidence are principally small scale and short duration; whereas, the repository application involves meter-scale drifts and times ranging from years of operations to perhaps longer periods.
- Additives: Most backfill research and repository design has been concerned with use of run-of-mine crushed salt without additives such as bentonite. Evidence suggests that performance characteristics could be improved with admixtures. Admixtures provide greater placement density and performance. This engineering achievement reduces uncertainty and perceived reliance on modeling.
- Low-porosity characteristics: Low porosity creates experimentally difficult conditions for permeability measurement. The fundamental transformation mechanisms that create low permeability could benefit from further laboratory study and analogue examples.

The spectrum of investigations is vast, ranging from laboratory experiments to natural and anthropogenic analogues. And despite a lingering uncertainty associated with modeling, a constitutive model that captures reconsolidation behavior is required in the framework of licensing. Additional analogue studies are recommended. For example, naturally consolidating large salt piles and active deposition of salt sediments in the Dead Sea could provide insight into consolidation under low-stress conditions. The BAMBUS experiment in the Asse mine has continued to consolidate under ambient conditions, so a reinvestigation would add ten more



years to the anecdotal information from there. In addition, the salt repository community should continue to pursue relevant information from forth-coming projects involved with abandoning conventional mines. We anticipate international collaboration to conduct these studies. Advancement in the geomechanical model and calculational methods for stress and time dependence of salt consolidation will take into account potential for pore pressure increase if drainage is restricted and documentation of microstructural processes, such as pressure-solution and redeposition. German and US researchers have an abiding collaboration concerned with salt reconsolidation research.

Given these perceptions, Hansen et al. (2015) recommended a research path that included capabilities of additives, such as moisture and clay. The reason for further experimental work is illustrated in Figure 7, which plots a significant amount of experimental consolidation data. Added moisture of less than one percent enhances reconsolidation appreciably, but what is the optimal moisture addition if the granular salt is mixed with clay? And what are the underlying reasons for rapid permeability reduction with clay additives and what are the consolidation processes that shut down permeability with relatively high porosity remaining? The nature of testing fluids (brine or gas) and the resultant permeability/porosity relationships warrant further examination. If bentonite is added, the compacted backfill becomes tighter at relatively greater porosity. Numerical modeling also has room for improvement for characteristics appearing at lower porosities.



**Figure 7. Permeability-porosity datasets for crushed salt and mixtures.**

Large databases support reconsolidation of granular salt to low porosity and low permeability, which equate to undisturbed native material. This review has summarized existing information with an outlook toward salt repository applications. The role of granular salt reconsolidation in a repository for heat-generating waste will vary among programs because attaining safety functions depends on the natural setting, waste inventory, and concept of operations. Contingent upon repository design and safety concept, reconsolidating crushed salt can function well as a sealing material in shafts or drifts, depending on construction techniques and time-dependent tightness evolution. Existing evidence provides high confidence for excellent reconsolidation performance because processes are well understood and achievable with practical engineering measures.

## 5.2 Modular Build and Close

A *Synthesis of Salt Reconsolidation Analogues* would not be complete without looking forward to potential implications for future salt repository operations and licensing. A concept styled *Modular Build and Close* for salt repositories may allow sequential certification and closure of large salt repositories. It is feasible that a salt repository could accommodate nearly unlimited volumes of nuclear waste generated in the next 100 years, regardless of the nuclear industry future in the USA. Such a repository would build on the enormous technical basis for salt disposal and rely essentially on salt reconsolidation performance to ensure operational safety and sequential closure. The *Modular Build and Close* concept would inherently minimize operational risk when unusual events occur, such as the fire and radioactive release at WIPP. Recent developments in terms of WIPP panel closure would seem to have moved positively toward the possible *Modular Build and Close* concept.

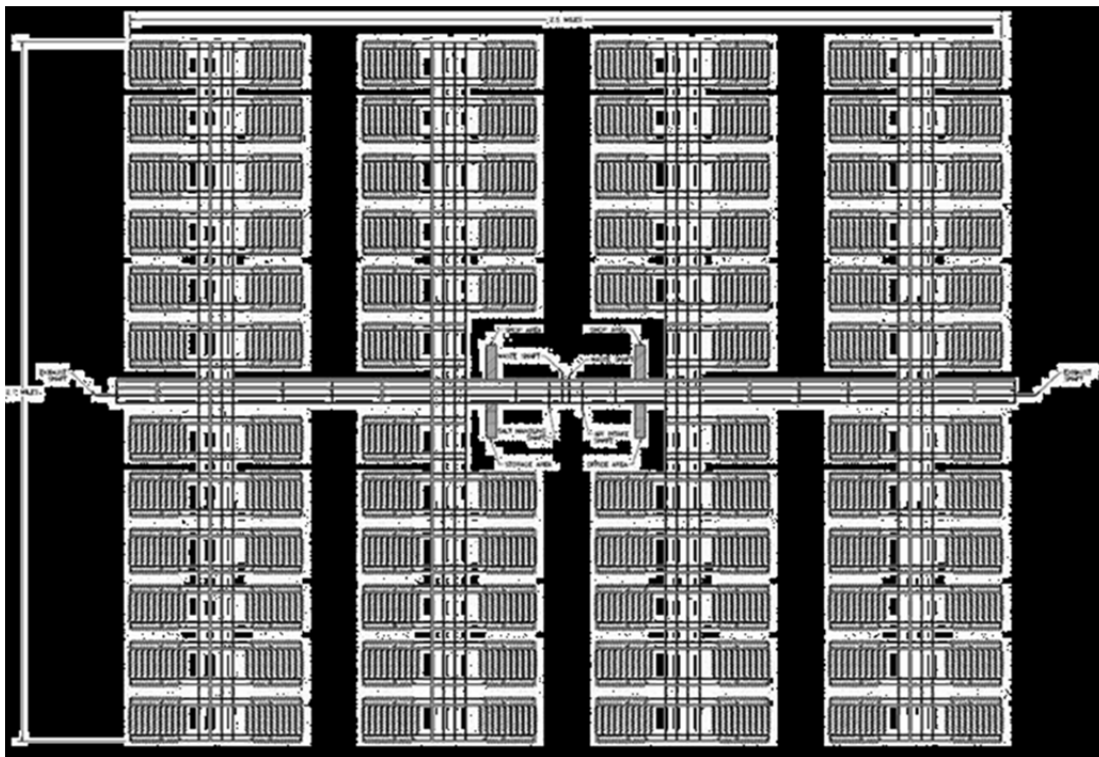
The regulatory authority for WIPP is the Environmental Protection Agency (EPA). Recently, the EPA approved of U.S. Department of Energy's (DOE) planned change request to implement a panel closure comprised mostly of run-of-mine salt. This change replaces a previous design without a crushed salt component, designated Option D in WIPP compliance documentation. Based on its review and on the results of the performance assessment, the EPA concluded that the WIPP will continue to comply with the EPA's disposal standard with the new panel closure design including a major element of 100 feet of run-of-mine salt. The EPA agreed with the use of a material that is physically and chemically compatible with the repository environment, and has relied on a body of data indicating that in time, the salt panel closure will return to a physical state similar to the halite that surrounds it (EPA 2014).

Recognition by the EPA that the salt panel closure element will *return to a physical state similar to native salt* is important because the crushed salt element of seal systems can be engineered to achieve performance characteristics within an operational period of a salt repository. The EPA drew their conclusion from a modeling study (Camphouse et al. 2012) that did not include advancement in the state-of-the art of salt reconsolidation applied to repository seals (Hansen et al. 2015). In the WIPP safety case, panel closures were not designed for long-term repository performance (DOE 1996) and studies have shown releases are insensitive to panel closure properties (Kirchner 2012). Nonetheless, a significant analysis of the new WIPP panel closure system includes run-of-mine salt placed in a horizontal drift. The revised panel closure will be consolidated by creep closure of the entry. Crushed salt is also proposed as one component of the shaft seal, and an assessment of the mechanical behavior of crushed salt is provided as part of the WIPP shaft sealing system design (DOE 1996, Appendix SEAL). If salt reconsolidation is unimpeded, the material will eventually achieve extremely low permeabilities approaching those of the native Salado Formation. Arguments brought forward from analogues in this text provide actual measureable and testable properties, as contrasted to modeling predictions.

Drawing from many previous studies, such as Hansen and Knowles (1999), Camphouse et al. (2012) restate that developments in support of the WIPP shaft seal system have produced confirming experimental results, constitutive material models, and construction methods that substantiate use of a salt column to create a low permeability seal component. Other advantages of using crushed salt for sealing systems is that as a replacement of the natural material in its original setting it ensures physical, chemical, and mechanical compatibility with the host formation (Hansen and Knowles 1999). Camphouse et al. (2012) also discuss the interplay

between reconsolidating salt and the disturbed rock zone. They conclude with an expectation that a completely consolidated salt-filled drift will achieve flow properties indistinguishable from natural Salado salt. Analogues support the idea that reconsolidation will occur expeditiously and experimental advances confirm that high performance reconsolidated drift seals can be engineered and monitored during operations. These actualities, taken together, lead to a salt repository concept for complete isolation in a modular design.

The concept of *Modular Build and Close* is predicated on sequential disposal followed by licensing and permanent closure of the filled module. A notional layout of large repository is shown in Figure 8. Nominally, outer dimensions might measure two miles by two miles. Production salt and potash mines are orders of magnitude larger than this hypothetical layout. Active mines exist today that have been in production for 100 years or more. Therefore, a salt repository of such areal dimensions and longevity is achievable. The geometry of underground openings can be engineered for functional and operational purposes. Ground control can be minimized by judicious selection of size, shape, extraction ratio, stratigraphic placement and sound mining practices. Of course, disposal modules would be excavated on a “just-in-time” basis giving due consideration to creep closure. Transport of mined salt can be minimized and optimized for real-time seal construction.



**Figure 8. A 100-year salt repository.**

Disposal would begin in a far corner and work progressively back toward the shafts. When a module of design dimension is filled, an advanced salt-based closure system would be erected. Design specifications for the closure systems can be based on information presented earlier in this document and further advancement of the research agenda, also described previously. Closing and permanently sealing each module as disposal operations move forward creates a

safety-by-design situation because exposure is progressively limited. Because disposal begins at the outer reach of the repository, underground manpower, equipment, and ventilation never breach the disposal module once it is filled, closed and licensed. In much the same way as performance assessment was persuasive with the EPA in the panel closure change request, experimental evidence and analogue properties will show modular closures to be impermeable and robust.

The state of knowledge regarding granular salt reconsolidation is well established. Crushed or run-of-mine salt makes an excellent backfill material for salt repositories because it reconsolidates readily under a wide range of conditions and will ultimately reestablish impermeability to brine flow and radionuclide transport. Laboratory testing, field-scale operational analogues, and natural geologic analogues attest to granular salt compressing and consolidating to assume properties of native formation salt. The science supporting the technical basis for properties of reconsolidating granular salt is objective and thorough. Remaining uncertainty within the safety case context can be reduced by focused research dedicated to achieving design specifications for drift seals as part of operational protocol.

Application of acquired knowledge to construction techniques could potentially achieve high-performance seal properties upon construction or during the repository operational period, which lessens reliance on modeling to argue for evolving engineering characteristics and attainment of sealing functions at some future time. The robust database could be augmented by select reconsolidation experiments with admixtures and analogue studies with appropriate documentation of microprocesses.

## References

Bechthold, W., E. Smailos, S. Heusermann, T. Bollingerfehr, B. Bazargan Sabet, T. Rothfuchs, P. Kamlot, J Grupa, S. Olivella, & F.D. Hansen. 2004. *Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS II Project)*. European Commission—EUR 20621 EN.

Bollingerfehr, W., W. Kudla, D. Freyer, M. Gruner, M. Jobmann, N. Müller-Hoeppe, F. Schreiter, & T. Wilsnack. 2013. *R&D Project ELSA (Sealing of Shafts in Salt and Clay Formations)*. Proceedings of the 4<sup>th</sup> US/German Workshop on Salt Repository Research, Design and Operation. <http://energy.sandia.gov/wp-content/gallery/uploads/Workshop-4-Proceedings.pdf>

Camphouse, R.C., M. Gross, C.G. Herrick, D.C. Kicker, & T.W. Thompson. 2012. *Recommendations and Justifications of Parameter Values for the Run-of-Mine Salt Panel Closure System Design Modeled in the PCS-2012 PA*. ERMS 557396. Sandia National Laboratories, Carlsbad, NM.

Casas, E. & T.K. Lowenstein. 1989. *Diagenesis of Saline Pan Halite: Comparison of Petrographic Features of Modern, Quaternary and Permian Halites*. Journal of Sedimentary Petrology. 59.



Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Appendix SEAL. U.S. Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office. Carlsbad, NM.

Environmental Protection Agency. 2014. *Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations; Panel Closure Redesign*. EPA-HQ-OAR-2013-0684.

Hansen, F.D., T. Popp, K. Wieczorek, & D. Stührenberg. 2015. *Salt Reconsolidation Applied to Repository Seals*. Mechanical Behavior of Salt VIII. Taylor & Francis Group, London. ISBN 978-1-138-02840-1.

Hansen, F.D. & M.K. Knowles. 1999. *Design and Analysis of a Shaft Seal System for the Waste Isolation Pilot Plant*. SAND99-0904J. Sandia National Laboratories, Albuquerque, NM.

IfG. 2012. Laboruntersuchungen am gemisch schnittsalz - Friedländer ton. *Institut für Gebirgsmechanik GmbH*, Leipzig.

Kaskiw, L., R. Morgan, & D. Ruse. 1989. *Backfilling at IMC (Canada) K2 Potash Mines*, Proc. 4<sup>th</sup> International Symposium on Innovation in Mining and Backfill Technology, Montreal QC.

Kirchner, T. 2012. *Sensitivity of the AP-161 (PCS-2012) PA Releases to Parameters*, Revision 0, ERMS 558342. Sandia National Laboratories, Carlsbad, NM.

Mauke, R. 2013. *In Situ Investigation of the Morsleben Drift Seal—Operating Experience and Preliminary Results*. Proceedings of the 4<sup>th</sup> US/German Workshop on Salt Repository Research, Design and Operation. <http://energy.sandia.gov/wp-content/gallery/uploads/Workshop-4-Proceedings.pdf>.

Minkley, W., M. Brückner, M. Knauth & C. Lüdeling. 2015. *Integrity of Saliferous Barriers for Heat-Generating Radioactive Waste – Natural Analogues and Geomechanical Requirements*. Mechanical Behavior of Salt VIII. Taylor & Francis Group, London. ISBN 978-1-138-02840-1.

Noseck, U. & J. Wolf. 2013. *Discussion on Specific Rock Salt Analogues*. Proceedings of the 4<sup>th</sup> US/German Workshop on Salt Repository Research, Design and Operation. <http://energy.sandia.gov/wp-content/gallery/uploads/Workshop-4-Proceedings.pdf>

Nuclear Energy Agency. 2014. *Natural Analogues for Safety Cases of Repositories in Rock Salt*. NEA/RWM/R(2013)10.

REPOPERM. 2009. *Restporosität und permeabilität von kompaktierendem Salzgrus-Versatz* (Residual porosity and permeability of compacting granular salt backfill). GRS-254. Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH.

Stahlmann, J., C. Missal, & A. Gährken. *Interaction between Salt Concrete Sealing Structures and Rock Salt*. Mechanical Behavior of Salt VIII. Taylor & Francis Group, London. ISBN 978-1-138-02840-1.

Spiers, C.J., & R.H. Brzesowsky. 1993. *Densification Behaviour of Wet Granular Salt: Theory versus Experiment*. Seventh Symposium on Salt Vol. I. Elsevier Science Publishers B.V., Amsterdam.

Van Sambeek, L.L., T.J. Eyerman, & F.D. Hansen. 1995. *Case Studies of Sealing Methods and Materials Used in the Salt and Potash Mining Industries*. SAND95-1120. Sandia National Laboratories. Albuquerque, NM.

Warren, J.K. 2005. *Evaporites: Sediments, Resources and Hydrocarbons*. Springer.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.