

F.D. Hansen, E.H. Ahrens, V.C. Tidwell and J.R. Tillerson  
Sandia National Laboratories, Albuquerque, NM 87185\*\*

Conf-950655--4

N.S. Brodsky  
RE/SPEC Inc., Rapid City, SD

**ABSTRACT:** A practical, large-scale demonstration of dynamic compaction of mine-run WIPP salt has been completed. The demonstration initially used salt with a natural 0.26 wt % water, whereas a subsequent demonstration used salt with an additional 1.0 wt % water. Fractional densities of the compacted salt approached 0.9. Gas permeabilities of several samples extracted from the compacted masses ranged from  $10^{-12}$  to  $10^{-13}$  m<sup>2</sup>. The demonstration of a potential construction technique coupled with initial measurements of key design parameters provide needed design input for the WIPP shaft seal system.

## 1 INTRODUCTION

Reconsolidated crushed salt is proposed as the sole long-term shaft seal between the Waste Isolation Pilot Plant (WIPP) and the biosphere. The concept for a long-term shaft seal for the WIPP repository is to place crushed salt in the four shafts and to develop an effective seal as the surrounding salt creeps into the shafts, reconsolidating the salt. Permeability of the salt components is calculated to achieve performance objectives at some acceptable time in the future, an expectation which is a key to performance assessment calculations for the WIPP. Such a seal has never been constructed, and until now no performance measurements have been made on an appropriately large scale. A full understanding of construction methods, achievable initial density and permeability and time-wise performance of reconsolidating salt is required. This paper discusses nearly full-scale dynamic compaction of mine-run WIPP salt, preliminary measurements of density and permeability, and their variability within a relatively large volume of compacted material.

Current proposed designs of the shaft seal system for the WIPP site include long-term salt seals for a 10,000-year-period and shorter-term seal components comprising concrete, bentonite, and chemical seal rings. The seal system design is based on interpreta-

tions of federal and state regulations requiring that the seal system prevent gases or brines from entering the repository or migrating out of the repository. A long-standing technical position supporting the disposal of waste in salt formations is that disaggregated salt can be reconsolidated to sufficient densities to prevent excavated openings from becoming preferred pathways for transport and possible release of hazardous materials. Laboratory testing to support this position has emphasized in-place reconsolidation of crushed salt, although manufactured salt blocks or quarried salt blocks are alternatives for initial placement of the long-term seal material. Until recently, it was estimated that initial placement of salt to 80% of its theoretical intact density (2140 Kg/m<sup>3</sup>) would achieve performance standards in approximately 100 years (Nowak et al., 1990). Ongoing creep calculations considering the potential age of the shafts suggest that an initial density of 85% may be needed to assure attainment of a seal in about 100 years (Van Sambeek et al., 1992).

Confidence in parameters for structural and fluid flow calculations is limited because of a lack of experience with the behavior of reconsolidated salt. At the same time, performance assessment calculations have identified permeability of the lower shaft salt seal to be very important in retarding gas flow (WIPP PA, 1993). Therefore, to obtain a credible seal system design, a comprehensive understanding of salt reconsoli-

\* Work supported by U.S. Dept. of Energy (DOE) under contract DE-AC04-94AL85000.

\*\* A DOE facility.

**MASTER**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

62

## **DISCLAIMER**

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

ation is needed. Construction feasibility begins with a demonstration of emplacement techniques. How well can salt be placed in the shafts? What is the initial density and permeability? What is the constitutive behavior of reconsolidating salt? What is the consolidation history given the inward creep of the surrounding salt and the potential backstress produced by the reconsolidating salt? In addition, how much engineering is warranted to optimize construction? A beginning has been made to answer these questions through the compaction demonstration reported here.

## 2 DYNAMIC COMPACTION PROCEDURE

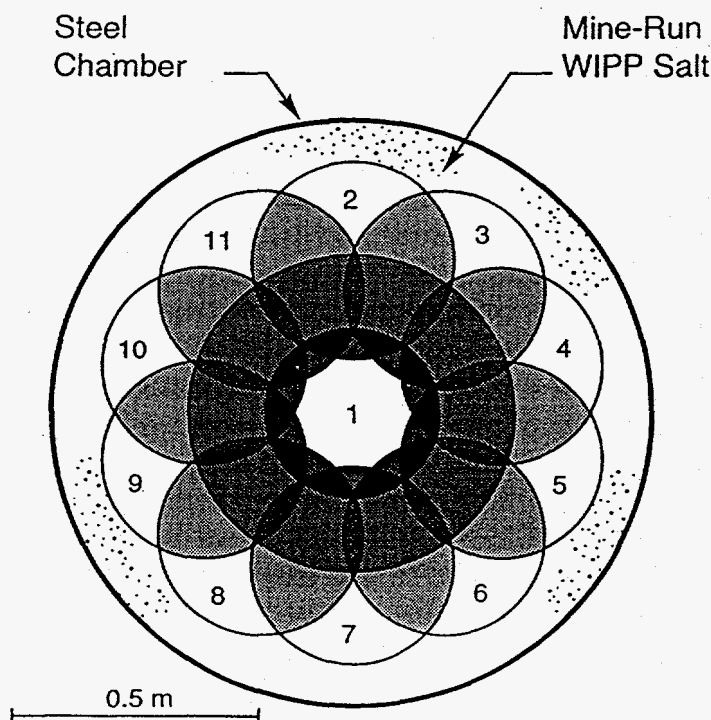
The compaction demonstrations were conducted at Sandia National Laboratories Area III Drop Tower Facility. Dynamic compaction was achieved by systematically dropping a cylindrical tamper into a chamber containing mine-run WIPP salt. The steel compaction chamber, 1.2 m in diameter and 1.8 m in height, was designed and built specially for these tests. The tamper weighed 890 kg, was 0.4 m in diameter, and 1.1 m in height. A clockwise tamping sequence illustrated in Figure 1 was used. The first drop was in the center followed by moving to the 12 o'clock position. Each sequential drop of the tamper overlapped the previous position by approximately one radius. Drop

height was 9 m. Accuracy of each drop was within 2.5 cm of the intended location.

Dynamic compaction was chosen because it is an effective technique for noncohesive soils—such as sands. Although the mechanisms of dynamic compaction of salt are not yet known, the response of salt was expected to be more similar to sand than to silts or clays. Compaction energy applied to the salt was based on typical highway construction experience (STS Consultants, 1986). Using empirical information, a vertical depth of compactive influence of about 1.5 m was calculated for the drop tower conditions. No attempt was made to optimize the compaction procedure at this initial stage. A nominal initial compaction effort approximating three times Modified Proctor Energy (MPE) was applied to two lifts: the first lift was 0.9 m high, and the second 0.6 m. To achieve one MPE the drop sequence illustrated in Figure 1 was executed by dropping the tamper three times in each position then moving to the next position. To achieve three MPE required a total of 99 individual drops of the tamper into the chamber.

One important reason for conducting dynamic compaction on an intermediate scale, such as undertaken here, is to capture the physics of the dynamic interactions between the tamper and the loose salt. Evaluation of this potential construction method is important to add credibility to the design basis. Because dynamic compaction of salt has never been attempted at a scale with construction significance, it was postulated by some that the disaggregated salt might just splash out of the chamber owing to tamper impact. Another speculation was that the salt would not compact at all; in which case we would be left with a chamber full of salt powder. Laboratory-scale tests, of course, do not simulate these construction-related concerns.

After the first lift (initially comprising 0.9 m of salt) was compacted to three MPE, measurements of the height of the salt lift were taken. Qualitatively, geometric measurements revealed how much of the void volume had been eliminated. Because of creation of salt dust on the upper portion of each lift, distortion of the chamber and minor salt loss, measurements of void space elimination was not exact. The first MPE application eliminated more than half the available void space. The second MPE removed another 20-25%, whereas the third MPE removed little void volume. A second 0.6-m lift of loose salt was placed over the first compacted lift. Nothing was done to the powder on the surface of the first lift. Three MPE were again applied to the second lift with similar void space removal accompanied by powder creation on the surface. However, the powder on the first lift surface was



TRI-6121-269-0

Figure 1. Plan view showing drop positions and sequence.

compacted to a very high density in the process of compacting the second lift.

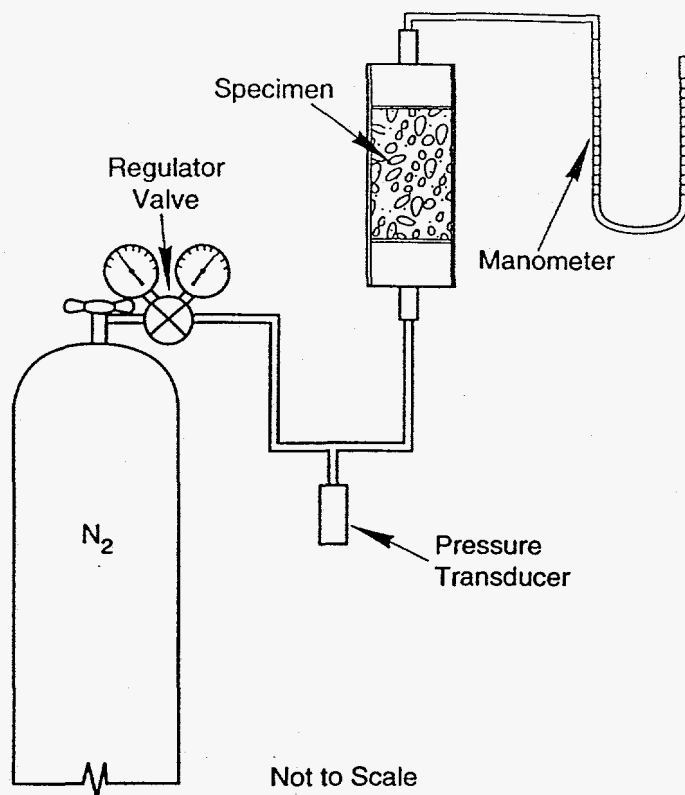
### 3 RESULTS

The first compaction demonstration (CD-1) used mine-run salt having 0.26 wt % moisture, drier than *in situ* salt which runs about 0.5 to 1.0 wt %. Geometric measurements suggested an overall fractional density of 0.87, and a few samples taken from the compacted mass averaged 0.86. A second test (CD-2) was conducted in which 1.0 wt % water was added to the loose salt. Less compactive effort (two MPE) was used. The achieved densities were over 90% of solid salt. After each of the two dynamic compaction demonstrations, an unsuccessful attempt was made to drill cores directly from the compacted mass within the chamber. The drillers could not stabilize the core barrel in DC-1. In DC-2, the cores were surprisingly friable and incohesive. Therefore, the chamber was opened and the compacted salt was cut into blocks, taken to the laboratory, and tested for permeability, density, and water content. Measurements of density and water content are straightforward; however, measurements of permeability warrant careful consideration, as discussed below.

#### 3.1 Specimen Permeability

Cored specimens were tested at RE/SPEC using two techniques: 1) a manometer system and 2) a flow meter system. Figure 2 is a schematic of the permeability apparatus with a manometer system. The gas flows through the specimen and then into one side (50 ml capacity) of a fluid-filled manometer. The rate at which the gas displaces the fluid is measured. This system was used initially on a specimen (CS/DC1-4-1/3/1) having a fractional density of 0.90. The rate of fluid displacement was rapid and the resolution was inadequate for our applications.

A flow-tube meter system commonly used for higher permeability materials (shown in Figure 3) was used for the remaining tests. A flow tube meter was used to measure the gas flow rate. Flow tube meters are calibrated to within  $\pm 5\%$  by the manufacturer for specific gases and specific inflow pressures. Only a single gas inflow pressure could be used and so the data are not Klinkenberg corrected. Table 1 is a summary of the gas permeabilities measured on dynamically compacted crushed salt. Unfortunately, Specimen CS/DC1-4-1/3/1 was epoxy-impregnated for observational work before the test system was re-configured and so permeability could not be measured using



TRI-6121-266-0

Figure 2. Schematic of permeability apparatus with manometer system.

Table 1. Summary of permeability measurements on dynamically compacted crushed salt specimens

Specimen ID <sup>(a)</sup>	Fractional Density <sup>(b)</sup>	Permeability (m <sup>2</sup> )	Measurement Method
CS/DC1-8-3	0.875	$2.43 \times 10^{-13}$	Flowmeter
CS/DC1-4-1/3/1	0.913	$2.50 \times 10^{-15}$	Manometer; Klinkenberg-corrected value
CS/DC2/MM-1/1	0.898	$1.71 \times 10^{-13}$	Flowmeter
CS/DC2/MM-2/1	0.840	$4.11 \times 10^{-13}$	Flowmeter
CS/DC2/T2S-1/1	0.882	$5.71 \times 10^{-13}$	Flowmeter
CS/DC2/T2S-3/2	0.853	$1.10 \times 10^{-12}$	Flowmeter

- (a) CS = Crushed Salt; DC1 = Dynamically Compacted, Dry, 3 MPE; DC2 = Dynamically Compacted, 1% Water Added, 2 MPE.
- (b) Fractional density is based on an intact density of  $2140 \text{ kg} \cdot \text{m}^{-3}$  and the specimen volume determined before permeability testing was initiated. The permeability tests were conducted at 1 MPa confining pressure and in some cases additional consolidation occurred during the test.

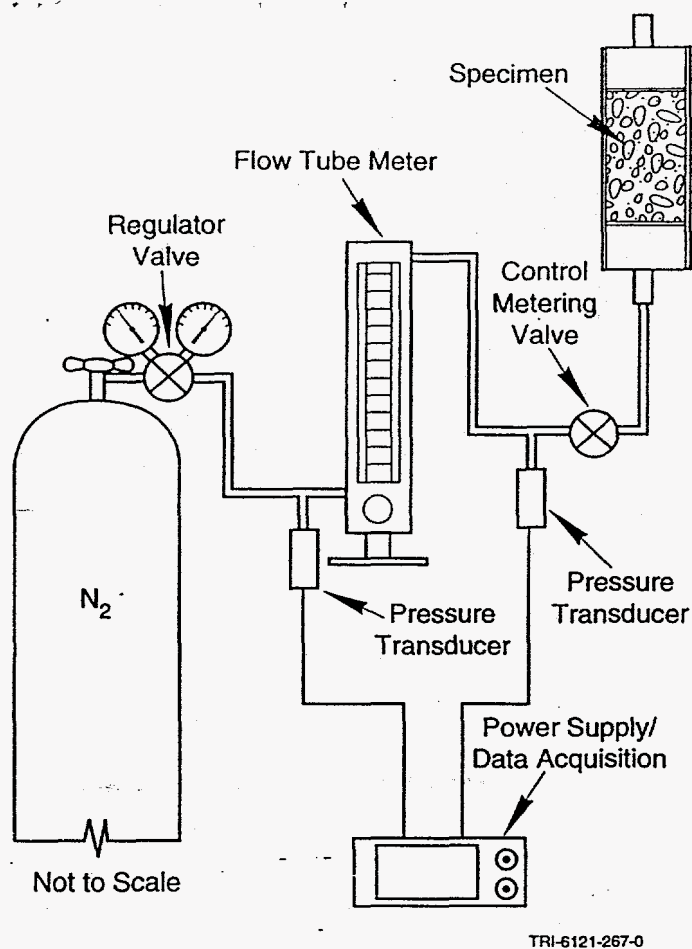


Figure 3. Schematic of permeability apparatus with flowmeter system.

a flowmeter. The permeability data are plotted in Figure 4 along with data from Brodsky (1993). Note that two samples from DC-1 (dry, 3 MPE) and four samples from DC-2 (1% water added, 2 MPE) were tested. There is no appreciable difference between the permeabilities measured for the two differently dynamically compacted masses. Based on relative permeability effects, the permeabilities of DC-2 specimens were expected to be lower than the DC-1 specimens. The gas permeabilities are above the projection of the straight line fit to the brine permeability data by about two orders of magnitude. Barring relative permeability effects, one would expect gas permeability to be higher than brine permeabilities. Brine transport and deposition of salt can also reduce permeability.

### 3.2 Spatial Variability of Gas Permeability

Laboratory testing of cored specimens was augmented by bulk measurements on large blocks using some recent technology (Tidwell, 1994). A mini-gas permeameter automated for laboratory use was employed to investigate spatial variability of gas permeability within an intact block of dynamically compacted salt.

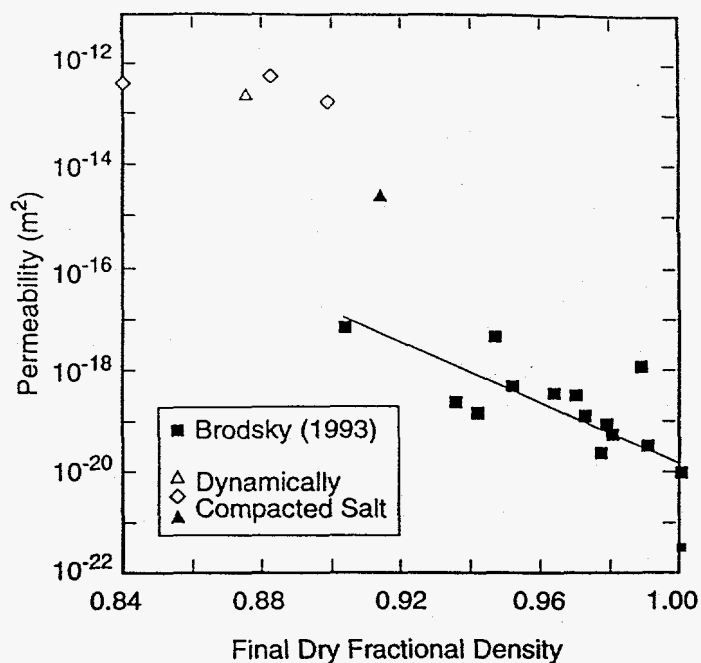


Figure 4. Permeability-versus-fractional density for crushed salt specimens. Solid squares represent brine permeability measurements given in Brodsky (1993) and a linear fit to that data is given. Triangles represent CS/DC1 specimens, and diamonds represent CS/DC2 specimens. Unfilled symbols (diamonds and one triangle) indicate use of a flow meter, and the solid triangle indicates use of a manometer and the application of a Klinkenberg correction.

The mini-gas permeameter, which has found widespread use in field and laboratory characterization of sandstones, carbonates and welded tuffs, is well suited for this study because it acquires data quickly, inexpensively and non-destructively. Measurements are made by compressing the permeameter-tip seal against a rock surface and injecting gas at a constant pressure into the rock while measuring the steady gas-flow rate.

The permeameter consists of four mass-flow meters each of differing sensitivity, a pressure transducer, a barometer, and a temperature sensor connected to a regulated source of compressed nitrogen (Figure 5). The permeameter has been automated for laboratory use via specially adapted PC-based software. An x-y positioning system coupled with a pneumatic piston has also been automated for positioning and compressing the permeameter-tip seal against the rock surface. The tip seal simply consists of a silicone rubber ring (0.31 cm ID and 0.63 cm OD) mounted on an aluminum piston. Gas permeability is calculated directly from information on tip-seal geometry, flow rate, and injection pressure. These calculations are accomplished by means of a modified form of Darcy's Law:

$$k = \frac{Q_1 \cdot P_1 \cdot \mu}{a \cdot G_0 \cdot 0.5 \cdot (P_1^2 - P_0^2)} \quad (1)$$

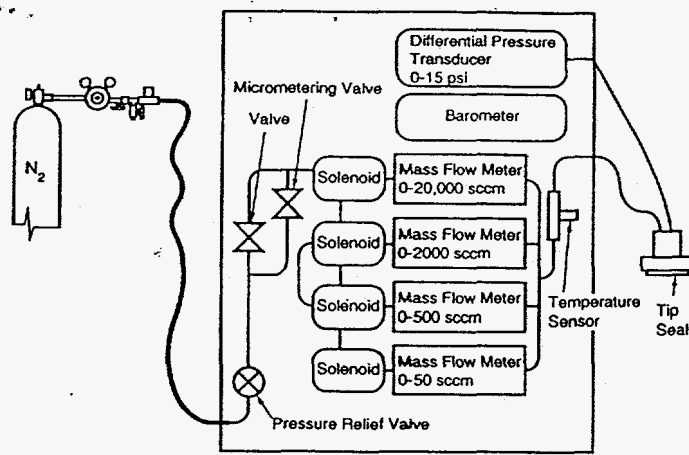
where  $k$  is gas permeability,  $Q_1$  is gas-flow rate,  $P_0$  is atmospheric pressure,  $P_1$  is gas injection pressure,  $\mu$  is gas viscosity,  $a$  is internal tip-seal radius, and  $G_0$  is an empirically derived geometric factor that accounts for complexities associated with the flow-field geometry.

Measurements were collected on a 10-by-5 grid (0.63 cm centers) from a single face of a 0.6 x 0.3 x 0.3 m block of compacted salt. Analysis of the data revealed that the gas permeability is log-normally distributed with a mean of  $2.1E-13 \text{ m}^2$  and standard deviation of  $9.1E-14 \text{ m}^2$ . The correlation length scale of the gas permeability, that is the length over the permeability is spatially correlated, was found to be approximately 1.9 cm. This corresponds closely with the average grain size of the crushed salt prior to compaction. To test the precision of the permeameter, these same measurements were repeated. The cumulative distributions for the two data sets were almost indistinguishable, thus supporting the precision of the instrument measurements.

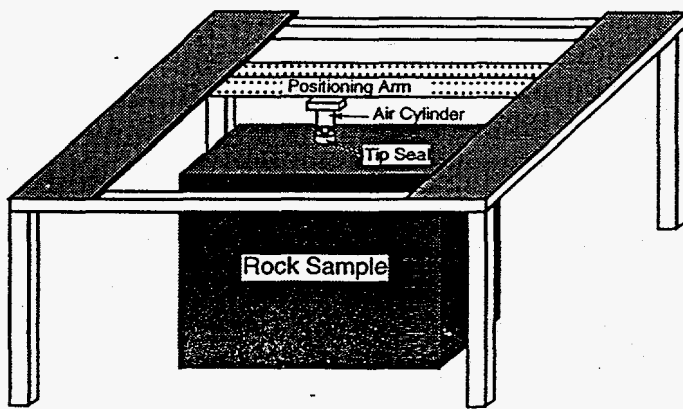
#### 4 DISCUSSION AND CONCLUSIONS

When this demonstration was conceived, it was far from clear that the compacted salt mass would be cohesive. The strategy adopted was to start with basic mine-run salt and not change it in any way. After the favorable results of the baseline compaction demonstration (DC-1), we decided to modify the WIPP salt in the second demonstration by adding 1 wt % water (DC-2). The overall effort was very basic, yet establishes first-of-its-kind parameters for a salt seal component. Laboratory evaluations of the compacted salt included simple measurements of water content and fractional density, and more sophisticated measurements of permeability. Measurements were somewhat limited in extent because of the demonstrational aspects of this initial work. These exploratory compaction results and laboratory measurements will guide testing associated with a large-scale (3-m-diameter) dynamic compaction test program currently being planned.

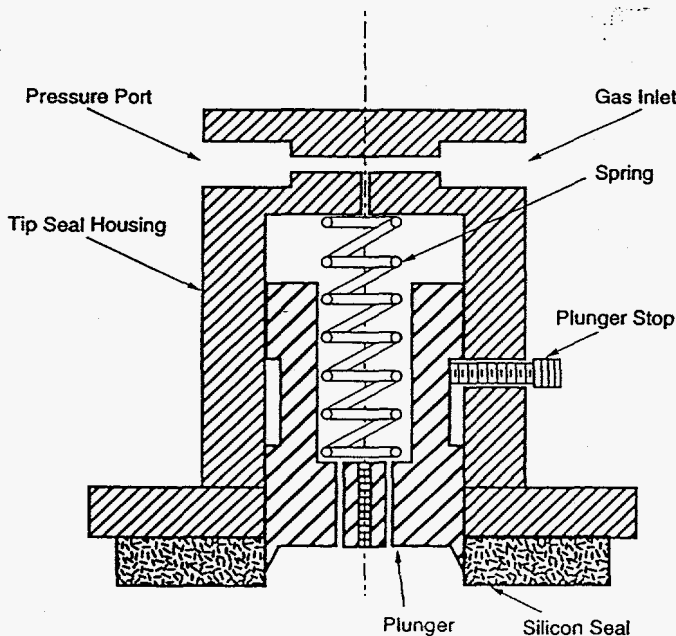
Whereas these results are encouraging, they remain only preliminary. Laboratory work continues to define the constitutive properties of reconsolidating salt. Observational microscopy is needed to define the processes of compaction and reconsolidation. The next series of large dynamic compaction demonstrations will



a).



b).



c).

TRI-6121-270-0

Figure 5. Automated gas-permeameter test system; a) schematic of electronic gas permeameter, b) schematic of positioning system, c) schematic of tip seal.

include a more rigorous sampling format to facilitate the complementary laboratory work. Bulk measurements of permeability are anticipated, if cores are successfully extracted from the compacted mass, and the boreholes will be flow-tested. Specimens will be further consolidated in the laboratory to measure the stress-strain-permeability relationship as the salt densifies.

We have demonstrated that mine-run WIPP salt can be uniformly compacted using readily available technology to reasonably high densities. Although construction of shaft seals for the WIPP site probably will not occur for a generation, a credible design must be submitted to regulators during the licensing process. Because of the uniqueness of the WIPP sealing strategy (to use reconsolidated salt as the long-term seal), demonstration of the feasibility and performance expectations are considered fundamentally important. New information gained by this initial dynamic compaction demonstration provides confidence in a salt placement technique. In addition, measurements of permeability and density have created a basis for seal system models and performance.

## REFERENCES

- Brodsky, N. S. 1993. *Hydrostatic and Shear Consolidation Tests with Permeability Measurements on Waste Isolation Pilot Plant Crushed Salt*, SAND93-7058. Sandia National Laboratories, Albuquerque, NM.
- Nowak, E. J., J. R. Tillerson and T. M. Torres. 1990. *Initial Reference Seal System Design: Waste Isolation Pilot Plant*. SAND90-0335. Sandia National Laboratories, Albuquerque, NM.
- STS Consultants, 1986. *Dynamic Compaction for Highway Construction-Volume 1, Design and Construction Guidelines*, U. S. Department of Commerce, National Technical Information Service, Springfield, VA.
- Tidwell, V. C. 1994. *Laboratory Investigation of Constitutive Property Scaling Behavior*, SPE 28456, Formation Evaluation and Reservoir Geology, pp. 947-957, 1994 Society of Petroleum Engineers Annual Technical Conference and Exhibition, New Orleans,
- Van Sambeek, L. L., D. D. Luo, M. S. Lin, W. Ostrowski, and D. Oyenuga. 1992. *Seal Design Alternatives Study*. SAND92-7340. Sandia National Laboratories, Albuquerque, NM.
- WIPP PA (Performance Assessment) Department. 1993. *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992*. Vol-

ume 5: *Uncertainty and Sensitivity Analyses of Gas and Brine Migration for Undisturbed Performance*. SAND92-0700/5. Sandia National Laboratories, Albuquerque, NM.

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.