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Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico

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STUDIES OF ELECTRICAL AND ELECTROMAGNETIC METHODS FOR CHARACTERIZING SALT PROPERTIES AT THE WIPP SITE, NEW MEXICO

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ABSTRACT

At the Waste Isolation Pilot Project Site in southeastern New Mexico, technical and engineering issues related to the long-term storage of hazardous wastes in bedded salt are being studied. For nuclear waste repositories with both long operational periods (50 yr) and long performance assessment periods (10000 yr), the Disturbed Rock Zone (the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation; abbreviated as DRZ) is important to both operational (e.g., slab or fracture failure of the excavation) and long-term performance (e.g., seal system performance and fluid transport). Because of the large contrast in electrical conductivity between crystalline salt and salt saturated with water, it is to be expected that electrical geophysical methods may play an important role in delineating portions of the DRZ. The Colorado School of Mines, under contract to Sandia National Laboratories, has carried out experimental surveys using the direct current electrical method and two electromagnetic methods underground in the mine workings. The results suggest that the various electrical methods are effective in locating low resistivity zones in the salt, which probably represent moisture-rich zones. Furthermore, it appears that such measurements might well be further optimized in terms of survey effort and design of systems to provide a high response to small-scale conductive features in the salt.

ACKNOWLEDGMENTS

The authors wish to thank Dr. David Borns and Sandia National Laboratories in Albuquerque, New Mexico for their assistance and financial support. Dan Garber of Sandia National Laboratories is thanked for his assistance in getting the manuscript ready for publication.

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STUDIES OF ELECTRICAL AND ELECTROMAGNETIC METHODS FOR CHARACTERIZING SALT PROPERTIES AT THE WIPP SITE, NEW MEXICO

Background

The Waste Isolation Pilot Plant (WIPP), located 23 miles east of Carlsbad in southeastern New Mexico, is being constructed in part to evaluate engineering and technical problems associated with the long-term storage of nuclear waste in bedded salt. The facility is being constructed in rocks of the Salado Formation of Permian age (see Figure 1), at a depth beneath the surface of approximately 650 meters. The Salado Formation is part of a 1.2-km-thick layered evaporite sequence in the Delaware Basin of southeastern New Mexico (Powers et al., 1978; Barrows and Fett, 1985). Rock units of interest in this report are Ochoan, with the exception of the underlying Delaware Mountain Group (DMG). The oldest Ochoan unit is the Castile Formation, which overlies the Bell Canyon Formation of the DMG (Figure 1). Locally, the Castile consists of three anhydrite units separated by two halite units. Above the Castile stratigraphically is the Salado Formation, which consists of halite, anhydritic and/or polyhalitic halite, and argillaceous halite. Overlying the Salado is the Rustler Formation, which contains siltstones, anhydrites, dolomitic siltstones, dolomites, and halite.

At the WIPP Site, the beds are almost flat, dipping to the southeast at only 10 meters per kilometer. Locally, deformation has produced anticlines in the Castile and lower Salado formation (Borns et al., 1983). Portions of the Rustler and Dewey Lake formations may exhibit local zones of dissolution, breccia pipes, joints, and fractures (Barrows and Fett, 1985). Underground at the WIPP Site within the Salado Formation, fractures within salt and anhydrite, and zones of brine influx have been observed from the excavation. The characterization of these fractures and zones of brine influx is important to the evaluation of operational (e.g., slab or fracture failure of the excavation) and long-term performance (e.g., seal system performance and fluid transport) of the WIPP Site. Therefore, in order to guide both construction and performance assessment, it is essential that the capability for detecting and mapping fractures and brine concentration in salt be developed.

The rock property which is most sensitive to the presence of water is the electrical resistivity *(or conductivity, which is the reciprocal of resistivity, and the units for conductivity [millisiemens] and resistivity [ohm-m] are used interchangeably)*. Pure (anhydrous) rock salt is an insulator, having a resistivity of thousands of Ω-m (Lishman, 1961). On the other hand, evaporite sequences with thin layers of anhydrite and a high content of hygroscopic salts have a resistivity of tens to hundreds of Ω-m (Kessels et al., 1985). The electrical resistivity of evaporites appears to obey Archie's law relating bulk resistivity to water content:

$$\frac{\rho_o}{\rho_w} = \frac{a}{\phi^m}$$

where:

ρ_o = the resistivity of the rock
ρ_w = the resistivity of the pore fluid
a = a constant
ϕ = the porosity
m = the cementation factor.

As a consequence, water contents as low as a few hundred parts per million (by weight)

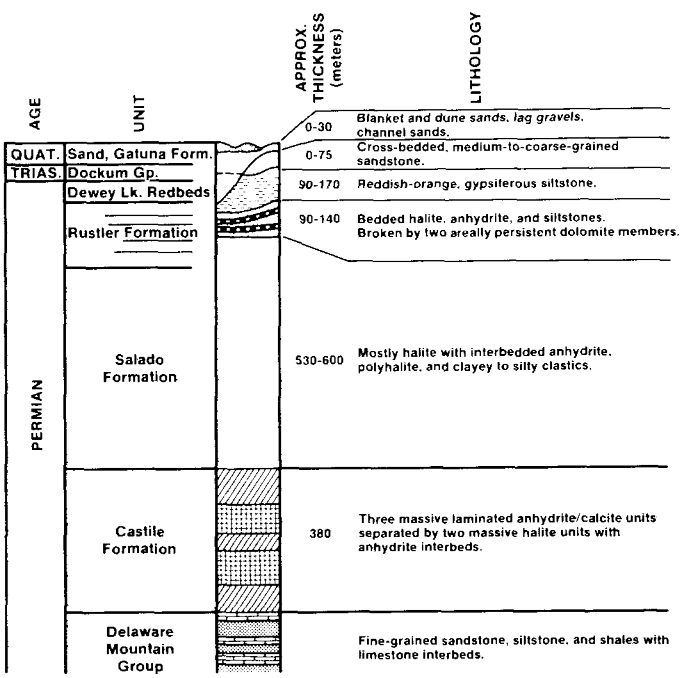

Figure. 1 Stratigraphic Section for the WIPP Site

will affect the bulk resistivity of pure salt markedly, as will water contents as low as 1000 or 2000 ppm in the less pure sequence of evaporites.

Electrical resistivity or conductivity is a diagnostic property in salt for detecting the presence of even small amounts of water, requiring only that an accurate and operable method for measuring resistivity (or conductivity) in place is available. Because of the oil and gas deposits in the vicinity of the WIPP Site, as well as the commercial deposits of evaporated minerals, extensive efforts to measure the resistivity of the section have been made over the past half-century. More recently, studies of resistivity have been carried out in conjunction with the GNOME experiment carried out by the U.S. Atomic Energy Commission (Keller, 1962), and with development of the WIPP Site using conventional electrical and electromagnetic methods on the Earth's surface (Washburne and Sternberg, 1985). On the basis of past work, it appears feasible to detect fractures and brine concentrations in the salt using these surface-based surveying techniques. However, the question remains as to how well such features can be detected if the surveying methods were optimized to the problem of detecting small conductive features in layered salt. The Department of Geophysics at the Colorado School of Mines (CSM) undertook a study of exploration methods using very general forms of transmitter and receiver arrays operating underground. The results of these field measurements were an evaluation of the survey approach, in terms of both sensitivity to small features in the salt, and evaluation of the compatibility of the survey technique with ordinary mine operations and constraints.

IN-MINE ELECTROMAGNETIC SURVEYS

The initial phase of the CSM study was the use of conventional electromagnetic coupling equipment of short range to make measurements of the electrical resistivity of wall rock in the tunnel openings at the WIPP Site. Two systems were used: the EM-31 and EM-34 systems manufactured by Geonics, Ltd., of Toronto, Canada. In both systems, the mutual coupling between two induction coils is measured and converted to apparent resistivity using self-contained analog computation circuits. With the EM-31 system, the two coils are separated by a distance of 3 meters and energized at a frequency of 10 kHz. In the EM-34 system, the two induction coils are separated by 20 meters, and energized at one of two frequencies (6.4 or 1.6 kHz). The distance of search for the two instruments is 1 to 2 meters (for the EM-31) or 10 to 20 meters (for the EM-34).

Measurements were carried out with the EM-31 equipment along lines in drift NIIOO between station E140 and E3000, in drift E300 between stations S400 and S2100, and in drift E140 between stations S3700 and S2100. Readings were made at intervals of 3.2 or 7.6 meters along these intervals. Locations are indicated on a map of the WIPP Site in Figure 2.

Two profiles of resistivity measurements made with the EM-31 equipment are shown in Figures 3 and 4. Apparent resistivities are the integrated resistivity of the volume of rock interogated by the system. Also, since conductivity is the reciprocal of resistivity, the two are used interchangeably. Measured conductivities range generally from 200 to 1000 Ω-m (1 to 5 millisiemens per meter). A distribution (histogram) of the conductivities measured with the EM-31 equipment is shown in Figure 5. This histogram shows that the bulk conductivity (the reciprocal of resistivity) near the tunnels is between 2.0 and 2.5 millisiemens per meter with some areas having a higher resistivity of approximately 3.25 millisiemens per meter.

A single profile was measured with the EM-34. These measurements were recorded in Drift NIIOO as the first EM-31 profile (Figure 6). This profile was measured in NIIOO as a comparison of the EM-31, and was used as a control to test the accuracy of the EM-31. In the case of the EM-34, measured conductivities ranged from 7 to 10 millisiemens per meter (resistivity from 100 to 140 Ω-m).

The deeper measurements (with the EM-34) show a conductivity several times larger than those measured with the EM-31 equipment. This may reflect an alteration in the conductivity of the rocks forming the walls of the tunnels, which are dried by the warm air of the ventilation system. Such a dried rind was observed by Keller(1962) in measurements made on the walls of tunnels in rhyolitic tuff at the Nevada Test Site.

The EM-34 gives much more uniform values than the EM-31. The EM-34 has a larger depth of penetration (up to 20 meters) so that it uses a larger rock volume to derive its resistivity than does the EM-31 (up to 4 meters). Because of this, the EM-31 is more able to detect small zones of higher or lower conductivity near the tunnels.

In Figure 7, the EM-31 and EM-34 resistivities are compared with the data Kessels et al. (1985) obtained from salt mines in Germany. Based on this comparison we expect the water content of the salt around the mine openings to increase from 0.8 to 1.0% (by weight) near the surface to between 2 and 3% at a depth of several meters.

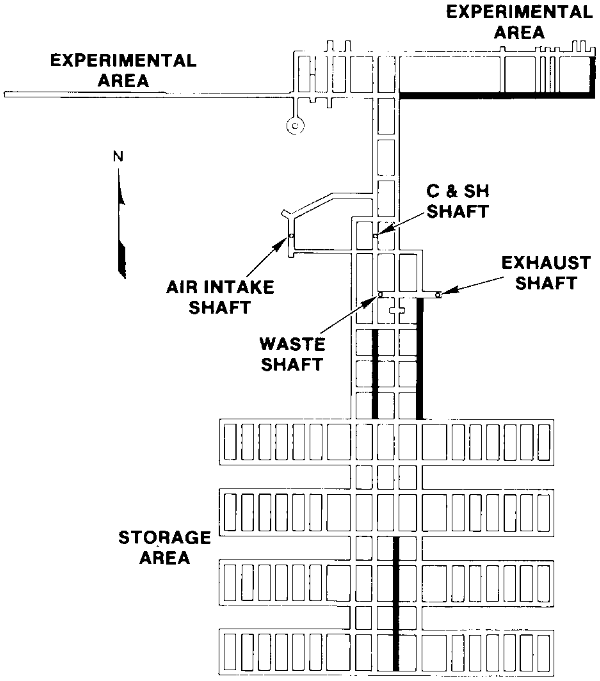

Figure 2. Location Map of EM-31 and EM-34 Traverses in the WIPP Underground Workings

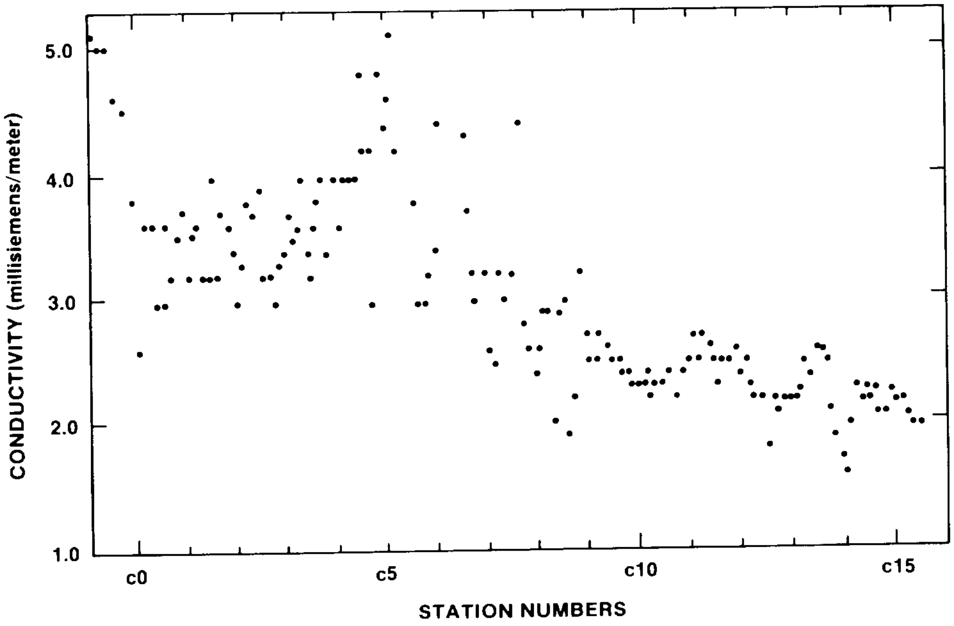

Figure 3. Plot of Conductivity vs. Distance for EM-31 Data Recorded in Drift N1100 between E140 and E1540

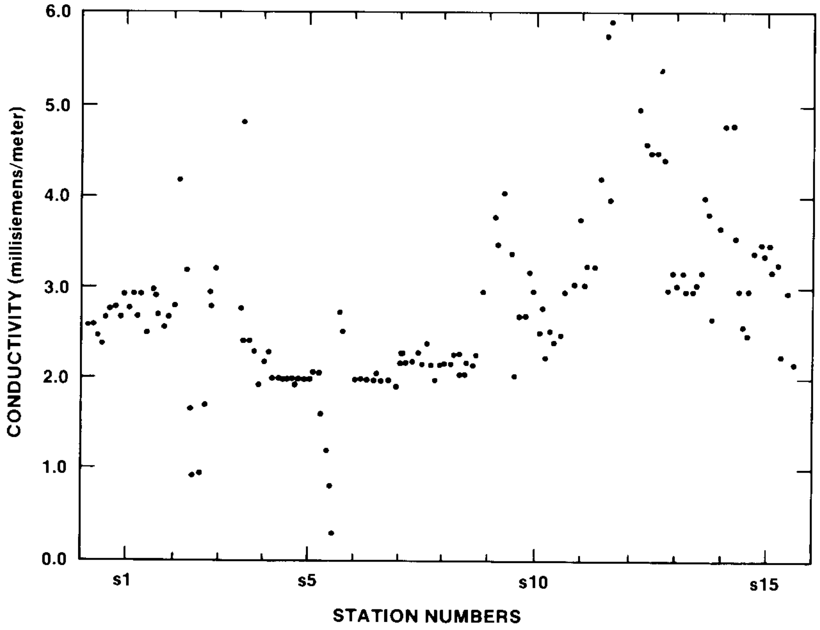

Figure 4. Conductivity vs. Distance in E140 from S3700

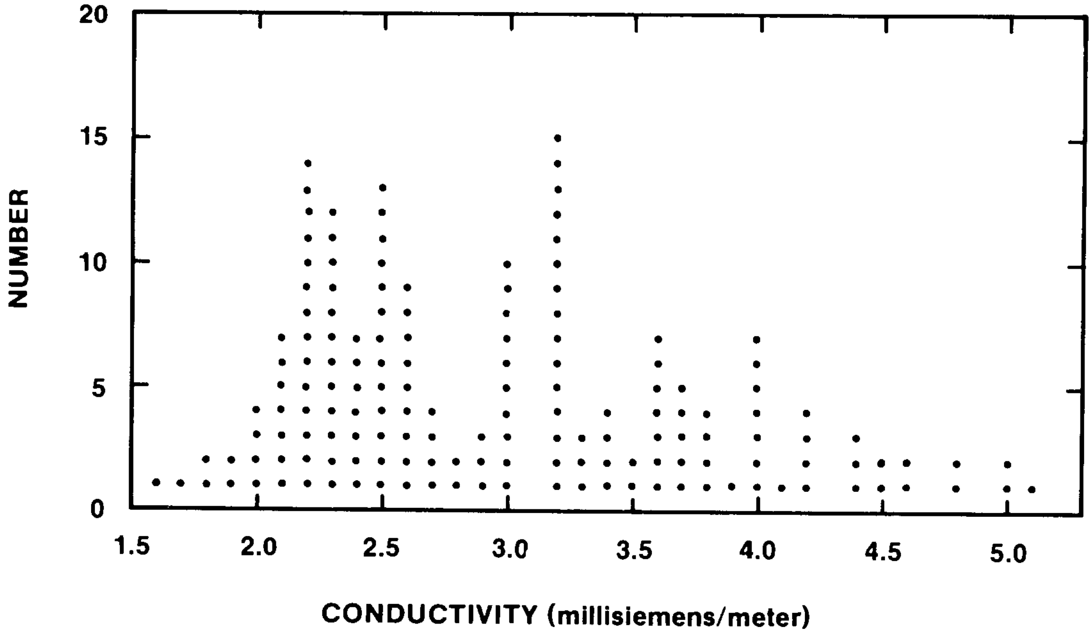

Figure 5. Histogram of Conductivity for Drift N1100 Measured with the EM-31

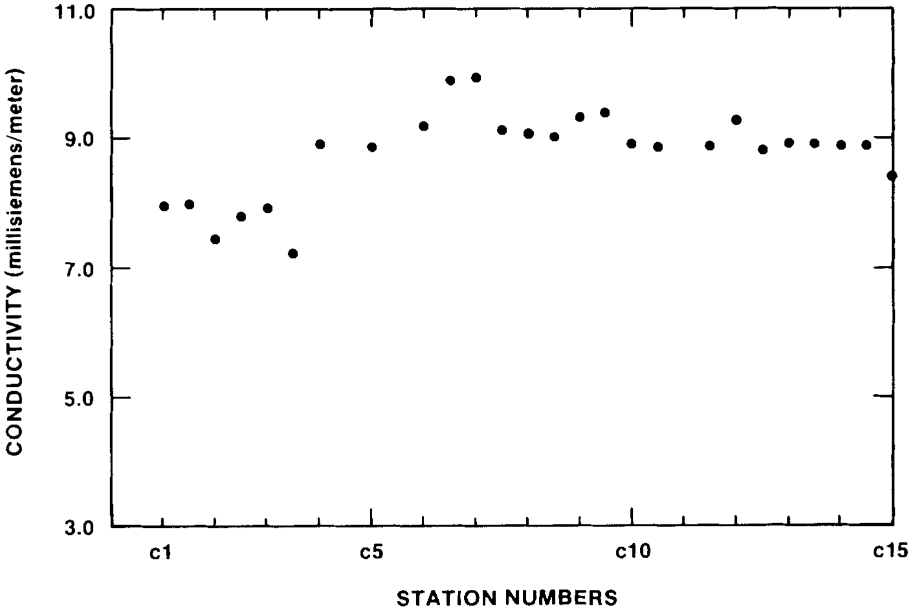

Figure 6. Conductivity vs. Distance in E140 from S3700 to S2100 in Drift N110 between E140 andE1540 with a 20-meter Loop Separation

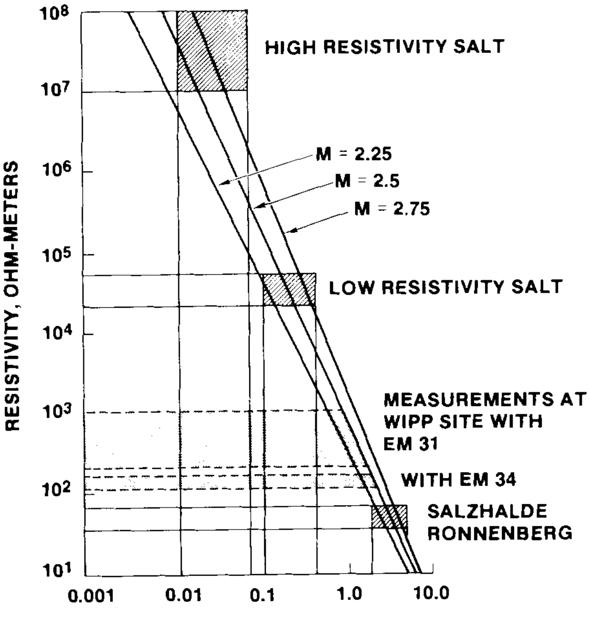

Figure 7. Relationship between Apparent Resistivity and Water Content for Different Factors of Concentration Showing Ranges for Resistivity and Water Contents

IN-MINE ELECTRICAL (DC) MEASUREMENTS

A major effort consisted of making electric field and electric potential measurements in the mine openings with a source of direct current sited on the surface, using a generalized resistivity mapping approach. Receiver locations are shown in Figure 8.

Experimental Setup

The rocks around the mine workings were energized using a fixed dipole source located on the earth's surface immediately to the north of the underground workings. Well casings extending to a depth of about 300 meters were used as electrodes; the two wells were located about 1.0 kilometer apart. The primary power supply used for this purpose was a 27-KVA, gasoline-engine-powered electrical generator. The AC output was converted to DC and switched at intervals of 4 s, to reverse the direction of current flow. The peak-to-peak level of the reversals in current to the source electrodes was nominally 200 amperes, though the level varied by about 10%, depending on line heating. Switching of the current to the source electrodes was controlled by a precision clock.

For the underground measurements, a temporary laboratory was established underground for the operation of a Digital Equipment Corporation MINC 11/23 computer as a data recording device. Voltages developed in the rock exposed in the mine were detected using pairs of copper/copper sulfate half-cells held against the rock forming the wall or floor of the tunnel at a measurement site. At each measurement site, four measurements were made; three of these were made with half-cells separated by 2 meters, and a fourth measurement was made of the voltage drop between one half-cell at the measurement site and another reference half-cell near the underground laboratory. For the three measurements made with half-cell pairs separated by two meters, it was assumed that the ratio of voltage difference to separation was approximately equal to the electric field component along the direction of separation. The fourth measurement was taken to be the potential at the recording site, by adding to it a reference potential from the half-cell at the underground laboratory.

The voltage from a pair of half-cells was amplified with a battery operated amplifier at the measurement site, before transmitting it over a twisted pair of wires to the underground laboratory. At the laboratory, the signal from the measurement site was converted to digital form with 12-bit resolution, and recorded on a flexible disc by the MINC 11/23 computer. Each reversal of the electric field or potential was sampled 1024 times, using a second precision clock to synchronize the recording interval with the transmitter. A typical record of a voltage reversal is shown in Figure 9. A total of 135 measurements was made at the 45 sites indicated in Figure 8.

Apparent Resistivity with a Uniform Earth as a Reference

In DC electrical surveys, the first step in interpretation is usually the computation of an apparent resistivity; often such an apparent resistivity is similar in magnitude to the rock resistivity and can be used directly in evaluating the electrical properties of the rock in which the measurements were made. The usual definition of apparent resistivity is that it is the resistivity for a uniform half-space (a reference earth) that would have lead to the observation of the same voltages as were ac-

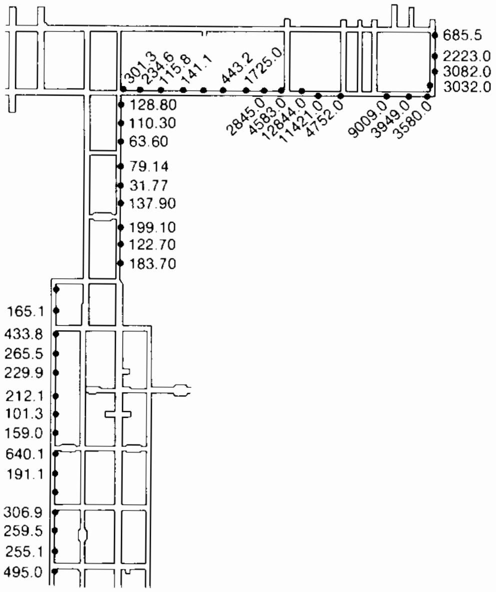

Figure 8. Location Map for DC-Resistivity Stations and Measured Apparent Restivities

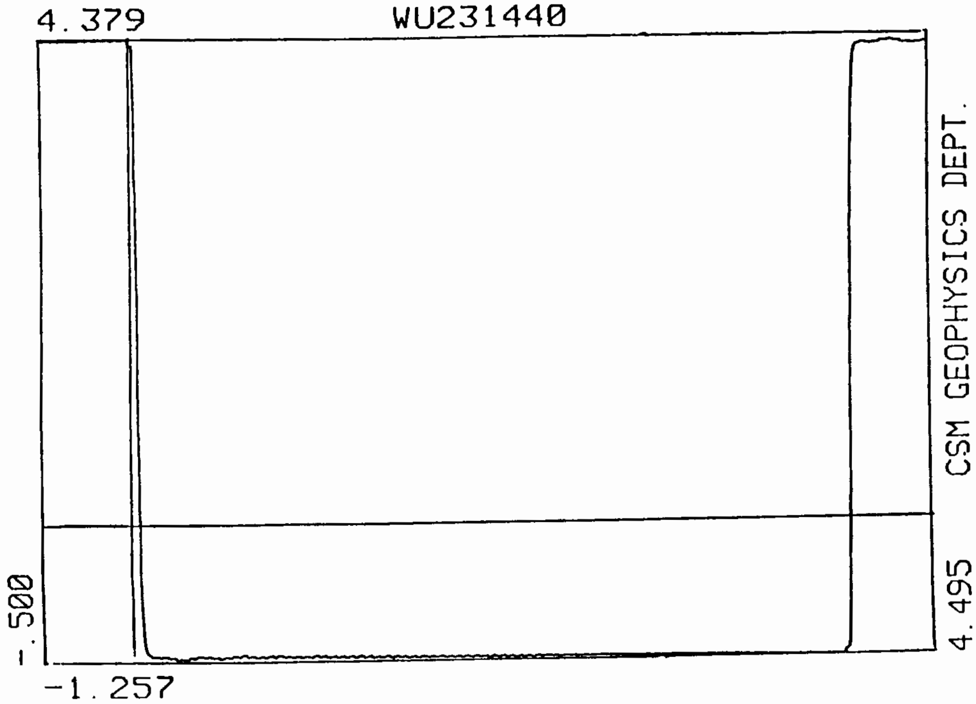

Figure 9. Typical DC Recording

tually observed in the real, usually inhomogeneous earth. Often, this apparent resistivity is viewed as a weighted average of the resistivities actually existing in the earth, with the weighting depending on how much of the excitation current enters any given part of the earth with a given resistivity. For a four-point array, the apparent resistivity can be calculated as:

$$\rho_{a,1} = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}} \quad \frac{V_{MN}}{I_{AB}} \qquad (1)$$

where AM, AN, BM, and BN are the distances between the source electrodes A or B and the receiver electrodes M or N, V is the voltage measured between M and N and I is the current driven between A and B.

Calculations using Eq. 1 are based on an assumption that current flows from each of the well casings as though each were a point electrode on the surface. Whether or not this is a reasonable assumption can be evaluated as follows. Flow of current from the length of casing at each well was simulated as ten individual flows from sections of casing at ten points along its extent. The location of these points and the fraction of current flowing in each was determined from the resistivity well log obtained in the well before casing. This resistivity log was integrated over the depth of each well to provide the conductance vs. depth curve shown in Figure 10. This curve has the character of a series of nearly straight-line segments, each segment representing an interval with relatively uniform resistivity. To simulate the full casing, it was assumed that a point electrode was located at each midpoint of an interval characterized by a straight-line segment. The amount of current assigned to each such point electrode was in proportion to the portion of the total conductance contributed by each layer. Equation (1) was again used to compute apparent resistivity, but in place of two

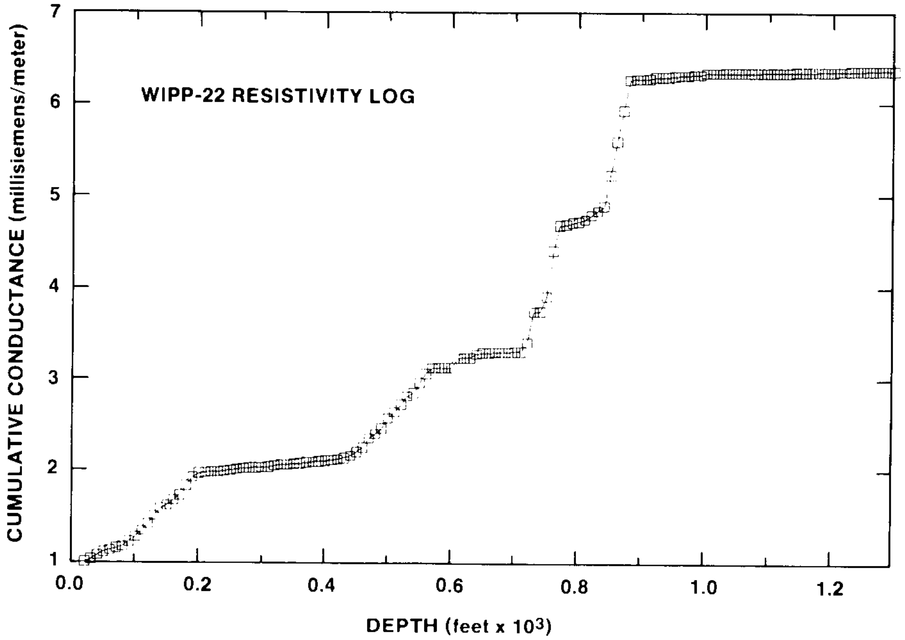

Figure 10. Cumulative Conductance vs Depth for WIPP 22 Resistivity Log

point electrodes, 20 point electrodes were used as sources. The differences found with this more exact approach were not overwhelming, though some values were changed up to 20%.

The distribution of apparent resistivity values was determined for the principal direction of the electric field. The range of apparent resistivities (tens and hundreds of Ω-m) appears as low for salt. However, this is due to definition of apparent resistivity used to characterize the salt. The definition assumes that the current entering the salt must have the same density as it would in a uniform earth. In fact, the current from the sources spreads through the more conductive surface layers of rock, with the current density flowing into the underlying salt being very low in comparison with that in a uniform earth. As an extreme case, if salt might be perfectly insulating, then no current would flow from the surface layer into the salt, the measured electric field would be zero, and the computed apparent resistivity would be zero. Because of this, we have chosen to define apparent resistivity in terms of a three-layer reference model, described in the next section.

Apparent Resistivity with a Three-Layer Reference Earth

Since the current entering the salt at the Rustler/Salado contact does not have the same current density as a model based on a uniform distribution of resistivities as discussed above, apparent resistivities are not accurately calculated by Equation (1) alone. Therefore, we have developed a three-layer model to compute apparent resistivity and to account for the stratigraphy at WIPP (Figure 11). The surface layer is characterized by a conductance (S_1: the ratio of thickness [h_1] to resistivity [ρ_1]), and is energized by vertical line electrodes (the well casings) providing a current, I, to the earth. The second layer is characterized by a transverse resistance, T_2 (product of thickness, h_2, and resistivity, ρ_2). The third layer is assumed to have negligible resistivity (well logs show that the third layer has a resistivity less than 10 Ω-m). The three layers approximate the Rustler Formation (water-bearing), the Salado/Castile Formations (salt and anhydrite-bearing) and the Bell Canyon Formation (water-bearing), respectively.

With this model the electric field and the potential at the surface of the earth and at the surface of the second layer are virtually the same if the resistivity of the second layer is much greater than the resistivity of the surface layer. The potential at the bottom of the salt layer is about zero because of the high resistivity. Knowing the potential at the top and bottom of the salt layer, one then can predict the magnitude of the electric field within the salt merely by dividing the potential drop by the thickness of the salt. This requires knowledge of the conductance of the surface layer and of the transverse resistance and thickness of the salt.

The electric field on the surface can be computed using well-known methods (Keller and Frischknecht, 1966). For the model assumed here the electric field will at first decrease in inverse proportion to distance from a single well casing:

$$E(r) = \frac{I}{2\pi r S_1} \qquad (2)$$

where r is the distance from casing to observation point, I is current, and S_1 is the conductance of the surface layer. At some large distance such that the area for vertical leakage of current from the first layer to the

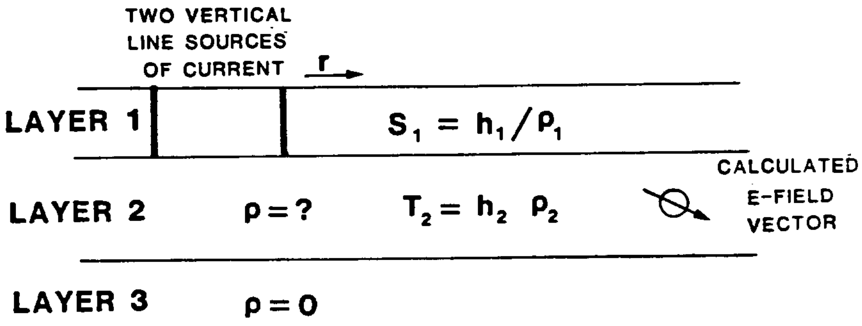

Figure 11. The Three-Layer Model

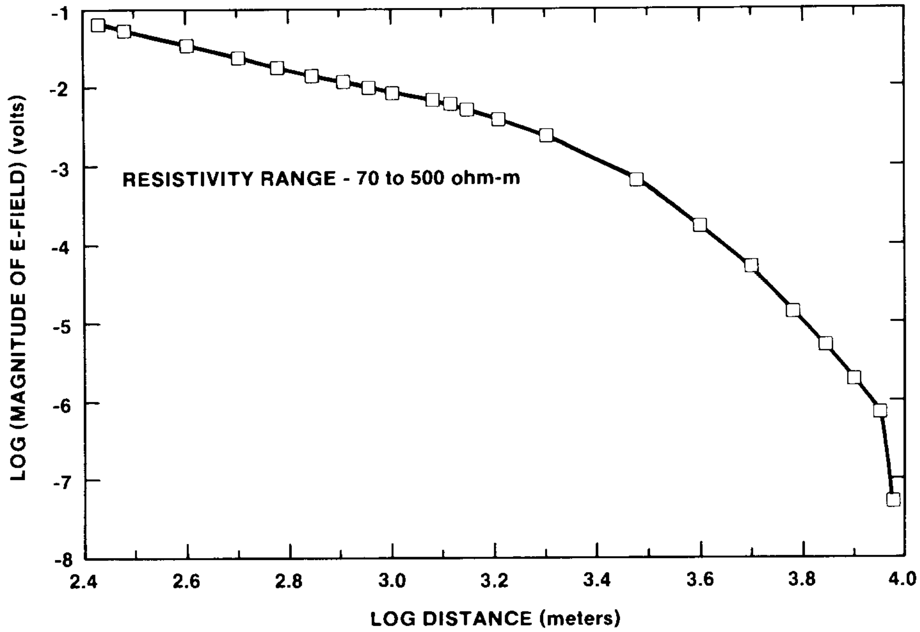

Figure 12. Electric Field Curve for a Three-Layer Earth

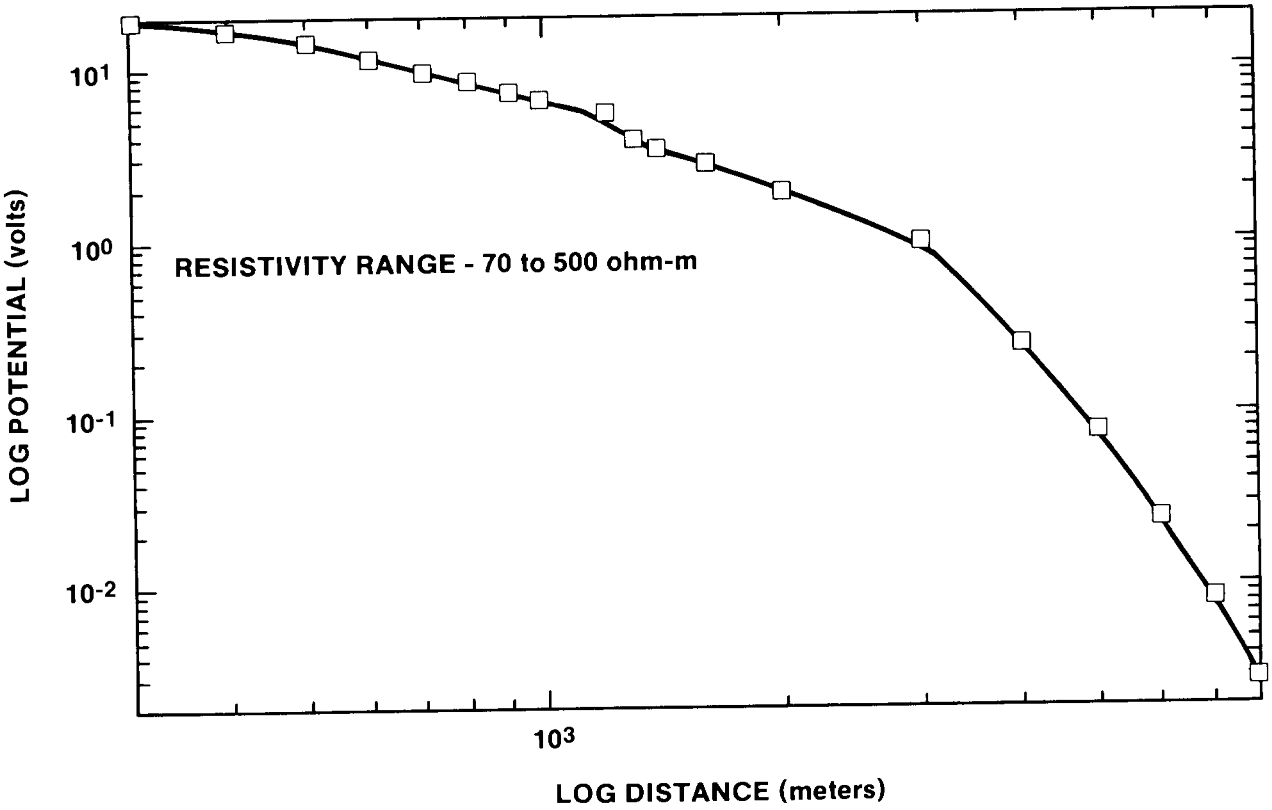

Figure 13. Total Potential Curve for Three-Layer Earth

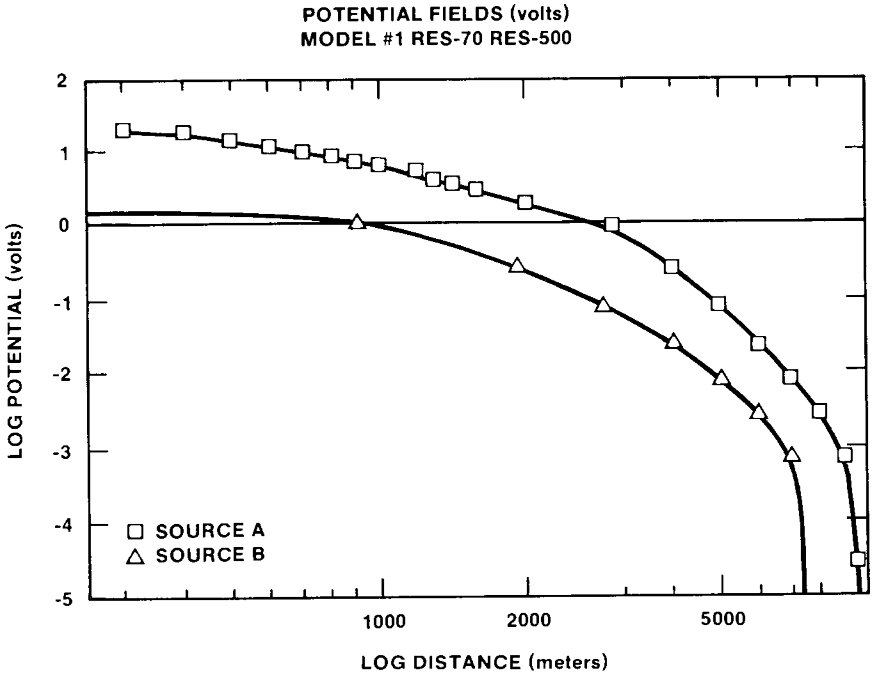

Figure 14. Potential Curves for Line Source A and B

third layer becomes adequate, the electric field will begin to fall rapidly with increasing distance (see Figure 12).

The potential, which is the quantity that we wish to know at the top surface of the salt, is found by integrating an electric field curve similar to the one shown in Figure 12 from infinity inwards to the point r, where the potential is to be evaluated. Because we have two vertical line sources, the net potential is the difference of the contribution from each (Figure 13). The potential was obtained by numerical integration and is shown by the curves in Figure 14.

In arriving at an apparent resistivity ($\rho_{a,2}$) for a three-layer reference earth, the following expression is used:

$$\rho_{a,2} = \frac{T_2 E_o}{h_2 E_r} \qquad (3)$$

where E_r is the reference electric field, E_o is the observed electric field, and $\rho_{a,2}$ is the resistivity assumed for unit 2 ($\rho_{a,2}$ is specified once values of T2 and h2 are assigned).

Values of apparent resistivity were calculated based on a specific three-layer reference model (Figure 15). The distribution of values is shown in the histogram of apparent resistivities in ohm-m (Figure 16). The high apparent resistivities (10^3 to 10^4 ohm-m) are measured near the heated rooms, and the lower resistivities (10 to 10^3 ohm) are measured away from the heated rooms at the facility horizon. These values are in general agreement with EM-31 values, again indicating a bulk water content in the salt of about 2% by weight.

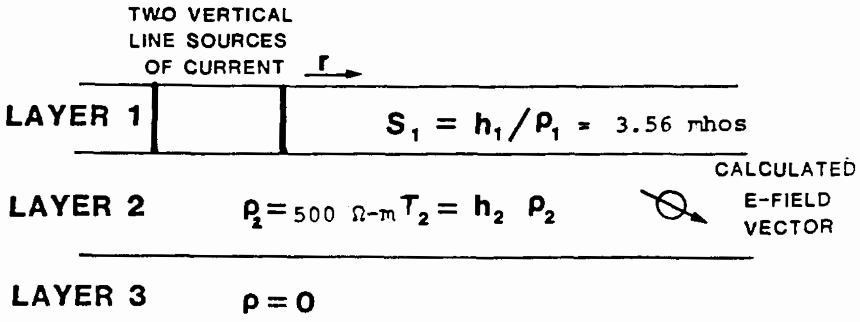

Figure 15. The Specific Three-Layer Model

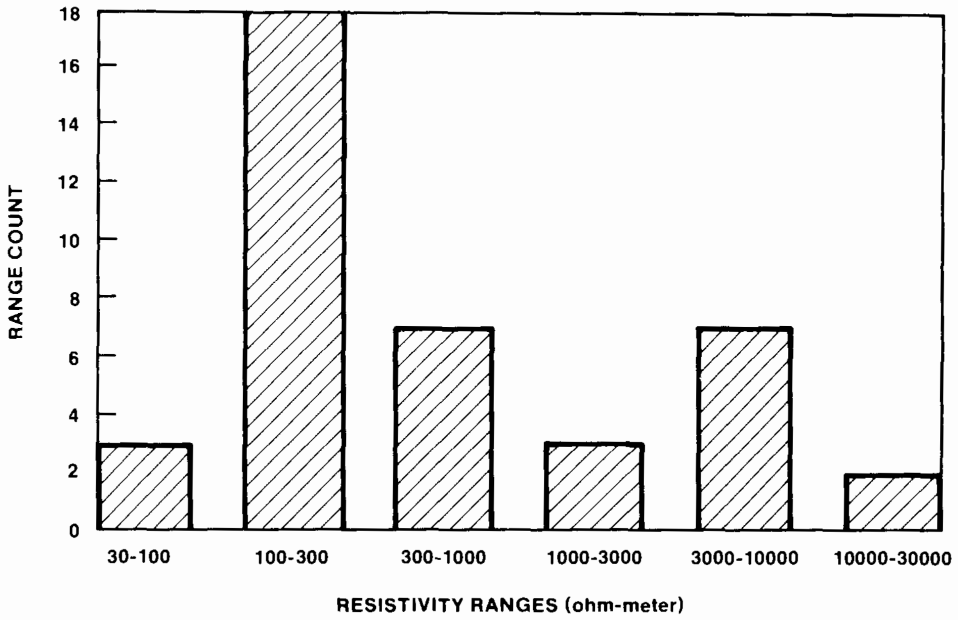

Figure 16. Distribution of Apparent Resistivites in omh-m for a Three-Layer Earth

CONCLUSIONS

From all of the data obtained the bulk water content is between 1 and 3% by weight. The methods used are shallow (0 to 10 m) investigative tools which may be used to detect wet zones or water-filled fractures near the tunnels. This may be of importance in characterizing the development of fractures around the excavations and delineating possible passageways for migration of introduced and formation water around the storage facilities. The next step in interpretation of the data is numerical modeling to simulate conductive anomalies in the vicinity of the tunnels.

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