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SAND96-0792C

CONF-9606115--4

LARGE-SCALE DYNAMIC COMPACTION OF NATURAL SALT[1]

Frank D. Hansen and Ernst H. Ahrens
Nuclear Waste Technology Repository Isolation Systems
Sandia National Laboratories
Albuquerque, NM USA 87185-0719

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ABSTRACT

A large-scale dynamic compaction demonstration of natural salt was successfully completed. Approximately 40 m^3 of salt were compacted in three, 2-m lifts by dropping a 9,000-kg weight from a height of 15 m in a systematic pattern to achieve desired compaction energy. To enhance compaction, 1 wt% water was added to the relatively dry mine-run salt. The average compacted mass fractional density was 0.90 of natural intact salt, and *in situ* nitrogen permeabilities averaged 9×10^{-14} m^2. This unique demonstration established viability for dynamic compaction as a potential technology for placement of salt shaft seal components. The demonstration also provided compacted salt parameters needed for shaft seal system design and performance assessments of the Waste Isolation Pilot Plant.[2]

INTRODUCTION

Reconsolidation of crushed rock salt is a phenomenon of international interest and importance to programs concerned with permanent isolation of hazardous materials in natural salt geologic settings. Of particular interest is the potential for disaggregated salt to be restored to a nearly impermeable state, enabling its use as a sealing material. Compacted and reconsolidated crushed salt is proposed as a major shaft seal component for the Waste Isolation Pilot Plant (WIPP) located in southeastern New Mexico USA. One element of the WIPP's robust seal system is a column of densely compacted crushed salt. An effective seal will develop as surrounding salt creeps into the sealed shafts, further consolidating the compacted salt column. Fundamental information on placement density and permeability is required to ensure attainment of the design function. The work reported here is the first evaluation of large-scale dynamic compaction as a potential shaft seal construction technique. The large-scale demonstration provides information on initial salt properties applicable to design, construction, and performance expectations.

Shaft seals at the WIPP have a statutory functional period of 10,000 years. Over time, a compacted salt shaft seal will become less permeable as it is compressed

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by creep closure of salt surrounding the shaft. Because permanent seals that take advantage of salt reconsolidation have never been constructed, performance measurements have not been made on an appropriately large scale for shaft seal conditions. An understanding of potential construction methods, achievable initial density, and permeability of reconsolidating salt over time is required for seal design and performance assessment. This paper is one of three related papers presented in the current *Proceedings*. All three examine the unique application of compacted salt as a sealing material. The other two papers discuss laboratory consolidation test data and microprocesses (Brodsky et al.), and evaluation and development of a constitutive model for performance calculations (Callahan et al.). This paper discusses (1) fielding and operations of a nearly full-scale demonstration of dynamic compaction of mine-run WIPP salt and (2) quantitative and qualitative results. The paper discusses preliminary compaction results from a previous intermediate-scale test that provided the justification and technical basis for the current large-scale demonstration; a description of the compaction procedure; qualitative and quantitative results of the large-scale compaction test; descriptions of equipment, facilities, operations, and procedures; and preliminary *in situ* gas permeability test results.

The proposed shaft sealing system components for the WIPP are illustrated in Figure 1. Each of four WIPP shafts, ranging in diameter from 3.5 to 6.1 m, will be filled with dense materials possessing low permeability and other desirable attributes. Seal materials include concrete, clay, asphalt, and compacted salt. Most seal components comprise common construction materials possessing known engineering properties. A column of reconsolidated natural WIPP salt is expected to seal the shafts permanently. If reconsolidation is unimpeded by fluid pore pressures, compacted salt will eventually achieve extremely low permeabilities approaching those of the native bedded salt where the repository is located. As Figure 1 shows, the sealing system design includes a 180-m compacted salt column placed near the bottom of the shafts where creep deformation of the surrounding salt formation is greatest.

BACKGROUND

The WIPP repository is located at a subsurface depth of 655 m in the Salado Formation. The Salado is a sequence of bedded evaporites approximately 600 m thick that were deposited during the Permian Period, which ended 225 million years ago. Salt has been identified as a good geologic medium to host a nuclear waste repository because of several favorable characteristics. Perhaps the most important advantage of salt is its ability to creep and ultimately entomb material placed in excavated openings. Other attributes of WIPP salt include its very low permeability, vertical and lateral stratigraphic extent, and tectonic stability. Creep closure also plays an important role in the shaft sealing strategy. The concept of returning excavated salt to the underground as part of the decommissioning process has been under consideration for decades. Compacted crushed salt has been a seal-component design option for at least twelve years. Recently sealing performance measures of reconsolidating salt have received additional attention.

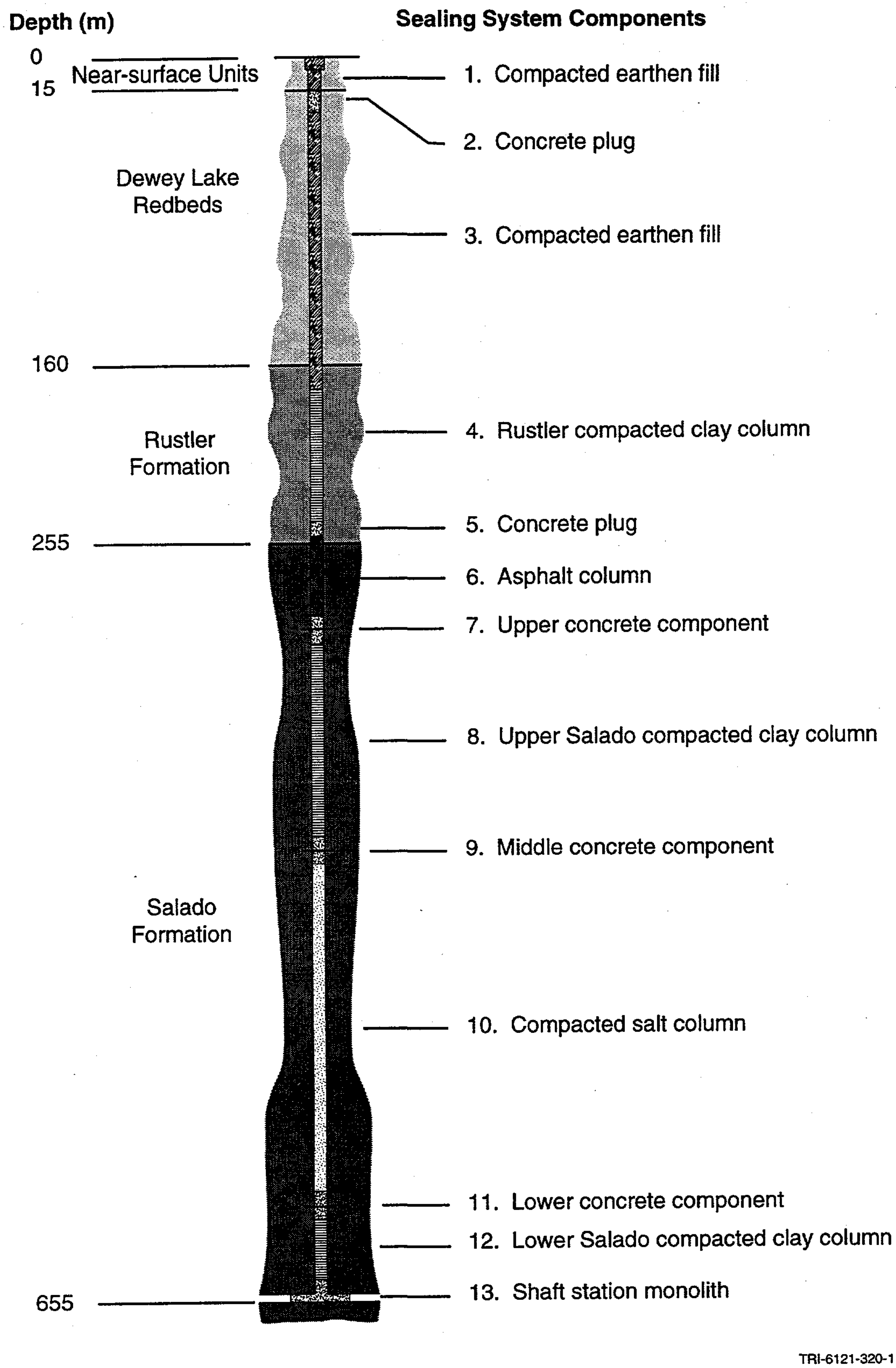


Figure 1. Proposed Seal Design for the WIPP (DOE, 1995).

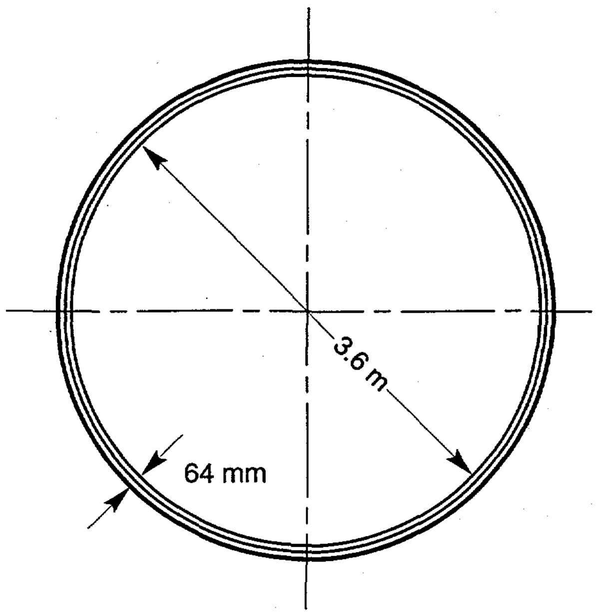
Implementation of the large compaction demonstration reported here follows an earlier intermediate-scale technology development demonstration reported by Hansen et al. (1995). Vertical dynamic compaction was chosen as the prototype compaction method over several commercially available options (e.g., vibratory or roller compaction) because it is a simple and effective technique for compacting noncohesive soils and appears amenable for shaft use. For the intermediate-scale demonstration, dynamic compaction was achieved by systematically dropping a cylindrical tamper into a chamber containing mine-run WIPP salt. The steel compaction chamber (1.2-m diameter and 1.8-m high) was designed and built specifically for these tests. Two such demonstrations were completed. The first compacted mine-run salt containing 0.26 wt% water. (Natural WIPP salt contains approximately 0.5 to 1.0 wt% water.) The second added approximately 1.0 wt% water. Greater compaction energy was used in the first test than in the second test.

Measurements at the field-test site provided qualitative information that was confirmed in the laboratory. Geometric measurements during compaction allowed approximate determination of fractional density, which relates compacted salt mass density to the density of intact Salado Formation salt (2160 kg/m^3). The first demonstration achieved an overall fractional density of 0.87. The second compacted salt to fractional densities approaching 0.90. After each of the two dynamic compaction demonstrations, an unsuccessful attempt was made to drill cores directly from the compacted mass within the chamber. Excessive lateral movement at the bit face resulted in poor core recovery. Therefore the chamber was opened and the compacted salt was cut into blocks that were shipped to the laboratory, where cores were tested for gas permeability, density, and moisture content (Hansen et al., 1995).

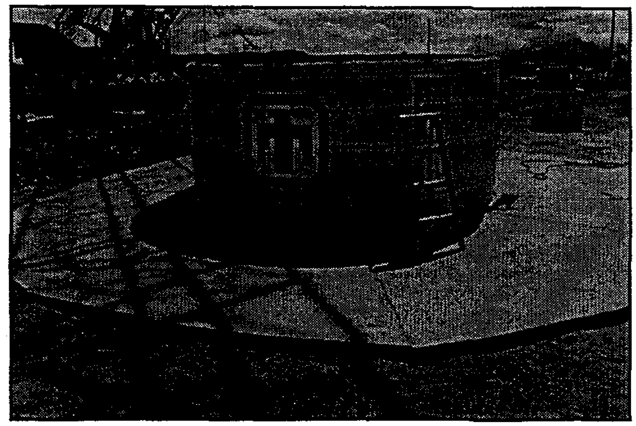
These preliminary intermediate-scale tests showed that dynamic compaction is a viable, straightforward, and practical method for compacting salt. Results provided a basis for undertaking the large-scale demonstration described in this paper. Field and laboratory testing was conducted within a quality assurance framework that included a reviewed and approved test plan. Large-scale compaction was preceded by completion of several tasks and was followed by a series of performance tests. The principal activities included

- design and analyses of the chamber and tamper,
- calculation of compaction energy,
- compaction of sub-base soil,
- compaction of mine-run WIPP salt, and
- *in situ* gas permeability tests of the compacted salt mass.

The steel compaction chamber, shown in Figure 2, was 3.6 m high and 3.6 m in diameter. To help assure relatively constant test temperatures, it was wrapped with band heaters and insulated. Precompaction of the underlying soil created a 2-m depression in which the chamber was situated, as shown in the photograph in Figure 2. The tamper consisted of 15 circular steel plates (10 cm thick and 124 cm in diameter) bolted together as shown in Figure 3. Total tamper weight was 9,144 kg. During the



Top View.



Chamber with Insulation and Flooring.

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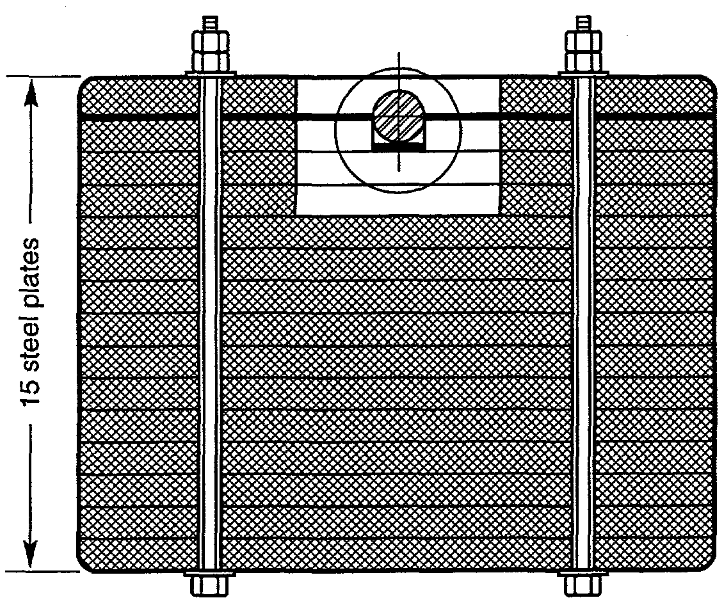
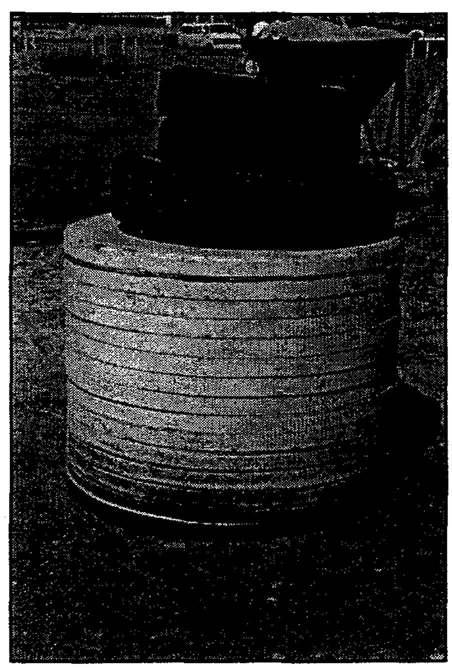
Figure 2. Steel Compaction Chamber



Side view.



Tamper.

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Figure 3. Tamper used for Dynamic Compaction.

compaction test, the tamper remained connected by cable to the hoisting drum on the crane. A swivel and nylon sling were placed between the cable and tamper. While compaction was in progress, the sling and swivel were shielded by car tires, which reduced impact between the tamper assembly and the compaction vessel (see the photograph in Figure 3). Compaction was systematic and well controlled; however, compaction procedures were not optimized. A nominal initial compaction effort exceeding three times Modified Proctor Energy (MPE) was applied to each of three lifts. One MPE equals 56,200 ft lb/ft^3 (2.7×10^6 J/m^3), where the volume of interest is directly below the tamper. Three 1.2-m lifts of salt were placed in the chamber, and each lift was compacted with 3 MPE. The lower and middle lifts were actually compacted with greater than 3 MPE because of the compactive influence from subsequent lifts.

COMPACTION PROCEDURE

Figure 4 is a comprehensive view of the dynamic compaction test site at Sandia National Laboratories. Salt was placed in the compaction chamber using a bucket normally used for concrete construction. A belt conveyor was positioned to load from the salt storage tent and to discharge into the bucket attached to the crane cable. A fine water mist was sprayed on the salt as it was discharged from the conveyor belt. The bucket was transported to the chamber using the crane, which was on site to hoist and drop the compaction tamper.

Moisture Adjustment

Mine-run salt was trucked from the WIPP site to the test area in Albuquerque, NM. The salt was stored in a large waterproof tent as preparations were made for placing it in the chamber. Before testing began, salt from the storage pile was sampled for moisture content. The volume of water necessary to achieve 1.0 wt% water was added uniformly using an airless sprayer. Water content averaged 1.0 wt% for samples taken from the chamber as each lift was loaded. With practice, the precalibrated amount of water was completely discharged as the last of the salt cascaded into the bucket.

Drop Procedure

One MPE required approximately 4.5 drops; therefore 5 drops were made in each position. A total of 495 drops was required for application of 3 MPE to each of three lifts. Figure 5 is a schematic of an ideal drop pattern showing 11 drop positions. Overlap of impact areas coupled with estimates of impact energy ensured that each lift was compacted with at least 3 MPE. The tamper was consistently dropped to within a few centimeters of its intended landing area, and it was consistently dropped within 10 cm of the compaction chamber edge. Depth of influence of the tamper impact was calculated to be 6 m. Observation of continued compaction of the soil beneath the chamber qualitatively affirmed the depth of influence. Depth of compactive influence may be a concern during placement of salt in the WIPP shafts.

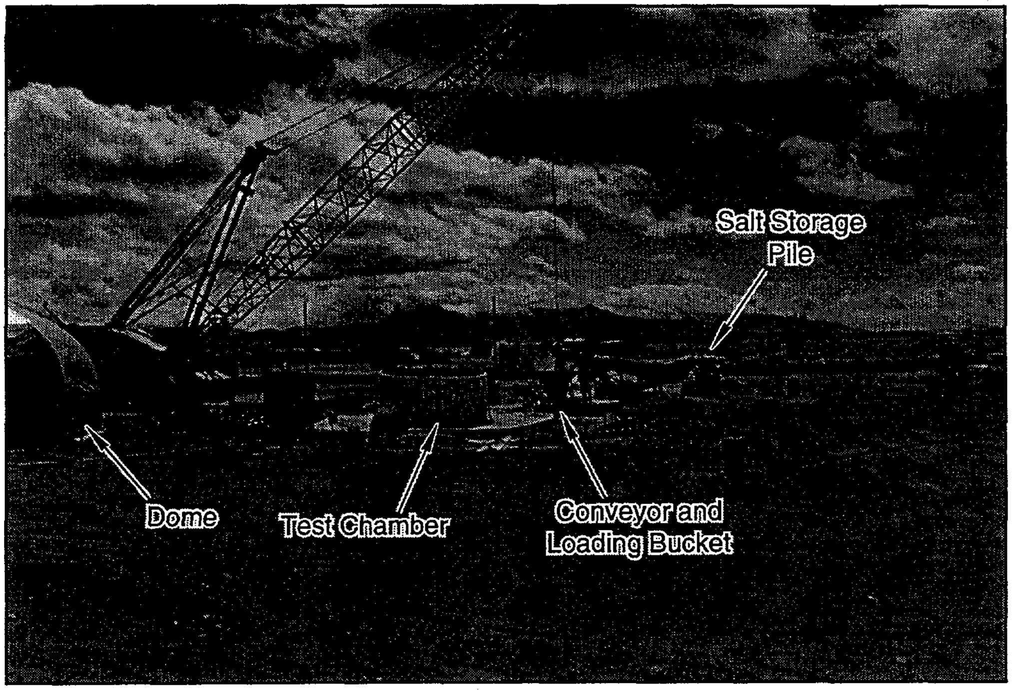

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Figure 4. Panorama of the Dynamic Compaction Test Area.

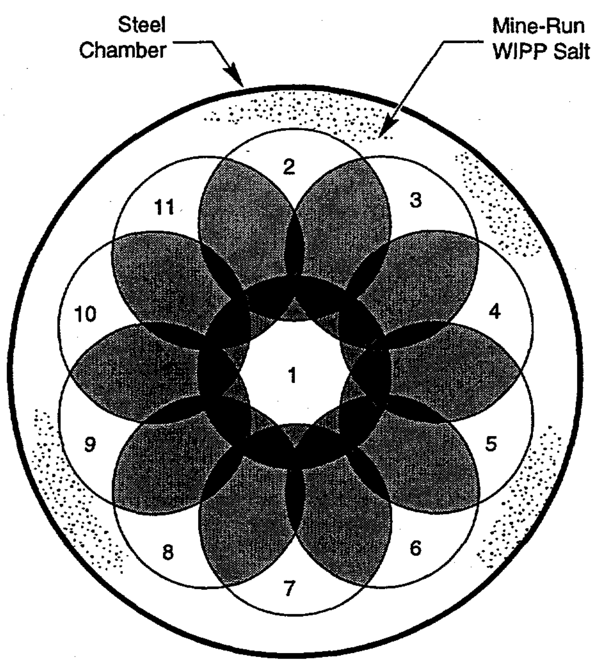

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Figure 5. Compaction Pattern.

Test Environment Concerns

Compaction demonstrations were conducted on the open mesa during winter. Protection of the salt both in the chamber and in the storage pile during inclement weather was assured. The test chamber and salt were actively heated to a relatively uniform temperature (25°C) similar to temperatures anticipated deep in the shafts at the WIPP site. A construction dome covered the entire chamber during shutdowns.

RESULTS

The Compacted Mass

The initial drop on uncompacted salt resulted in approximately 0.5 m of tamper penetration. Salt was compacted vertically and displaced laterally, forming an impact crater that bulged upward approximately 5 to 10 cm. Successive drops penetrated progressively less as the salt was compacted. Impact pulverized a fraction of the salt so that, after compaction, the surface of each lift was covered with approximately 0.4 m of powdered salt. The powder was underlain by compacted salt in which cohesiveness and density apparently increased with depth. Compaction of each subsequent lift compressed the powder of the preceding lift into a dense, indurated mass. When tamping was completed and the salt was removed from the chamber, average fractional density of the competent mass was approximately 0.9.

Compacted salt strongly adhered to all interior surfaces of the compaction chamber, indicating lateral compaction. The compactive influence expands outward from the base of the tamper and downward, which results in the salt being strongly compacted against the walls of the chamber, as it would be against the more compatible salt in the WIPP shafts. Depth of compaction clearly indicates that the lowest lift (Lift 1) was compacted further during compaction of the second and third lifts. This multiple compaction effect would advance up the shaft as salt is compacted in successive lifts.

In Situ Gas Permeability

Gas flow testing was conducted using well-established techniques. A four-packer tool provided isolated guard zones on either side of the test interval. *In situ* gas permeability testing was conducted immediately after compaction. Seven 100-mm-diameter diamond drill holes were sequentially drilled, tested for permeability, and then sealed with an expansive, quick-setting cement to prevent communication with a new test hole. All holes were drilled parallel to the walls of the chamber. One intact core of sufficient length for laboratory testing was obtained (see Brodsky et al, 1996).

Testing was accomplished by placing the four-packer tool in a freshly drilled borehole and inflating the packers. After completing a 30-minute packer compliance procedure, the data acquisition system was activated and verifications of packer set pressure, reservoir pressure, and regulator set pressure were performed. After pressure verifications were completed, test and guard zones were vented and then shut-in to the transducers. Flow was started into the test zone interval and continued until the desired reservoir pressure was observed. Flow to the interval was then stopped, and decay of test zone pressure was monitored until it had fallen to ambient pressure for a sufficient time so that each complete gas flow test lasted at least 30 minutes.

Decay of gas pressure in the test zone is a function of the flow rate into the test zone. The ability of the compacted mass to dissipate the gas is a function of several properties, including gas permeability of the material. Data acquired during test conduct enabled derivation of permeability estimates. Quantitative permeability values of the compacted mass were developed by a computer-aided analysis tool known as the Graph Theoretical Field Model (GTFM). The theoretical basis and procedures associated with the GTFM are described in Beauheim et al. (1993).

Data collected during the tests were entered into a commercial spreadsheet to perform the calculations necessary to output (1) elapsed test time in seconds, (2) test zone pressure in pascals, (3) cumulative gas flow in cubic meters at standard temperature and pressure, and (4) change in test zone pressure from the beginning of the pressure-decay cycle. These data were input into the GTFM to find optimized estimates of gas permeability and flow dimension index. The index provides an estimate of the flow path of the injected fluid. An index of 2.0 indicates that the flow follows a radial path from the cylindrical borehole. The average index for these tests was 2.7, indicating both radial and axial flow. Values of the formation thickness were assumed to be equivalent to the test zone length and porosity was assumed to be 7%. The dynamic-viscosity value for the nitrogen gas was obtained from tables in the *CRC Handbook of Chemistry and Physics* (CRC, 1994/1995).

Each of the seven boreholes was tested at two depths. Tests proceeded smoothly and quickly. Results indicate that the mass is very uniform with respect to gas permeability. Flow dimensions fit by GTFM (all were >2.0) indicate that the flow moved radially as well as axially through the mass. Table 1 is a summary of the field test results. The test identifiers follow a protocol of three-letter test series designation (DCT for Dynamic Compaction Test), two-digit borehole number, and L1 or L2, depending on the lift tested. In a homogeneous mass, calculated flow dimensions would be equal. Values average 2.5 for the bottom lift (L1) and almost 3.0 for the middle lift (L2). This variance indicates less axial flow in the compacted salt of the lowest lift, where compactive effort was greatest.

Laboratory Moisture Content

Although coring broke the compacted salt into untestable lengths, water content was readily determined from remnants. Table 2 summarizes four water-content measurements taken after compaction and field testing were completed. A calibrated amount of water yielding 1.0 wt% was added to the crushed salt as it was loaded into the chamber, and measurements taken before compaction verified that a uniform distribution was achieved. It is apparent that moisture had been lost by the time the demonstration was terminated. Because total duration of the compaction demonstration was about three months, it is likely that maintenance of a constant temperature of 25°C and imperfect insulation allowed the compacted salt to dry.

Table 1. Permeability Values of Compacted Salt Mass

Test Number	Date Tested	Estimated k_{gas}	Flow Dimension
DCT01L1	04/06/95	1.3×10^{-13} m^2	2.3
DCT01L2	04/06/95	1.1×10^{-13} m^2	2.7
DCT02L1	04/07/95	8.9×10^{-14} m^2	2.4
DCT02L2	04/10/95	1.3×10^{-13} m^2	2.7
DCT03L1	04/11/95	4.0×10^{-14} m^2	2.8
DCT03L2	04/11/95	5.5×10^{-14} m^2	3.0
DCT04L1	04/11/95	7.4×10^{-14} m^2	2.5
DCT04L2	04/11/95	5.2×10^{-14} m^2	3.2
DCT05L1	04/12/95	1.3×10^{-13} m^2	2.2
DCT05L2	04/12/95	1.2×10^{-13} m^2	2.8
DCT06L1	04/12/95	8.1×10^{-14} m^2	2.5
DCT06L2	04/12/95	1.1×10^{-13} m^2	2.8
DCT07L1	04/13/95	8.6×10^{-14} m^2	2.6
DCT07L2	04/13/95	4.0×10^{-14} m^2	3.5
AVERAGE	ALL TESTS	9.0×10^{-14} m^2	2.7

Note: L1 is the bottom lift; L2 is the middle lift.

Table 2. Moisture Content after Compaction

Specimen	Moisture Content (%)
12' DC - 1 - 3 Specimen 1	0.53
12' DC - 1 - 3 Specimen 2	0.50
12' DC - 1 - 3 Specimen 3	1.03
12' DC - 1 - 3 Specimen 4	0.69

Laboratory Permeability Testing

Extensive laboratory test results are given in a companion paper in the current *Proceedings* (Brodsky et al.). Only one sample of sufficient length for permeability testing was recovered during coring of *in situ* permeability test holes. Its fractional density was 0.899, based on an intact salt density of 2,160 kg/m^3. Visually, most of the compacted mass was of comparable density. This core sample was tested immediately for nitrogen permeability. Its initial permeability of 5×10^{-14} m^2 agreed well with *in situ* measurements of the compacted mass. The sample was further consolidated to 5 MPa, achieving a density of 0.98 and a permeability of 3×10^{-18} m^2. A significant result of laboratory experiments is the mathematical relationship describing permeability decrease as a function of density increase, which will be used in design and performance assessment.

A chain saw equipped with tungsten carbide cutters was used to extract three large samples (0.1 m^3) during decommissioning of the field site. These blocks were sealed and shipped to RE/SPEC Inc., where they were cored and tested for density, gas permeability, and moisture content. Final removal of salt from the chamber required a grinder equipped with a coarse wire wheel and a vacuum. The salt was returned to the surface spoil pile at the WIPP site.

CONCLUDING REMARKS

Measurements taken during *in situ* flow tests are the first of their kind, providing valuable information for WIPP shaft seal design. Values of permeability are used for seal evaluation as well as for WIPP Performance Assessment (PA) computations. Because compacted salt is expected to seal the repository for 10,000 years, its range of initial properties is very meaningful. PA activities require the use of conceptual models for the repository and the shaft seal system. Because the conceptual models used for seal design and PA are inherently coarse and involve other uncertainties, derivation of permeabilities within an order of magnitude falls within the range of uncertainty of the model. As the preliminary results show, the compaction demonstrations have greatly reduced the uncertainty regarding achievable initial permeability of a compacted crushed salt seal element.

Most of this text documents successful dynamic compaction of mine-run salt using technology suitable for placing seal components in the WIPP shafts. Fractional densities approaching 0.90 of intact salt were achieved within the compacted mass. This constitutes fundamental design information because design assumptions based on laboratory tests suggest fairly low initial placement densities. Permeabilities achieved in the compacted mass were on the order of 9×10^{-14} m^2 and were uniform throughout. Previous laboratory studies suggested lower permeabilities at a fractional density of 0.9, so these large-scale tests provide important information with respect to the performance of compacted salt seal components in the early years after placement.

It is certain that this compaction demonstration is only a first step toward understanding large-scale dynamic compaction of salt. Work reported here is a demonstration, not an optimization. Statements can be made with respect to placement conditions that are likely to increase density and decrease permeability. Based on the observation from this demonstration that powdered salt is thoroughly indurated by compaction, it is very probable that *in situ* permeability could be lowered if salt were ground prior to compaction. In addition, a slightly higher moisture content would likely result in increased density of dynamically compacted salt. Additional water beyond 1.0 wt% would be adsorbed on a greatly increased surface area created by crushing mine-run salt. Although the microprocesses governing time-dependent densification are just now being documented, evidence to date suggests that pressure solution and reprecipitation play key roles in void space elimination (Brodsky et al., 1996). Small amounts of moisture on grain boundaries greatly enhance this process.

With minor, easily implemented changes to the salt product before compaction, as-placed characteristics are expected to be very favorable relative to performance specifications.

Dynamic compaction appears to be an efficient and practical construction technology that could be adapted for compacting hundreds of vertical feet of salt in each of the four shafts at the WIPP. The large-scale compaction demonstration discussed in this paper utilized existing, commercially available equipment. Adaptation of surface-based equipment to shaft seal applications is under development and conceptually achievable. Application of dynamic compaction to the construction of crushed-salt seal components is capable of producing a high density column with very positive seal characteristics. Pulverization and addition of 2 wt% water may be suitable parameter changes if another compaction demonstration is attempted. With such changes to the construction method from those used in this demonstration, compaction of salt in the shaft could readily increase densities and reduce permeabilities from those reported here.

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NOTES

[1] Work supported by U. S. Dept. of Energy (DOE) under contract DE-AC04-94AL85000.

[2] A DOE facility.