Reconsolidated Salt as a Geotechnical Barrier 16535

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ABSTRACT

Salt as a geologic medium has several attributes favorable to long-term isolation of waste placed in mined openings. Salt formations are largely impermeable and induced fractures heal as stress returns to equilibrium. Permanent isolation also depends upon the ability to construct geotechnical barriers that achieve nearly the same high-performance characteristics attributed to the native salt formation. Salt repository seal concepts often include elements of reconstituted granular salt. As a specific case in point, the Waste Isolation Pilot Plant recently received regulatory approval to change the disposal panel closure design from an engineered barrier constructed of a salt-based concrete to one that employs simple run-of-mine salt and temporary bulkheads for isolation from ventilation. The Waste Isolation Pilot Plant is a radioactive waste disposal repository for defense related transuranic elements mined from the Permian evaporite salt beds in southeast New Mexico. Its approved shaft seal design incorporates barrier components comprising salt-based concrete, bentonite, and substantial depths of crushed salt compacted to enhance reconsolidation. This paper will focus on crushed salt behavior when applied as drift closures to isolate disposal rooms during operations.

Scientific aspects of salt reconsolidation have been studied extensively. The technical basis for geotechnical barrier performance has been strengthened by recent experimental findings and analogue comparisons. The panel closure change was accompanied by recognition that granular salt will return to a physical state similar to the halite surrounding it. Use of run-of-mine salt ensures physical and chemical compatibility with the repository environment and simplifies ongoing disposal operations. 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 repositories. Mined salt repositories have the potential to isolate permanently vast inventories of radioactive and hazardous wastes.

INTRODUCTION

Drawing from recent developments and subsequent publications [1, 2] we examine a breadth of issues pertaining to granular salt reconsolidation as a geotechnical barrier for disposal of radioactive waste. Together, these two contemporary publications establish a new baseline for drift seal systems in salt, along with an achievable research agenda that foretells design improvement and inherent operational safety. The first [1] explains the approval of a change to drift closures at the Waste Isolation Pilot Plant (WIPP). The second [2] describes the scientific basis for salt reconsolidation and achievement of low permeability, while strengthening these arguments with analogue examples. 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 here pertains to geotechnical seal systems of which the primary seal function is achieved by reconsolidating crushed salt, with or without additives. Salt reconsolidation has a licensing role in the performance assessment of WIPP 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 practical experience appropriate for 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 must resort to calculations of performance objectives using models. Though modeling serves many 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 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 permit 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.

We begin with a description of the panel closure change from a dominantly concrete design to a practical seal element comprising run-of-mine salt. This straightforward change is underpinned by subsequent discussion of how crushed salt is used in practice and in a repository. The mechanisms by which granular salt reconsolidates are explained along with the influence of moisture. A range of analogue examples is provided. Findings lead to recommendations for a research agenda and conclude with a description of how this body of knowledge can be leveraged to develop the next-generation of salt repositories with enormous potential.

DESCRIPTION

The Environmental Protection Agency (EPA) mandated a specific panel closure design as Condition 1 of the WIPP Certification under 40CFR191 [3]. The State of New Mexico Environmental Department adopted the requirement, as well. There were 24 locations in the repository configuration where the closures were intended to be placed. The panel closure was called Option D of several alternative closures (A, B, C, and D). Figure 1 is a cross-sectional drawing of the Option D panel closure. Main elements include a block wall and a mass-concrete monolith. The block wall—called an explosion wall—was to protect against a hypothetical conflagration. The concrete monolith increased protection against volatile organic compound release during operations. Gas monitoring established that no flammable or explosive gas was ever detected in the disposal rooms. The Salado Mass Concrete specifications were found to be problematic. Construction along disposal routes would be incompatible with disposal operations. And, Option D was complex and expensive.

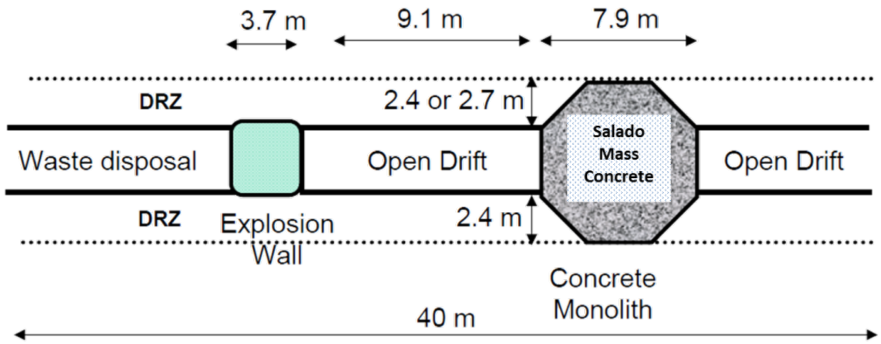


Figure 1. Option D panel closure.

Thus, there existed a strong motivation to revisit the Option D requirement and work with the regulatory agencies to replace it with a constructible and equivalently protective design. Seal concepts for international salt repositories and salt industry applications almost always include elements of granular salt reconsolidation. Replacement of Option D with a 100-foot reach of crushed salt, as illustrated in Figure 2, was put forward as a reasonable replacement design. Numerous technical exchanges with the EPA provided a forum to demonstrate the concept through testing and modeling results. The basic geomechanics surrounding performance of run-of-mine backfill in a creeping underground setting are well understood. Creep closure of the surrounding salt will reconsolidate the granular material to porosity and permeability characteristics approaching those of the host salt formation.

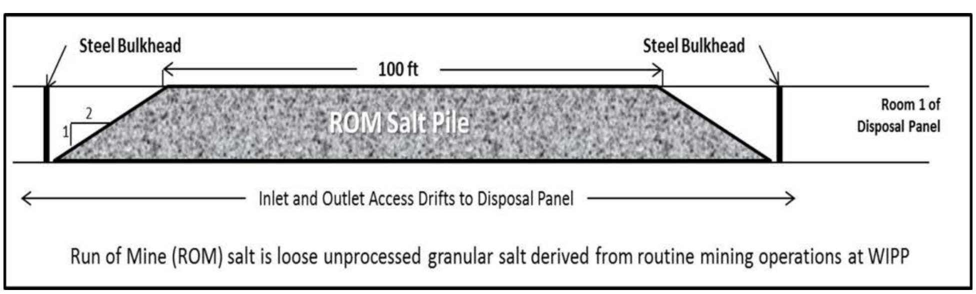


Figure 2. Redesigned panel closure of run-of-mine salt

Long-term performance calculations [4] showed the new panel closure would not affect total-system safety standard compliance. As discussed throughout this paper, the promise of enhanced closure capability presented by crushed salt, with or without additives, has important implications for the next-generation salt repositories.

DISCUSSION

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 embody significant engineering to achieve performance specifications. Functional improvement of barriers containing crushed salt remains an active research and development goal in salt repository programs.

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 require knowledge of thermal, mechanical, and fluid transport properties of reconsolidating granular salt. In addition to mechanical and thermal properties, the most essential phenomenon pertains 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.

Reconsolidation of granular salt is of high interest in the USA and Germany, countries actively collaborating in salt repository research, design, and operation [5]. The realm of salt consolidation for nuclear waste disposal includes routine room backfill for structural stability, engineered systems to affect low-permeability seal capability relatively quickly, and in some cases 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.

In the salt disposal concept, crushed salt is naturally the most suitable backfill material. 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
- Protect structural integrity of repository excavations

- Provide low permeability and/or diffusivity and/or long-term retardation
- Conduct heat generated from the waste to the host rock.

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 [6]. Research efforts have addressed this recognized need for a number of years resulting in a 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 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.

Consolidation Processes

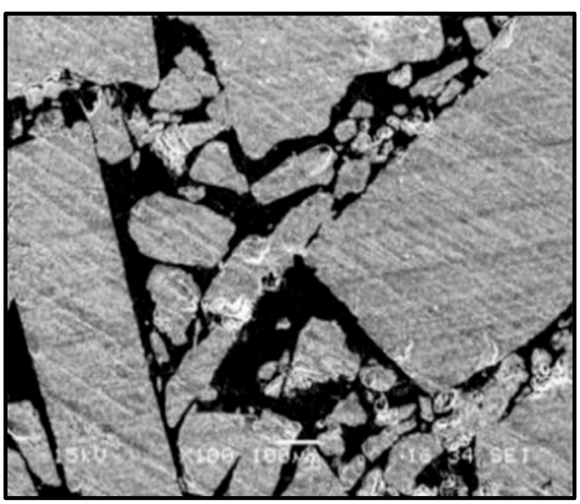
For purposes of salt repository applications and related industrial functions, micromechanical mechanisms during late stages of consolidation are the most relevant. Brittle consolidation processes are likely to accompany construction practices, such as shown in Figure 3, which is a run-of-mine drift-closure demonstration at WIPP. Dynamic compaction, as intended for shaft seal construction, would pulverize grains during construction. A desired outcome of construction is to place geotechnical barrier material at an initial condition of relatively low porosity and thereby minimize the time between placement and functionality.

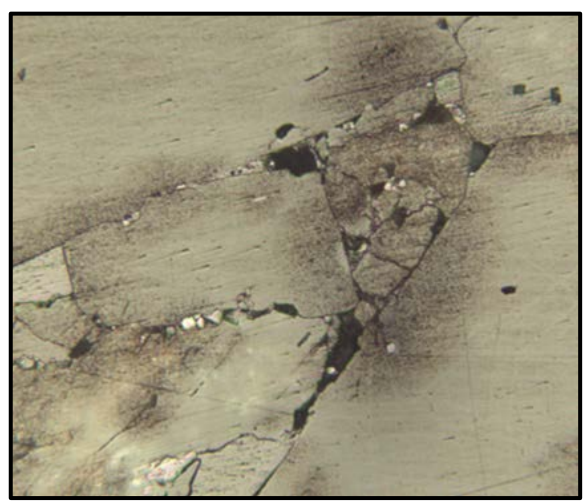
Figure 3. Evaluation of drift seal placement methods

Salt reconsolidation mechanics have been investigated by means of several experimental procedures, with increasing sophistication and test parameter control over time. Improvements in laboratory techniques as well as test-to-test comparisons have enabled a more complete analysis of test data and consolidation processes than possible earlier. Interpretation of the effects of temperature, stress, moisture, and test techniques is basic to deciphering laboratory results and extending them to repository-relevant applications.

How does salt reconsolidate? 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 distortion.

Examples in Figure 4 include representative stages of progressive consolidation processes from high porosity to low porosity [5]. Figure 4a is taken from the large-scale BAMBUS II field test [7] and depicts brittle cleavage fracture and translational sliding at 25% porosity. In practice, this substructure represents a relatively early stage of reconsolidation of dry granular salt that was placed in situ by pneumatic stowing. Figure 4b is another analogue sample from a room that was back-filled with salt slurry. The sharp, straight edges exemplify brittle cleavage fracture whereas the finer particles result from pulverization along grain boundaries. The well-meshed grain boundaries are achieved through pressure solution. Figure 4c is taken from a thin-sectioned laboratory sample that was consolidated at 250°C to a normalized density of 0.93. It characterizes well-sutured grain boundaries in the larger view (left) and extensive plastic deformation of individual grains at higher magnification (right).

a) 

b) 

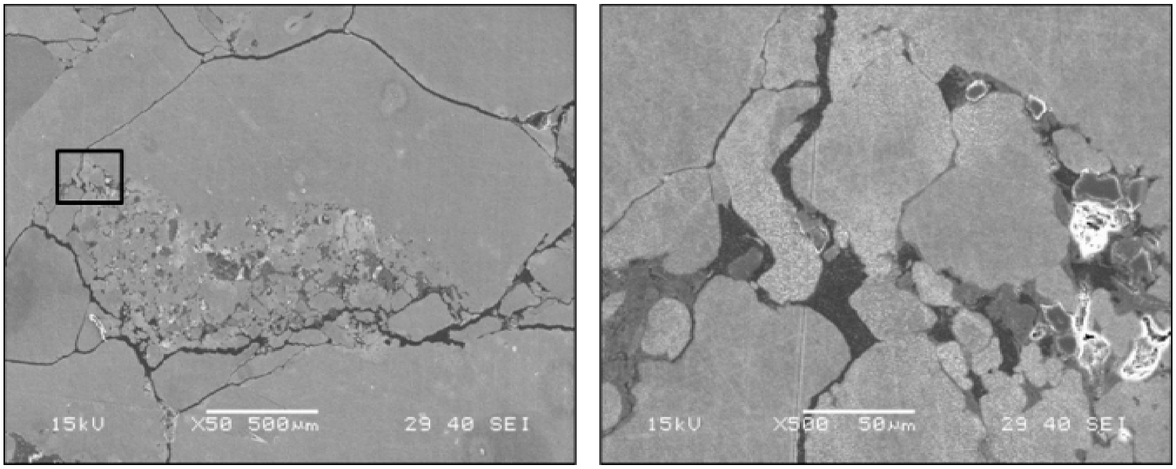
c) 

Figure 4. Examples of consolidation processes from high (a) to low (c) porosity.

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 [8] 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.

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. The availability of brine on grain boundaries is key to the consolidation process, and bedded salt of the Salado Formation contains adequate moisture in the form of fluid inclusions, grain-boundary fluid, and hydrous minerals to sustain fluid-assisted processes.

Analogues

The next generation of salt repositories should make use of scientific advances and operational lessons learned. Pertinent experience includes nuclear waste disposal operations at the 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 robust design concepts. 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 represent 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, microscopic observations can be used to establish that the same micromechanical processes operate at the laboratory and field-scale.

The BAMBUS and BAMBUS II projects [7] provide the best available full-scale, long-term, thermomechanical information on granular salt reconsolidation under simulated repository 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 [7]) involved an emplacement drift that was electrically heated to between 170 and 200^{o}C for more than 8 years. The photograph in Figure 5 shows a BAMBUS II heater surrounded by partially reconsolidated granular salt. Porosity measurement 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.

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 during earlier operations. The Sigmundshall sample exhibited nearly complete reconsolidation (porosity of only 1.4 %), as can appreciated from the scanning electron micrograph in Figure 6. 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.

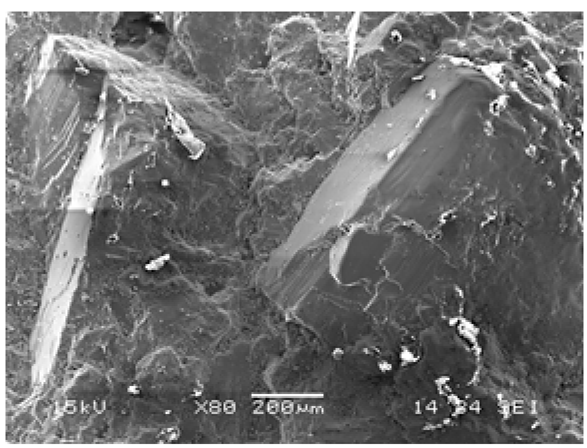


Figure 6. Reconsolidated backfill from Sigmundshall.

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 [9]. The slurry was approximately 30 percent solids consisting of salt tailings. Rooms were filled completely with slurry and excess brine drained by gravity. Room closure rate was measured at 1–2 inches per year in rooms 25 feet wide and 12 feet tall. As natural creep closes the room, remaining water is expelled as pressure solution/re-deposition removes the void space. 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 can be seen in Figure 4b, presented previously. Reconsolidation of granular salt has practical structural and production implications, such as at the K2 Mine. 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.

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. [10] 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. [10] 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 [11]. For instance, Casas & Lowenstein [12] 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 (at conditions of low stress) 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.

CONCLUSIONS

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 this body of information, to advocate for future salt repositories that include safety-by-design in a modular build-and-close concept.

Research Agenda

International collaboration has helped define a research agenda and concurrence of primary researchers on this topic can be found in recent literature [5], 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 helps a nontechnical audience to fully understand. 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 expected 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 international community should continue to pursue relevant information from forth-coming projects involved with abandoning conventional mines.

Given these perceptions, a research path was recommended that included capabilities of additives, such as moisture and clay [5]. 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? What are the underlying reasons for rapid permeability reduction with clay additives? 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. What are the consolidation processes by which this occurs?

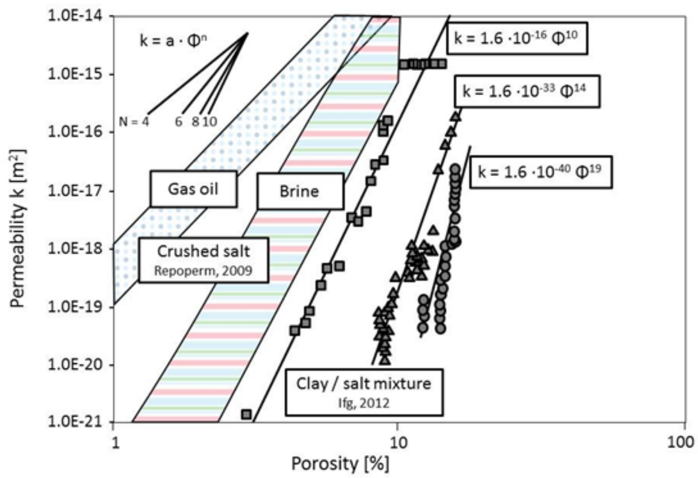


Figure 7. Permeability-porosity datasets for crushed salt and mixtures [13,14].

Large databases support reconsolidation of granular salt to low porosity and low permeability, which equate to undisturbed native material. The summarized information provides an outlook toward salt repository applications. The role of granular salt reconsolidation in a repository for heat-generating waste will vary among programs because operational and post-closure safety 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.

Modular Build and Close

Geotechnical barriers made of crushed salt have the potential to become impermeable during the operational period of a salt repository. There is persuasive evidence that reconsolidation can be furthered by improved construction techniques and enhanced by use of additives. These developments have significant implications for future salt repository operations and licensing. A concept styled *Modular Build and Close* for salt repositories may allow sequential sub-unit certification and closure in 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 of the United States. 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 a *Modular Build and Close* concept.

Recently, the EPA (regulatory authority for WIPP) approved DOE's 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 [15].

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 [16] that did not include advancement in the state-of-the art of salt reconsolidation applied to repository seals [5]. In the WIPP safety case, panel closures were not designed for long-term repository performance [3] and studies have shown releases are insensitive to panel closure properties [4]. 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 [3]. If salt reconsolidation is unimpeded, the material will eventually achieve extremely low permeabilities approaching those of the native Salado Formation. Further arguments from analogues provide actual measureable and testable properties, as contrasted to modeling predictions.

Drawing from many previous studies, such as [17], Camphouse et al. [16] 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 [17]. Camphouse et al. [16] 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. 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 challenges 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.

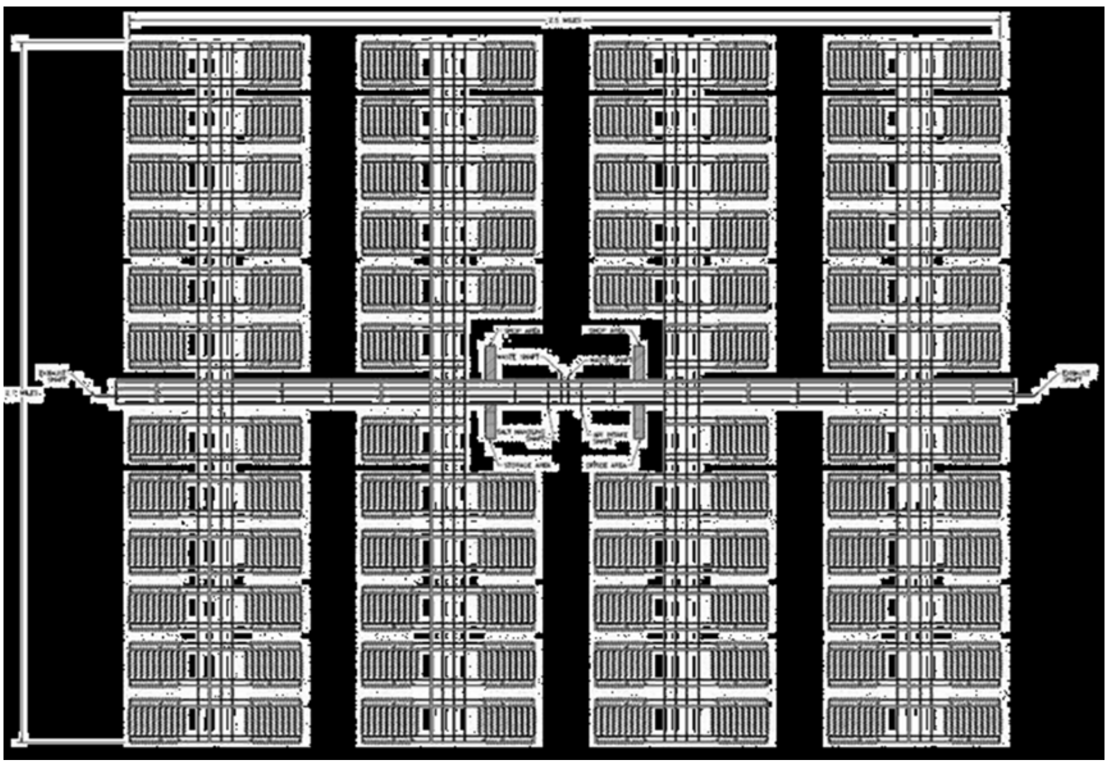


Figure 8. A 100-year salt repository.

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 emplaced. 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 since 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.

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.

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