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Results of Brine Flow Testing and Disassembly of a Crushed Salt/Bentonite Block Seal at the Waste Isolation Pilot Plant

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ABSTRACT

The Small-Scale Seal Performance Tests, Series C, a set of in situ experiments conducted at the Waste Isolation Pilot Plant, are designed to evaluate the performance of various seal materials emplaced in large (0.9-m-diameter) boreholes. This report documents the results of fluid (brine) flow testing and water and clay content analyses performed on one emplaced seal comprised of 100% salt blocks and 50%/50% crushed salt/bentonite blocks and disassembled after nearly three years of brine injection testing. Results from the water content analyses of 212 samples taken from within this seal show uniform water content throughout the 50%/50% salt/bentonite blocks with saturations about 100%. Clay content analyses from the 100% salt endcaps of the seal show a background clay content of about 1% by weight uniformly distributed, with the exception of samples taken at the base of the seal at the borehole wall interface. These samples show clay contents up to 3% by weight, which suggests some bentonite may have migrated under pressure to that interface. Results of the brine-flow testing show that the permeability to brine for this seal was about 2 to 3 x 10^{-4} darcy (2 to 3 x 10^{-16} m^2).

ACKNOWLEDGMENTS

The authors thank Drs. Barry Butcher and Frank Hansen for their insightful comments reviewing this report.

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1.0 BACKGROUND

The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico as a research and development facility for demonstrating safe underground disposal of radioactive waste resulting from U.S. defense programs (Public Law 96-164). The WIPP disposal horizon is located 658 m (2,160 ft) below ground surface in a 600-m-thick sequence of bedded evaporites (sedimentary salts) deposited during the Permian period over 225 million years ago.

One part of WIPP research and development is the Sealing Program, conducted by Sandia National Laboratories (SNL), which is engaged in the process of designing and demonstrating effective barriers for mitigating fluid flow into and out of the repository. Integrated under this program are numerical modeling, component design, laboratory materials testing, and in situ tests to develop acceptable shaft and drift sealing technology for eventual decommissioning of the WIPP facility (Nowak et al., 1990).

The test discussed in this report is one part of the seal materials testing program: the Small-Scale Seal Performance Tests (SSSPTs), which are a set of in situ experiments designed to evaluate the performance of various seal materials emplaced in underground boreholes in various configurations. Materials are selected for their potential to impede fluid flow. The performance of the SSSPT seal systems will be evaluated using structural and fluid-flow data generated under expected repository conditions.

Five SSSPT test series (A, B, C, D, F) are currently in progress. Series C (SSSPT-C), discussed in this report, was designed to provide data for evaluating the hydrologic, thermal, and mechanical performance of seals made from pressed blocks of salt and salt plus bentonite (Stormont and Howard, 1987). The test configuration involves drilling a large-diameter hole (for seal material emplacement) and a small-diameter access hole (for instrumentation and/or fluid introduction) into the rib or invert of a room. Emplacement borehole diameters vary from 15.2 to 97.0 cm (6.0 to 38.2 in.). Seals are emplaced in the large hole, forming a seal system that includes the seal, the seal/rock interface, and the adjacent rock. Fluid is introduced to isolated spaces behind or between seals to test the systems. SSSPT-C consists of eight seals (four of crushed salt blocks and four of crushed salt/bentonite blocks) emplaced in six, 91-cm (36-in.)-diameter horizontal boreholes drilled into the east rib of test Room M. The location of Room M in the WIPP underground is shown in Figure 1-1.

The six large SSSPT-C boreholes were prepared for seal installation by cutting away a section approximately midway down each hole with a chipping

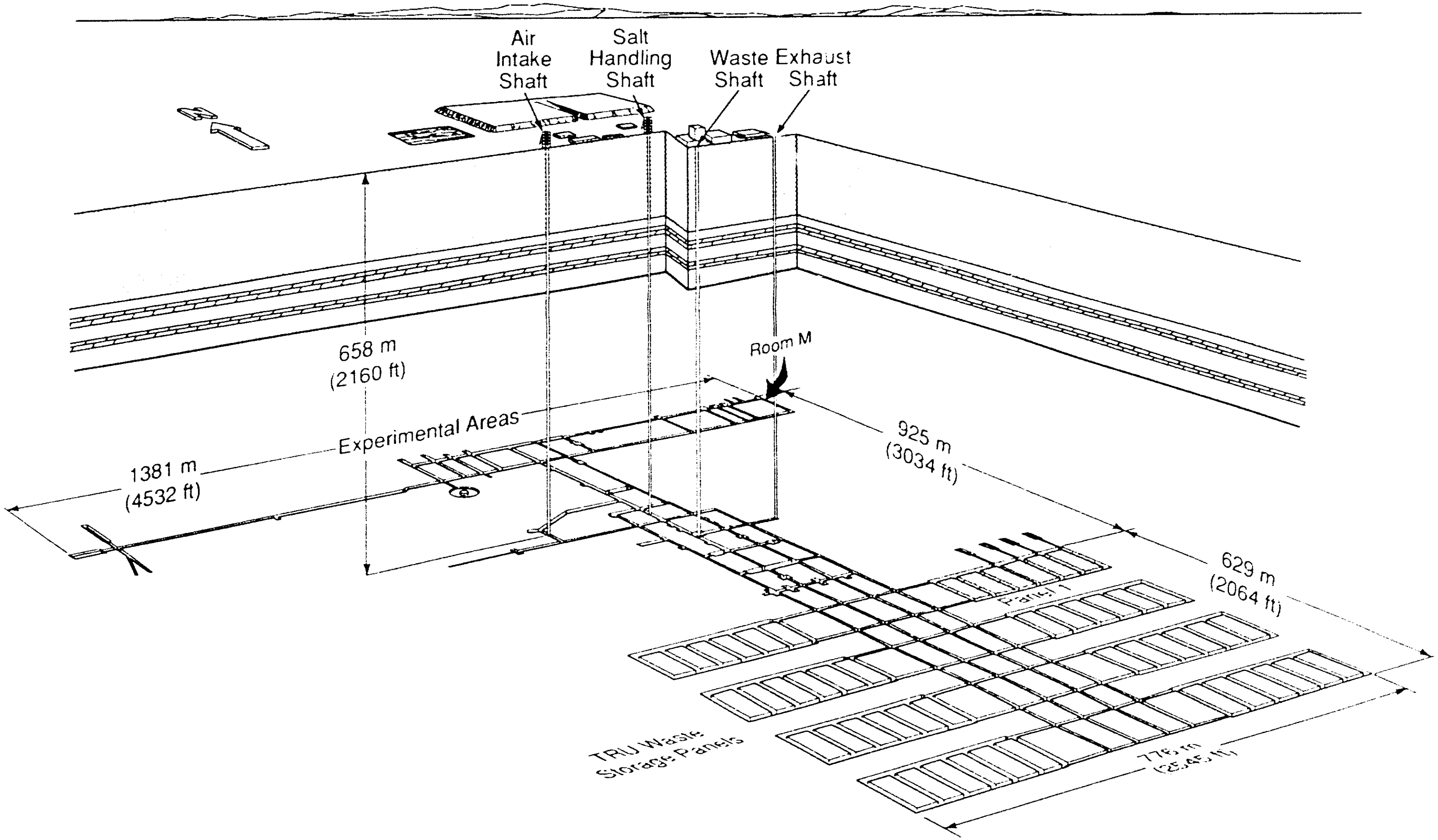


Figure 1-1. Location of WIPP test Room M.

hammer, which created a box-shaped chamber into which compressed blocks of sealing material were placed. Seal blocks were emplaced using typical masonry techniques. The blocks were made on site with a portable block machine, then hand fitted into the box-shaped chamber. Use of block-shaped seal components permitted considerable control over the production and emplacement of the seals.

Smaller access holes were drilled near the emplacement holes at oblique angles to intersect the isolated fluid-containment zones. Fluid flow testing was initiated after seal installation by introducing brine through the access holes into the isolated zones. Brine that flowed through the seals was collected and measured, then recirculated via the access hole to the zone behind the seal. A schematic diagram of the test configuration specific to this report is given in Section 2.

2.0 TEST CONFIGURATION

SSSPT-C was designed to provide data about the structural and fluid-flow behavior of both 100% crushed salt and 50%/50% crushed-salt/bentonite pressed-block seal materials. The complete test involved drilling six emplacement and six access holes into the east rib of test Room M. One of these access and emplacement hole configurations is the subject of this report. Two holes were drilled. The larger emplacement hole (MCE33) was 4.24 m (13.90 ft) deep and had a 91.4-cm (36.0 in.) diameter. The smaller access hole (MCA33) had a 12.7-cm (5.0 in.) diameter for the first 1.1 m (3.6 ft), decreasing to 10.2 cm (4.0 in.) for the remaining distance. The access hole was intentionally collared at an elevation 7.6 cm (3.0 in.) higher than the top of the emplacement hole. It sloped to intersect the deep end of the emplacement hole from the north at midheight so the isolated zone behind the seal could be continuously filled with brine. A plan view of the 2-hole configuration, showing the relevant dimensions and the brine reservoir, is presented in Figure 2-1.

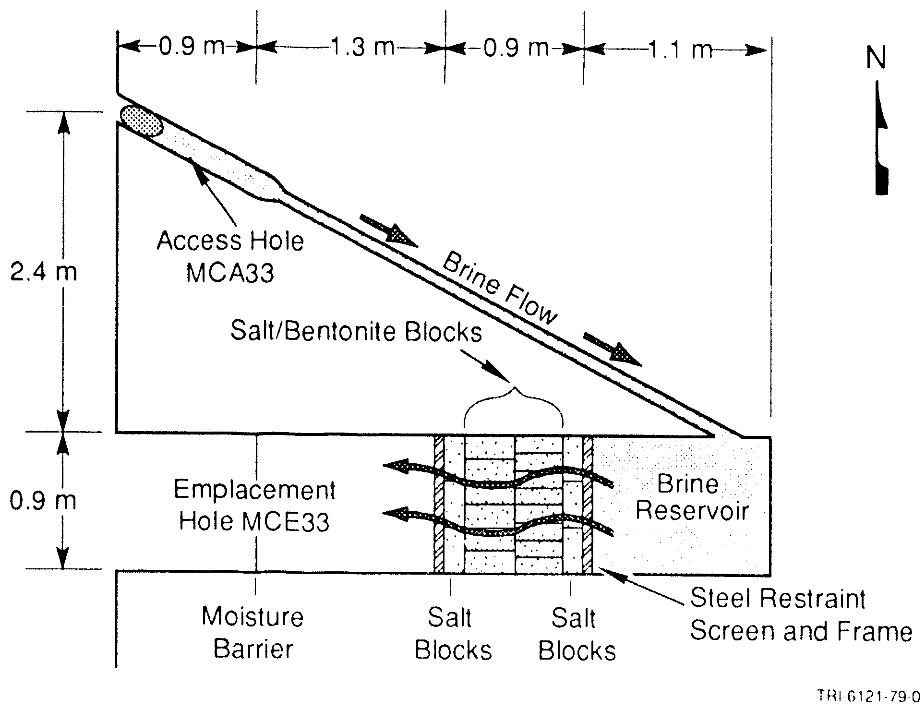


Figure 2-1. Plan view of MCA33/MCE33 configuration.

After drilling operations were completed, the seal interval of the emplacement hole was enlarged with a hand-held Ramset chipping hammer to form a square chamber about midway down the emplacement hole. The dimensions of the box-shaped seal interval were 91.4 cm (36.0 in.) by 91.4 cm (36.0 in.) by 1.0 m (40 in.).

2.1 Seal Block Construction

SSSPT-C required fabricating two different types of seal blocks that were composed of two materials: salt and bentonite clay. The primary source material was crushed salt retrieved from the continuous miner at the WIPP. The secondary material, bentonite clay, was shipped to the WIPP. One group of blocks was made from 100% WIPP tailings. A second group was made by combining 50 wt% WIPP salt material with 50 wt% bentonite.

2.1.1 Salt Blocks

The mined material used to make the 100% salt blocks was more than 90% halite with traces of polyhalite, anhydrite, and clay. Tailings from the continuous miner were recovered and screened to obtain consistent particle size because studies conducted between 1984 and 1987 indicated that dense, durable blocks could be made with salt of 9.6-mm (3/8-in.) maximum particle size (Stormont and Howard, 1987). This material was pressed into blocks with 2 wt% added moisture at 26.2 MPa (3800 psi) in a modified pressed-earth block machine manufactured by Compact Systems of Albuquerque, NM. Finished blocks measured 31.1 cm (12.2 in.) by 10.5 cm (4.1 in.) by 15.2 cm (6.0 in.), weighed approximately 9 kg (20 lb), and had a density of about 82.2% relative to intact rock salt. The dry density and water content of the finished salt blocks were 1.79 g/cc (112 lbs/ft^3) and 2.5 wt%, respectively (modified from Stormont and Howard, 1987).

2.1.2 Salt/Bentointe Blocks

The salt/bentonite blocks were pressed from a 1:1 mixture by weight of screened WIPP salt and granular sodium bentonite. The bentonite, obtained from the American Colloid Company of Arlington Heights, IL, was over 90% pure sodium bentonite, with traces of feldspar, biotite, and selenite. The measured moisture content of the as-received bentonite was about 1 to 2 wt%. After the salt and bentonite were mixed, the blocks were pressed with 3.5 wt% added moisture at 26.2 MPa (3800 psi) in the block machine. Finished salt/bentonite blocks measured the same as the 100% salt blocks and had a density of 77.8% relative to a theoretical mixture of completely consolidated salt and bentonite. The dry density and moisture content of the finished blocks were 1.87 g/cc (117 lbs/ft^3) and 5.5 wt%, respectively. Table 2-1 lists the average measured and mechanical properties of both types of blocks.

Table 2-1. Average Block Properties

	Salt	Salt/Bentonite
Density (g/cc)	1.82	1.97
(lbs/ft^3)	114.	123.
Dry density (g/cc)	1.79	1.87
(lbs/ft^3)	112.	117.
Relative density (%)	82.2	77.8
Moisture content (wt%)	2.5	5.5
Porosity (%)	18.	22.
Saturation (%)	17.	42.
Compressive strength (MPa)	3.2	4.8
(psi)	460.	700.
Young's modulus (MPa)	6417.	4337.
(psi)	9.3×10^5	6.3×10^5
Poisson's ratio	.15	.12
Gas permeability (darcy)*	10^{-3}	10^{-3}
Brine permeability (darcy)*	10^{-3}	$<10^{-6}$

Block machine foot pressure = 26.2 MPa for 31.1 cm x 10.5 cm x ~15 cm (3800 psi for 12 1/4" x 4 1/8" x ~6").
* for as-made blocks.

(Table adapted from Stormont and Howard, 1987)

2.2 Seal Block Emplacement

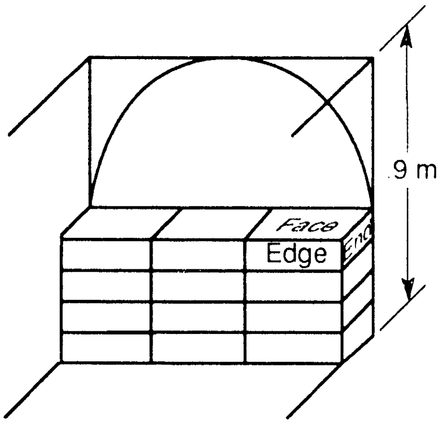
The seal blocks were emplaced in the squared interval of MCE33 in four steps, as shown in Figures 2-2a through 2-2d. The inner- and outermost layers (courses) were constructed of 100% salt blocks. Sandwiched between these salt-block courses were two courses of 50%/50% salt/bentonite blocks. The completed seal consisted of four tightly fitted block courses.

The first step in seal construction was the emplacement of an inner seal restraint consisting of heavy steel framing and perforated aluminum plate. The seal restraint was designed to restrict axial elongation of the block seal without impeding fluid flow. The location of the steel restraint is shown in Figure 2-1.

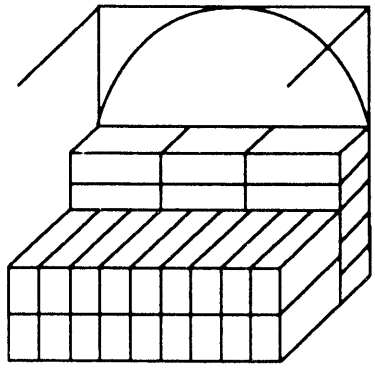
After installation of the inner restraint, the first course of seal blocks was emplaced. It consisted of 100% salt blocks with their long axes laid north to south, perpendicular to the axis of the hole, as shown in Figure 2-2a. Two complete blocks and one partial block were used in each row to fit the width of the emplacement chamber. All partial blocks were stacked on the same side of the chamber to ease emplacement. Any dimensionally uneven sides in the first course of blocks were oriented to the back of the seal, thus reducing unnecessary voids in the seal interior. Workers manually sprayed 908.5 cm^3 (2.4 lb) of brine on and between the blocks of the first course during installation to counteract evaporative moisture loss and promote bonding between blocks. After the blocks were emplaced, 4.5 kg (10.0 lb) of salt mortar (described in Section 2.3) were used to fill spaces around the first course. Spaces were most common at the interface between the blocks and the chamber walls, particularly along the top.

Construction of the second course began after the first course was fully emplaced. The second course was composed of salt/bentonite blocks that were positioned in the chamber with their long axes running east to west, parallel to the hole axis. The block ends were set flush against the edges of the first course, as shown in Figure 2-2b. Workers sprayed 454.0 cm^3 (1.2 lb) of brine on and between these blocks to replace lost moisture. After the blocks were in place, 9 kg (20 lb) of salt/bentonite mortar were used to fill voids around the seal.

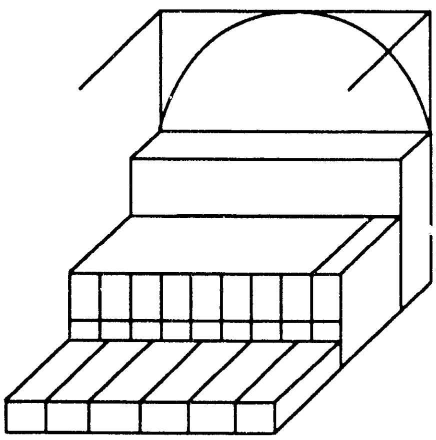
After the second course was finished, the third course was emplaced. The seal blocks were identical in composition to those in the second course and were set with their long axes parallel to the hole axis, as shown in Figure 2-2c. Brine was sprayed on and between the blocks during installation. After block emplacement, 9 kg (20 lb) of salt/bentonite mortar were used to fill voids around the seal.



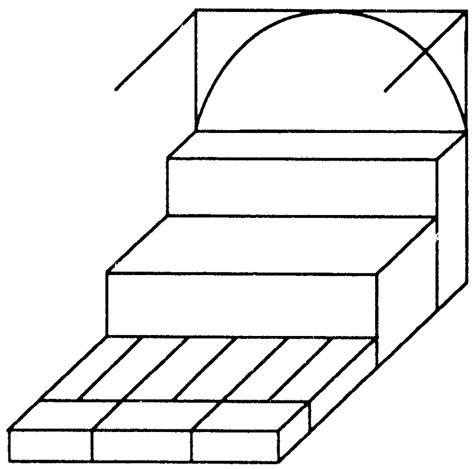
2a. First course, 100% salt blocks.



2b. Second course, 50/50 salt/bentonite blocks.



2c. Third course, 50/50 salt/bentonite blocks.



2d. Fourth course, 100% salt blocks.

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Figure 2-2. Block installation arrangement.

The fourth and outermost course of the seal was identical in composition and configuration to the first. The blocks were composed of pure WIPP salt and laid in the seal interval with their long axes oriented north to south, as shown in Figure 2-2d. Any unevenness in these blocks was oriented to the exterior of the seal. The blocks were sprayed with a fine mist of brine during installation, and 9 kg (20 lb) of salt mortar were used to fill voids around the seal.

The final steps of seal construction were the installation of the outer seal restraint and the moisture vapor barrier. To limit evaporative moisture loss and drying of the seals, a vapor barrier was installed about 122 cm (4 ft) in front of the seals. It consisted of a circular sheet of 6.40-mm (.25-in.) plexiglas measuring 91.4 cm (3.0 ft) in diameter, which was held against a 6.40-mm (.25-in.) aluminum hoop bolted to the borehole wall. The hoop/wall and plexiglas/hoop interfaces were sealed with silicon caulking compound, making the barrier almost airtight. A 5.1-cm (2.0-in.) sealable access port, used for brine recovery and recirculation during testing, was located near the bottom of the barrier.

The completed seal contained no instrumentation; this resulted in fewer potential pathways for brine transport. Uninstrumented seals like MCE33 were used for permeability and fluid-flow testing.

2.3 Mortar

Mortar was needed during seal installation to fill spaces where block emplacement was impractical. To minimize mortar use, none was placed between blocks unless they did not make substantial contact with each other, leaving a void unfilled. The primary use of the mortar was to fill whatever void existed between the blocks and the hole wall. To reduce potential inconsistencies in the seal material, the mortar was made from the same materials as the blocks. The mortar for the salt-block seals was made from powdered drill cuttings with about 20 wt% added water. The mortar for the salt/bentonite-block seals was made from a 1:1 mixture of salt powder and bentonite with about 33% added water. A consistency comparable to a cementitious mortar was achieved, and the relative density of both mortars was 67 to 70% (Stormont and Howard, 1987).

3.0 BRINE TESTING OF SEAL MCE33

The seal testing process began about two months after seal emplacement with the addition of brine to the reservoir zone in MCE33. The reservoir was filled and fluid flow through the seal was monitored.

3.1 Brine Introduction

Saturated brine (prepared to be chemically similar to native WIPP brines) was gravity-fed into the MCE33 reservoir at a slow rate through the access hole, beginning with the addition of 37.8 L (10.0 gal) on April 16, 1987. Then 11.3 L (3.0 gal) were added per day, five days per week, until the void was filled and brine reached the neck of the access hole. The procedure required 935 L (247 gal) of brine and took 127 days. Five days later a small amount of brine was observed in front of the seal (Stormont and Howard, 1987). At that time, the maximum differential pressure exerted at the base of the seal, a result of the hydraulic head, was about .012 MPa (1.73 psi).

The intent of the test was to saturate the MCE33 seal and record the brine outflow rate to gather information for assessing the integrity of the seal system and the durability of the salt and salt/bentonite block seal.

3.2 Brine Recirculation

During the testing period, any brine that seeped through the seal was recirculated back to the test interval. To perform the brine recirculation procedure, workers removed the port cap from the front of the vapor barrier seal. Then they inserted a piece of tubing through the port and submerged it in the brine that had accumulated on the invert in front of the seal. The brine was pumped through the tubing with a vacuum and discharged into a 1.0-L graduated cylinder. After the brine in front of the seal was collected, the total volume was recorded, the filled 1.0-L cylinders were emptied into a bucket, the port cap was replaced on the vapor barrier seal, and the recovered brine was pumped from the bucket into the access hole to recharge the brine reservoir. Detailed brine recirculation data are presented in Appendix B.

The time from initiation of the brine recirculation procedure until completion of the testing was 762 days. After the testing period, a syphon drain system was used to withdraw the brine from the reservoir. The seal dismantling process began 9 days after the reservoir was syphoned. Disassembly required 26 days.

No attempt was made to evaluate any effects that the steel restraint system (see figure 2-1) may have had on the swelling pressure in the bentonite and on the fluid-flow performance of the seal system. It should be noted that these restraints were simply bolted into the borehole wall and were therefore of only limited value in restraining the expansive bentonite.

4.0 POST-TEST PROCEDURES

The seal was systematically disassembled so workers could extract and recover samples of material from within it. The sample material was subsequently tested for moisture and clay content.

4.1 Seal Disassembly and Core Sampling Process

The two primary objectives of the seal disassembly were: 1) to evaluate the condition of the seal components (100% salt versus 50%/50% salt/bentonite) as affected by closure and brine interaction, and 2) to map the flow patterns of the brine and the movement of bentonite through the seal. During disassembly, core samples were removed from the seal at eight different intervals, as shown in the isometric diagram in Figure 4-1.

On November 1, 1989, a syphon system was used to withdraw the brine from the test interval via the access hole. On November 6, the vapor seal was removed from the emplacement hole. A small (unmeasured) amount of brine was observed in the invert of the hole. The outer seal restraint was removed on November 9. Workers then entered the borehole to reach the block seal and initiate the seal disassembly and core sampling processes. They began by marking a reference point on the bottom of the hole 12.7 cm (5.0 in.) west of the face of the seal along the east-west axis. This reference point, designated by a bolt, was used to establish elevation, direction, and distance coordinates (x,y,z) for all the sample coreholes.

The outermost layer of the seal, identified as sample plane 1 (see Figure 4-1), was examined by extracting fourteen 5.1-cm (2-in.)-diameter cores from various locations on the outside wall (west face) of the seal. Some cores were drilled at block/block interfaces, some at block/wall interfaces, and some at "non-interface" locations within individual blocks.

After the core samples from the first plane were removed and logged, approximately 7.6 cm (3.0 in.) of the seal were chipped away to expose a sampling interval at the approximate center of the fourth course of salt blocks; that is, half the width of the outer course was removed to reach the second sample plane. Here, where any influence of the interfaces between courses was reduced and measurements of non-interface locations could be taken, 21 cores were drilled and logged.

Workers then removed another 7.6 cm (3.0 in.) of the seal to expose the approximate interface of the salt and salt/bentonite blocks between courses 3 and 4. Moisture had obliterated most signs of division between the blocks in

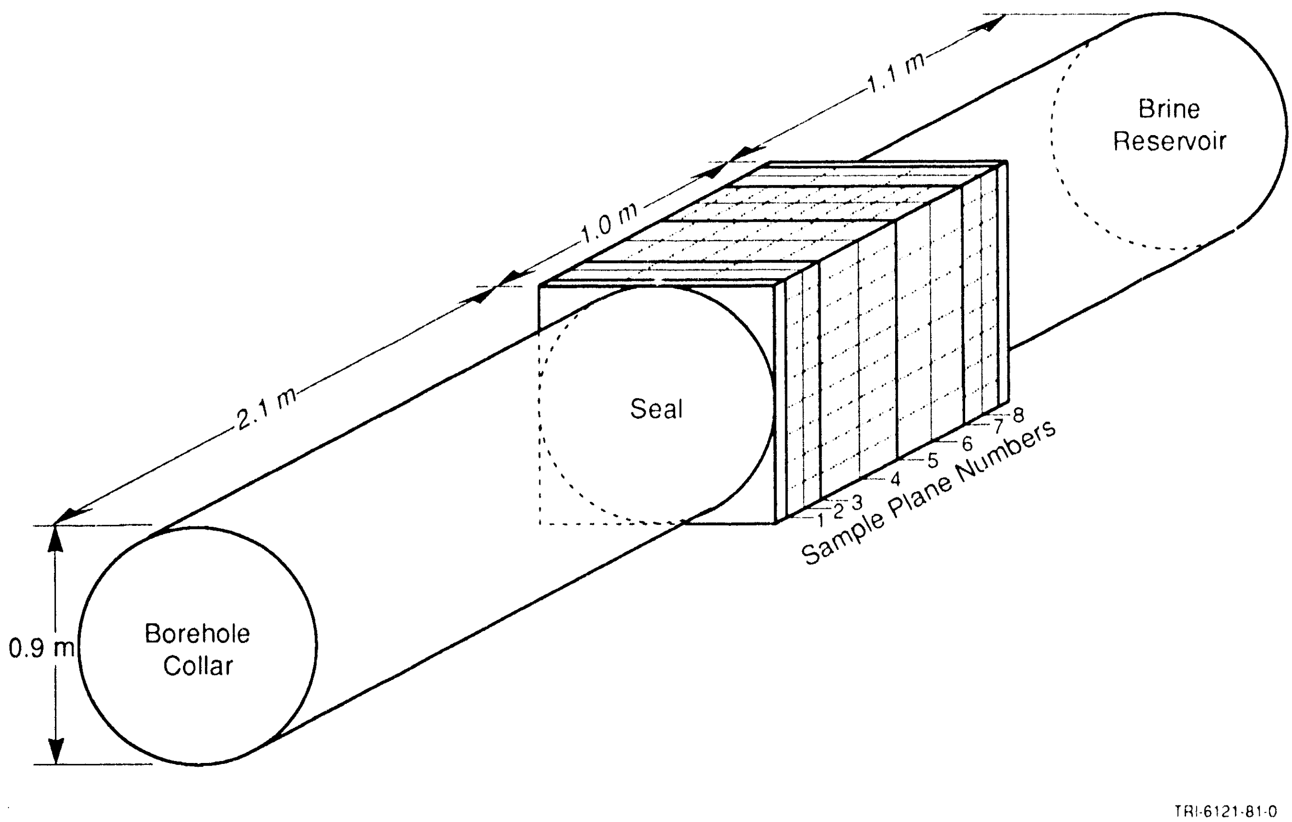

Figure 4-1. Isometric view of MCE33 showing sampling locations.

course 3, which appeared as a solid wall. Moisture penetration looked uniform. Workers withdrew 34 core samples from this third sample plane.

Workers then dug into the seal to a point 43.2 cm (17.0 in.) from the reference point (plane 4 in Figure 4-1) where they extracted and logged 34 core samples. This process of seal dissection and core extraction continued until the seal was completely disassembled and the eight sample intervals shown in Figure 4-1 had been systematically examined. In total, 212 core samples were removed; all were analyzed for water content, and 65 were also analyzed for clay content. Appendix A provides a complete listing of the core sample locations, water content in wt%, and clay content in wt%.

4.2 Water and Clay Content Analyses

The core samples recovered during seal disassembly were analyzed in two groups: 100% salt samples were analyzed for both clay and water content; salt/bentonite samples were analyzed for water content only.

To evaluate the amount of bentonite migration through the seal, the 100% salt samples were analyzed for clay content. Specimens consisted of coarsely crushed material taken from the salt block sample cores and weighed into 150-gr batches. These were dissolved in deionized water, the insoluble residue was allowed to settle, and the brine was decanted off. The residue was then transferred to centrifuge bottles and resuspended in approximately 200 mL of deionized water. These specimens were centrifuged, the water again decanted, and the residue washed into teflon evaporating dishes. This residue was taken to dryness in an oven at 100°C, then reweighed to determine the percentage of insoluble residue in the original sample. After crushing, 1 gr of the residual sample was weighed and mixed with 9.1 gr of lithium tetraborate flux, placed in a platinum crucible, and fused in a furnace for 15 minutes at 1000°C. The resulting melt was analyzed on the Rigaky x-ray fluorescence spectrometer at the University of New Mexico. X-ray diffraction analysis of the samples provided an accurate measurement of clay present in the samples. Although this technique did not differentiate between the added bentonite and native clays present (in small amounts) in the WIPP halite, post-test results (discussed in Section 5) indicate that native clay content was about 1 wt%.

The water content of the cores was determined by desiccating 10-gr samples. These samples were first weighed into a preheated watchglass, then heated at 110°C for two hours, then cooled in a desiccator for one hour. The desiccated samples were reweighed, and the water content was determined by the weight difference between the desiccated and original samples.

5.0 RESULTS

The MCE33 seal was in place for almost 31 months—from April 16, 1987 to November 6, 1989. During this time, operators recirculated about 225 L of brine through the test interval. The cumulative volume of recirculated brine is shown in graph form in Figure 5-1. The rate of flow through the seal is plotted in Figure 5-2. Brine recirculation data are tabulated in Appendix B.

5.1 Permeability Estimate

Figure 5-2 shows the flow rate in mL/day over the lifetime of the seal. The steady-state flow rate is approximately 250 mL/day. Assuming that all flow occurs through the seal and that one-dimensional Darcy flow approximations are valid, the permeability of the 50%/50% salt/bentonite seal components in MCE33 can be calculated from the following equation:

$$K = \frac{Q\mu\ell}{A\Delta p} \qquad (1)$$

where

Q = steady-state flow rate (~250 mL/day) = (~2.89 x 10^{-3} mL/sec)
A = cross-sectional area (~91 cm x 91 cm)
μ = viscosity (~1.26 cP)
Δp = pressure gradient (0.012 MPa) = (~0.12 atm.)
ℓ = length of 50/50 salt/bentonite (~63.5 cm).

Using Equation 1 yields a permeability of 2 to 3 x 10^{-4} darcy for seal MCE33. This permeability is approximately two orders of magnitude higher than premeabilities reported for similar concrete seals (Stormont, 1986). The approximate permeability measured here compares favorably with estimates by Butcher et al. (1991) for 70%/30% salt/bentonite backfill at about 80% relative density.

5.2 Core Sample Analyses

Results of the core specimen analyses are shown graphically in the data plots presented at the end of this section. An examination of the plots reveals moisture and clay distribution patterns throughout the seal. The water content (in wt%) is given for all cores extracted from all sample planes. The clay content (in wt%) is given for cores taken from the salt blocks on the outer ends of the seal.

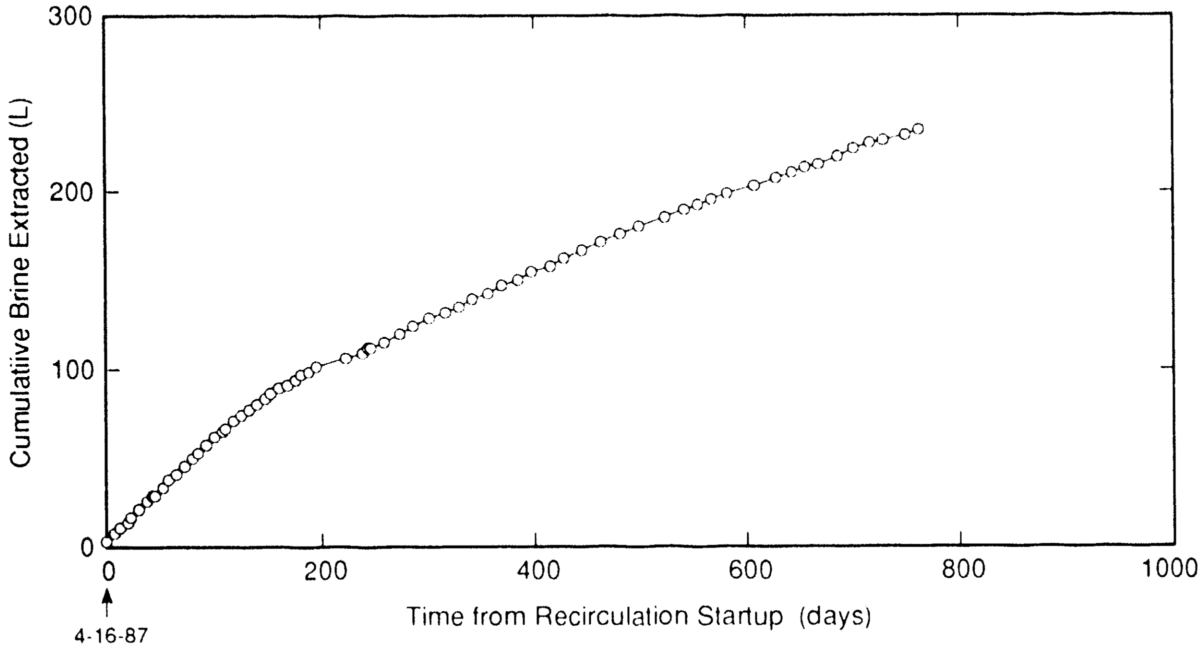

Figure 5-1. Cumulative volume in MCE33.

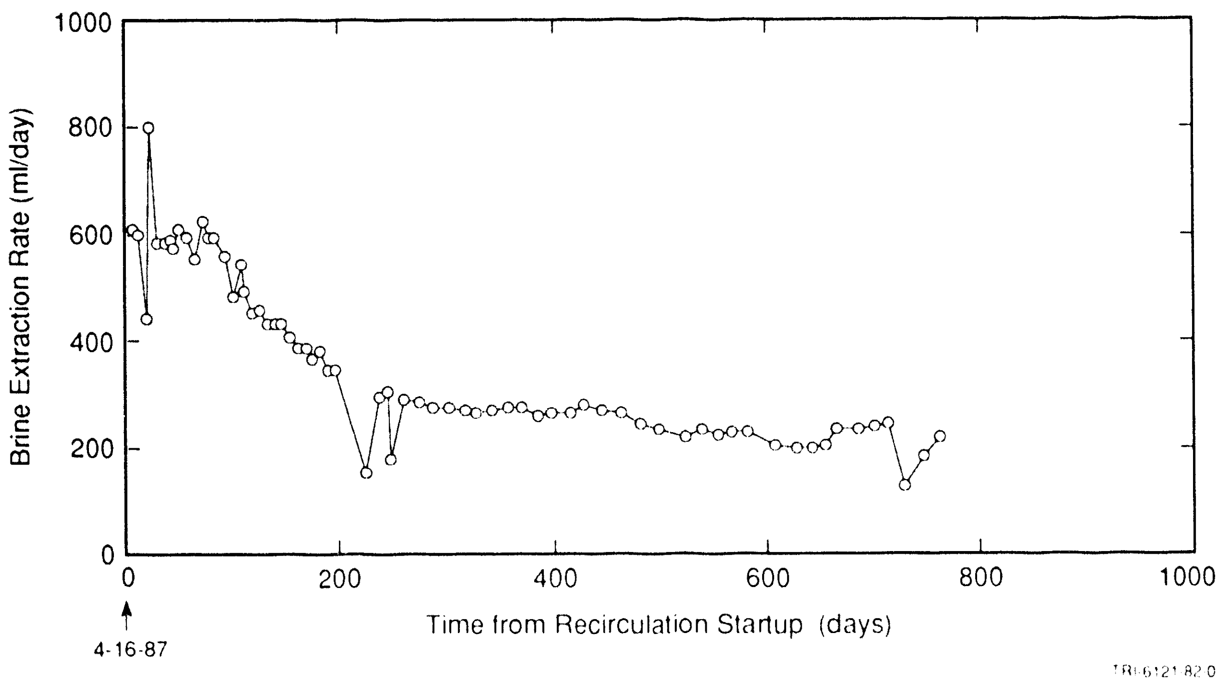

Figure 5-2. Rate of flow in MCE33.

Water content is shown in Figures 5-3 through 5-10. The water content from sample planes 1 and 2, in the salt-block course at the west end of the seal (Figures 5-3 and 5-4), is non-uniform, clearly showing vertical drainage from the top to the bottom. The water content in samples recovered from the salt blocks at the east end of the seal is more uniform (Figures 5-9 and 5-10). Using hole-closure data presented in Stormont and Howard (1987), and extrapolating for the life of the seal (assuming no axial elongation) the relative density for the 100% salt blocks at disassembly is about 85.7% for seal MCE33. This density suggests that the maximum saturation in any of the 100% crushed salt block samples was about 65%, measured near the base in sample plane 2. In contrast, the saturation at the top of the outermost planes was about 14%. The inner two planes showed a more uniform saturation distribution, from about 29% at the top to about 50% at the bottom. Clearly, the high permeability in the 100% salt blocks allowed for brine drainage immediately before and during disassembly. This drainage could account for the salt blocks' unsaturated condition, especially the layer at the back of the seal.

The measured water content within the 50%/50% salt/bentonite blocks was quite uniform from top to bottom and front to back. The water content averaged about 13 wt% throughout the salt/bentonite seal core. The uniformity of water content in the salt/bentonite blocks is not unexpected, owing to bentonite's strong affinity for sorbing free water. The measured water contents in the salt/bentonite blocks correspond to saturations of about 100%. However, limitations in measurements of volumes and weights of solids make exact estimates of saturation impossible. The reported numbers for water content at disassembly correspond to saturations near 100% for porosities near 20%.

Clay content is shown in Figures 5-11 through 5-14. The results of clay-content analyses in the 100% salt blocks on the outer ends of the seal, in general, show a uniform concentration of clay throughout. A possible minor exception is seen in one sample from the lower left front of sample plane 2, which shows an approximate threefold increase (see Figure 5-12). This increase may be the result of a potential "zone of weakness" along the block/wall interface, although no piping failure was observed during the test. The swelling potential of the bentonite constituents may have been on the order of 1.37 to 1.72 MPa (200 to 250 psi), based on the swelling pressures of 70%/30% salt/bentonite mixtures with equivalent dry densities as reported by Butcher (1991). This swelling pressure, along with brine flow along the block/wall interface, could have caused nearby bentonite constituents to migrate toward this region until the zone of weakness was plugged. Remember that the clay content analyses did not distinguish between clays native to the WIPP horizon and those in the added bentonite.

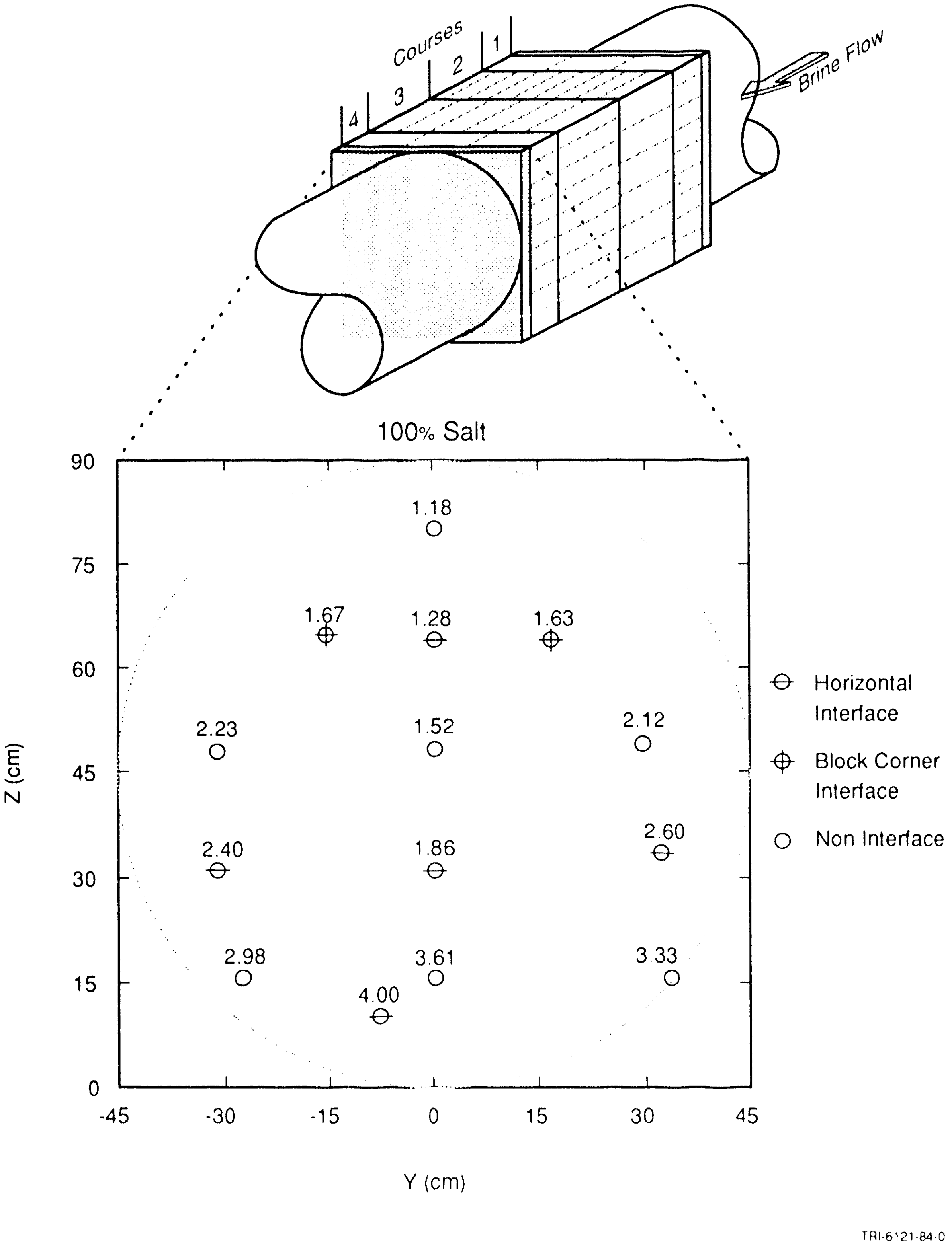

Figure 5-3. Water content (wt%) map of sample plane 1.

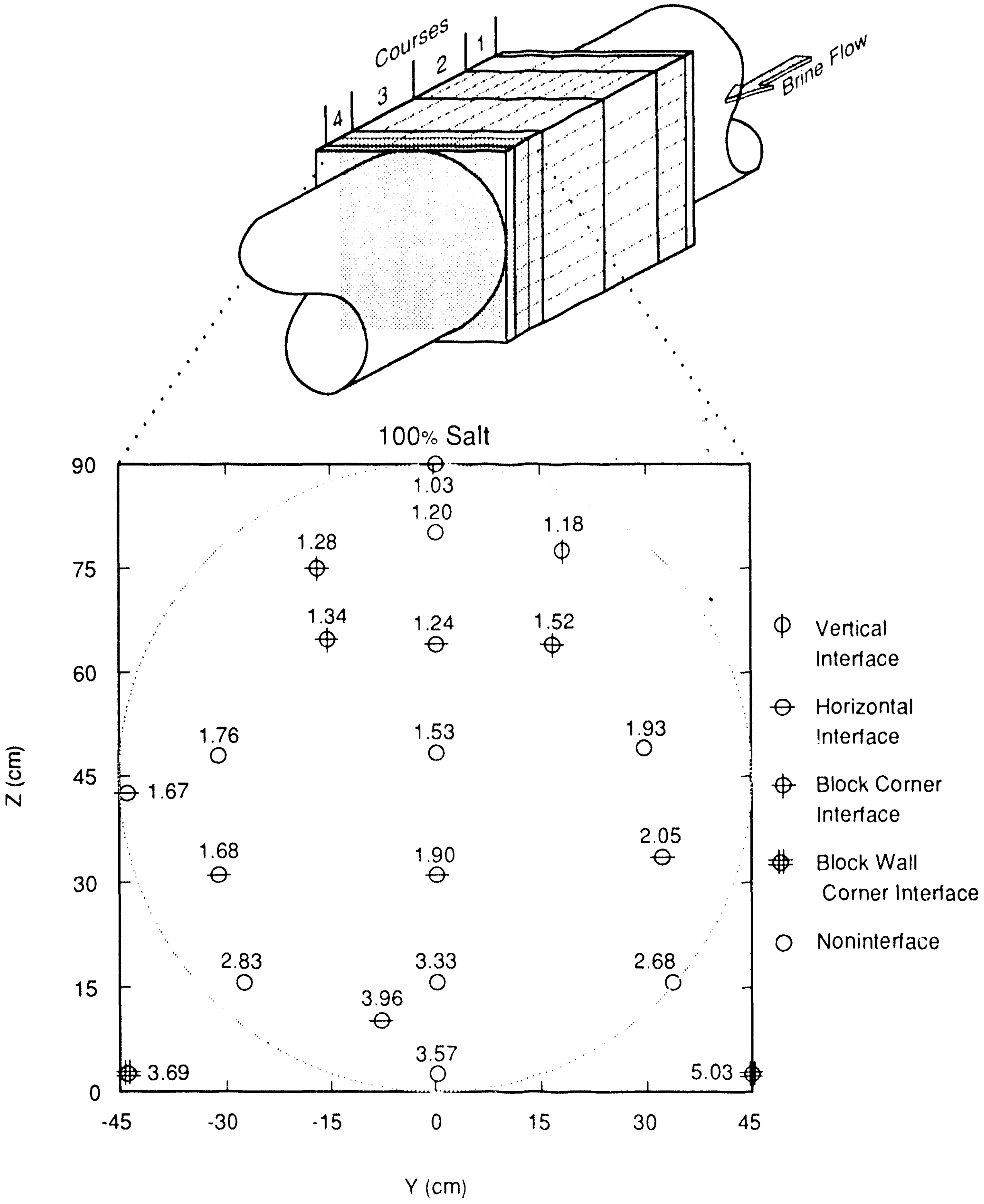

Figure 5-4. Water content (wt%) map of sample plane 2.

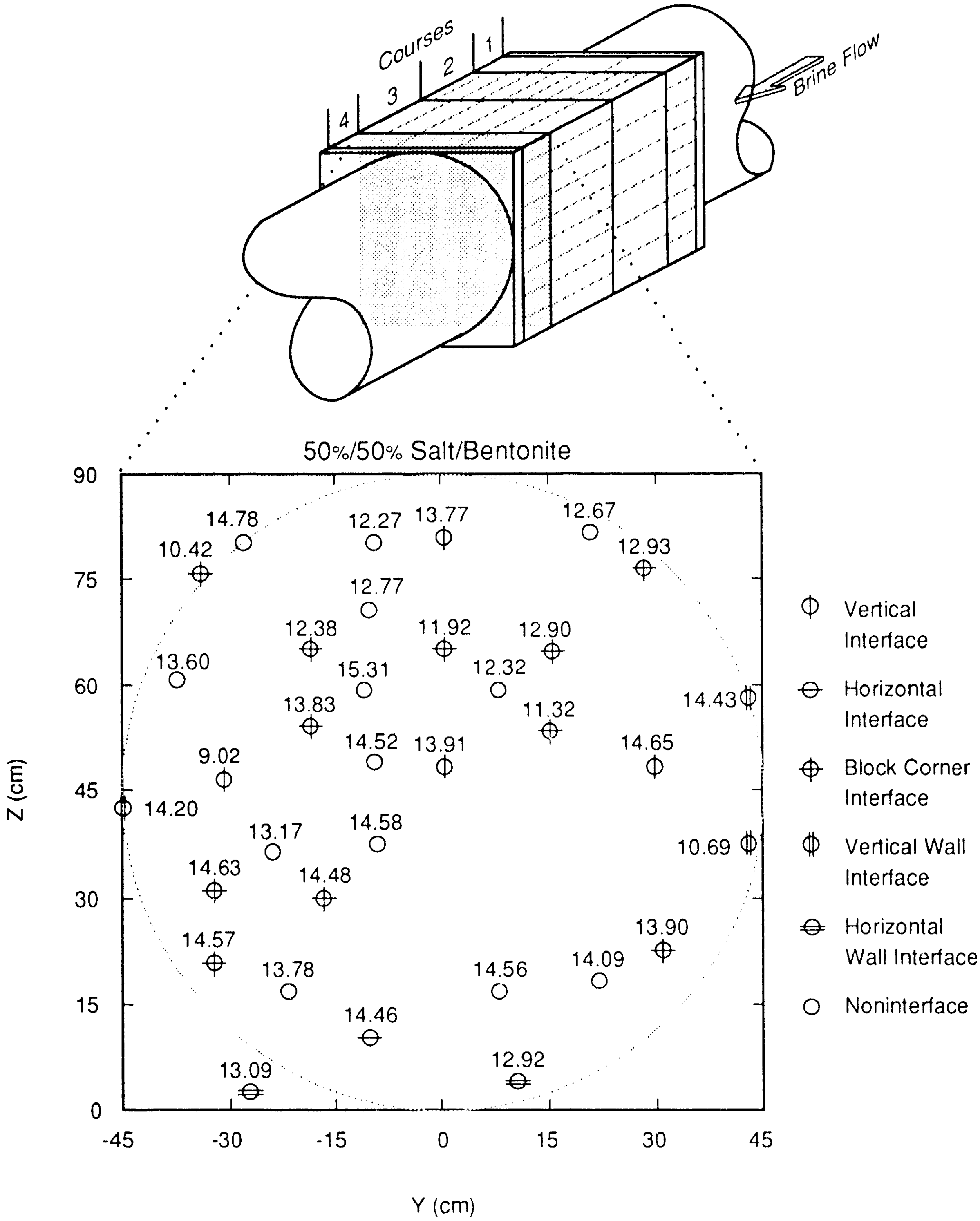

Figure 5-5. Water content (wt%) map of sample plane 3.

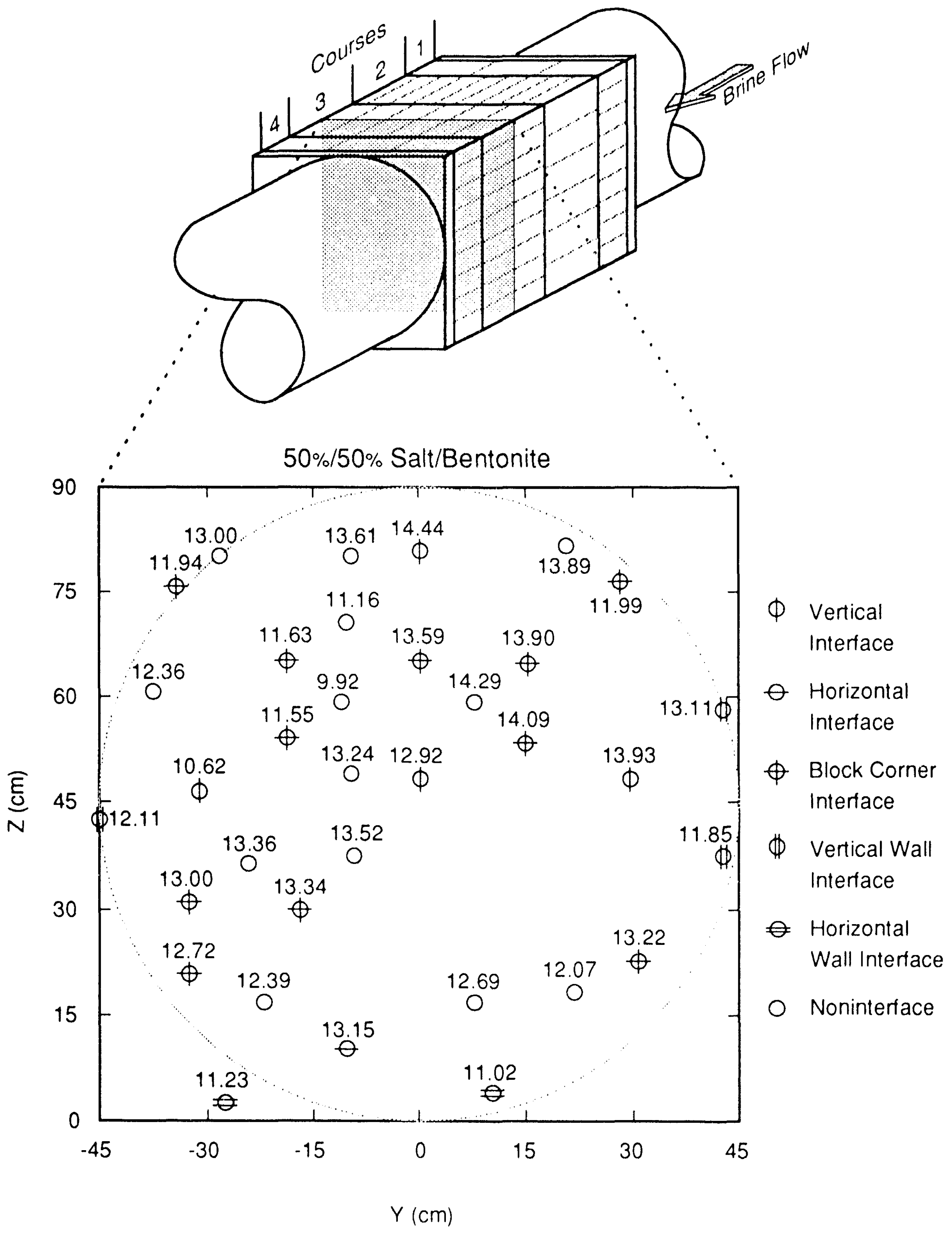

Figure 5-6. Water content (wt%) map of sample plane 4.

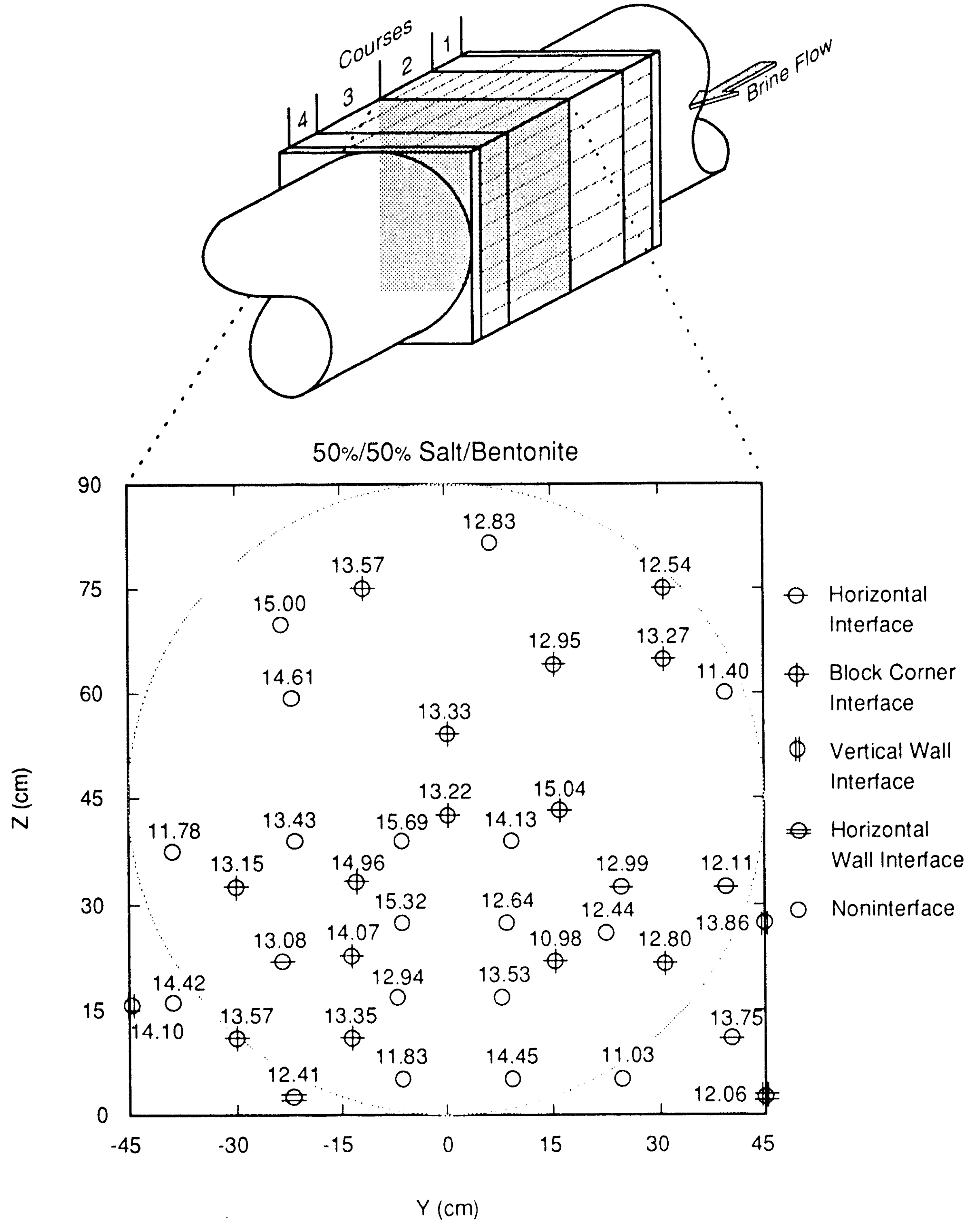

Figure 5-7. Water content (wt%) map of sample plane 5.

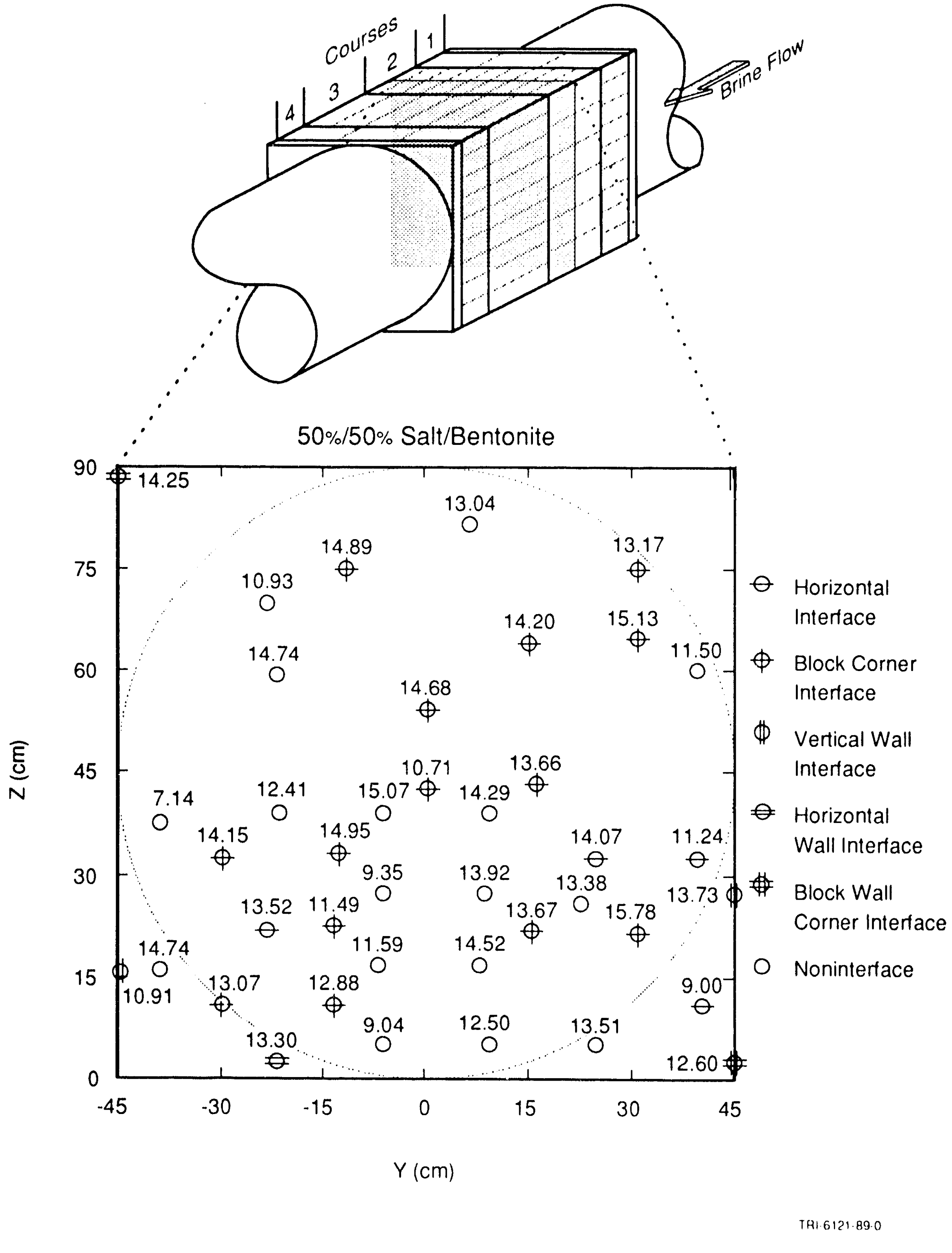

Figure 5-8. Water content (wt%) map of sample plane 6.

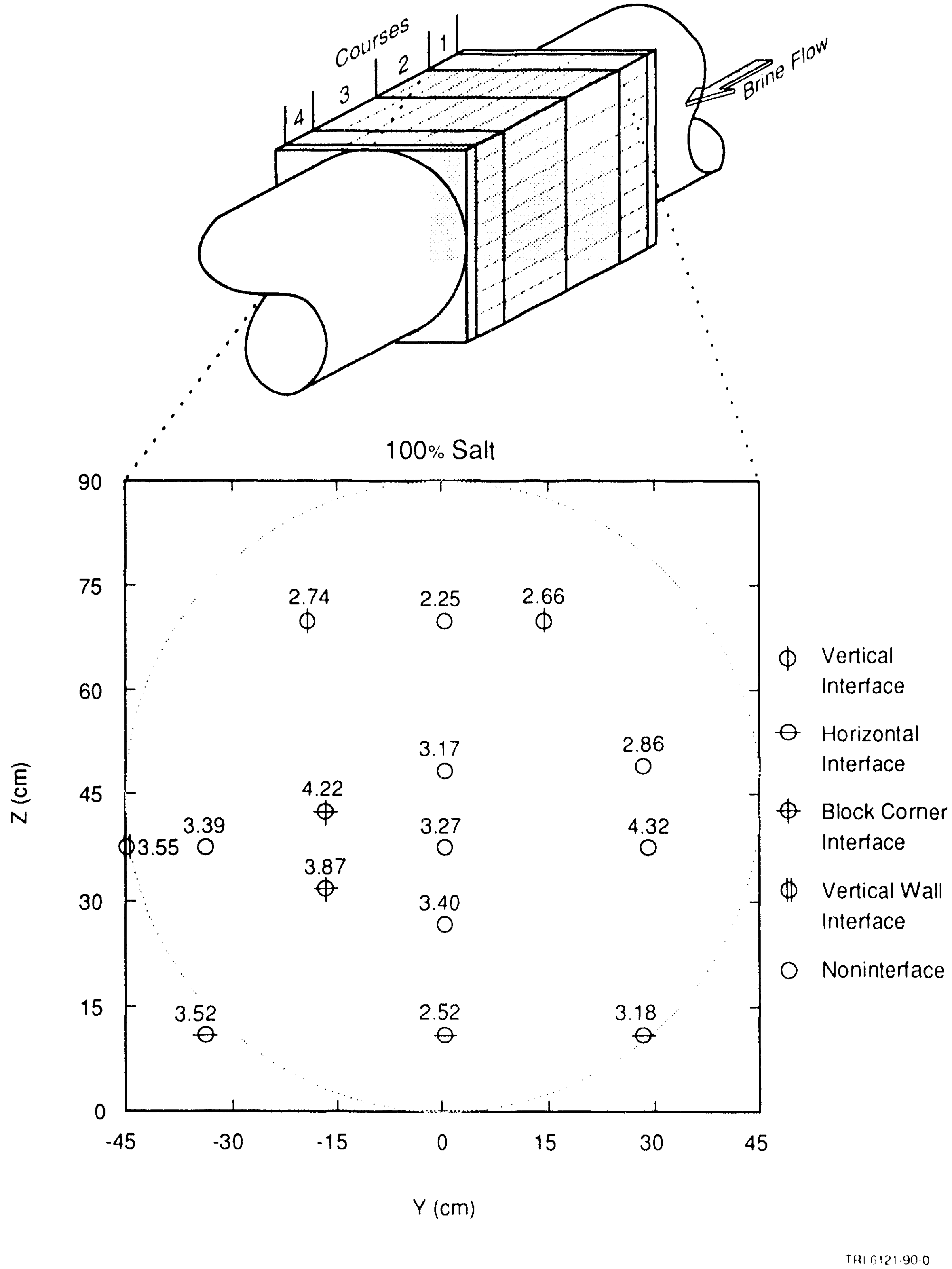

Figure 5-9. Water content (wt %) map of sample plane 7.

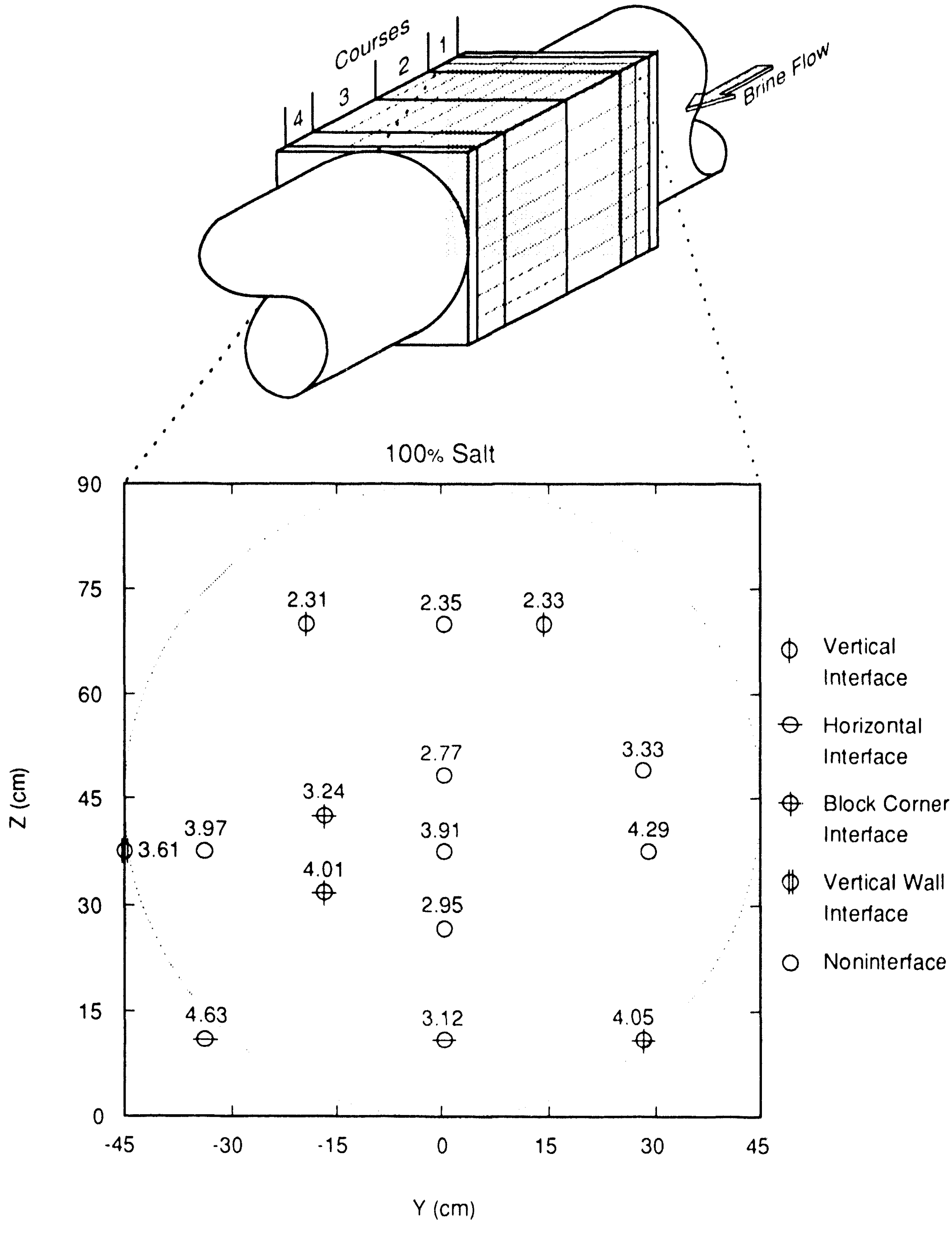

Figure 5-10. Water content (wt %) map of sample plane 8.

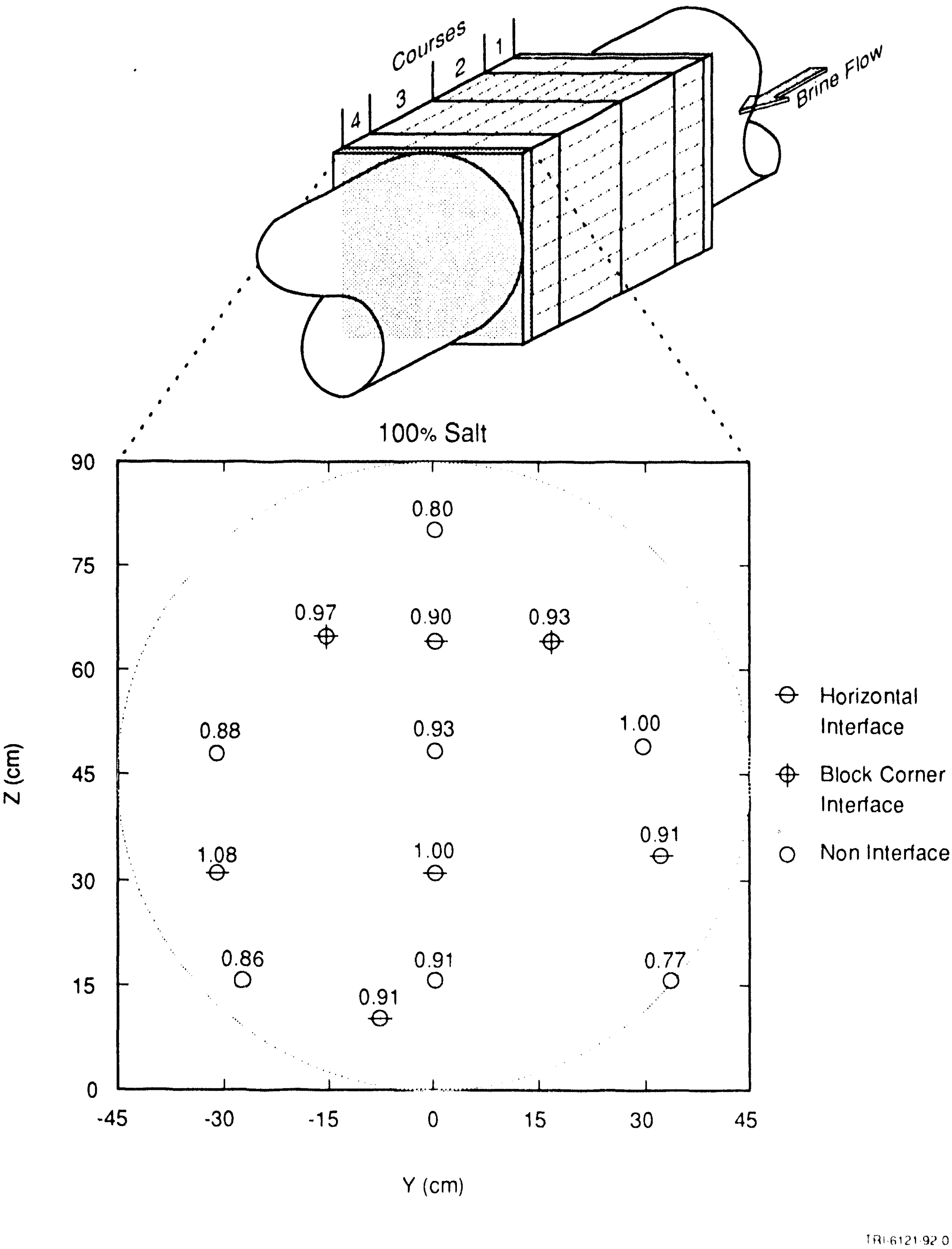

Figure 5-11. Clay content (wt %) map of sample plane 1.

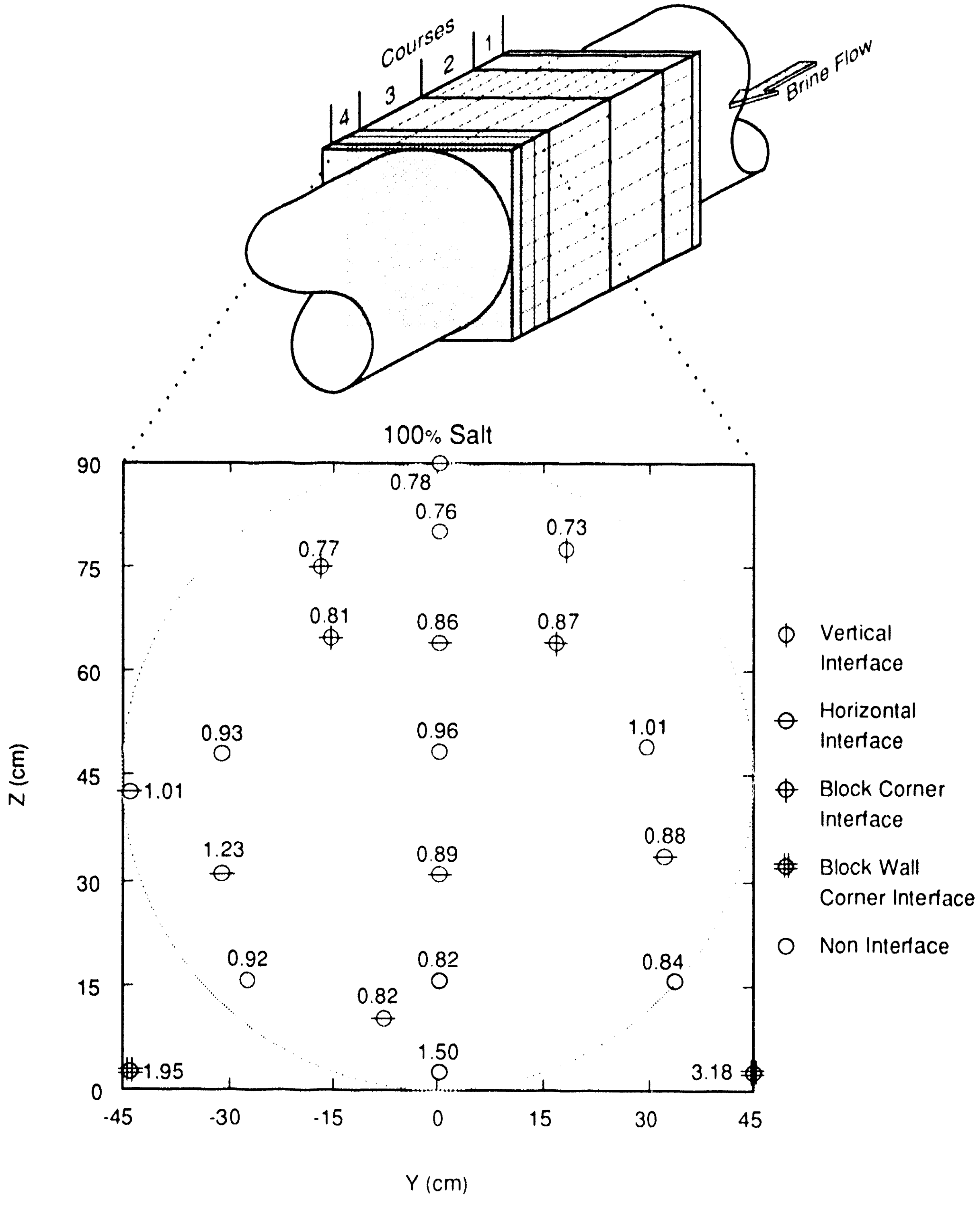

Figure 5-12. Clay content (wt%) map of sample plane 2.

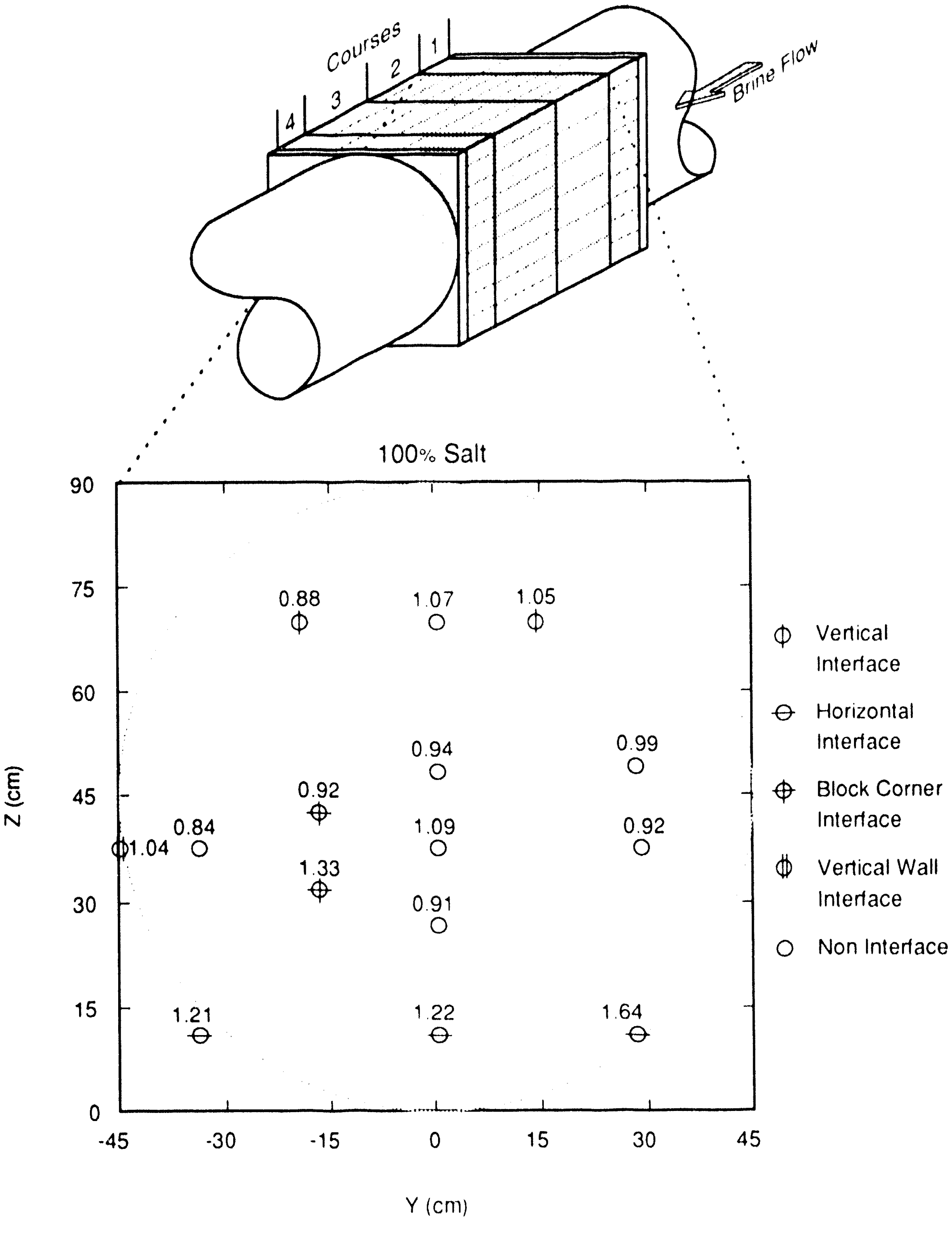

Figure 5-13. Clay content (wt %) map of sample plane 7.

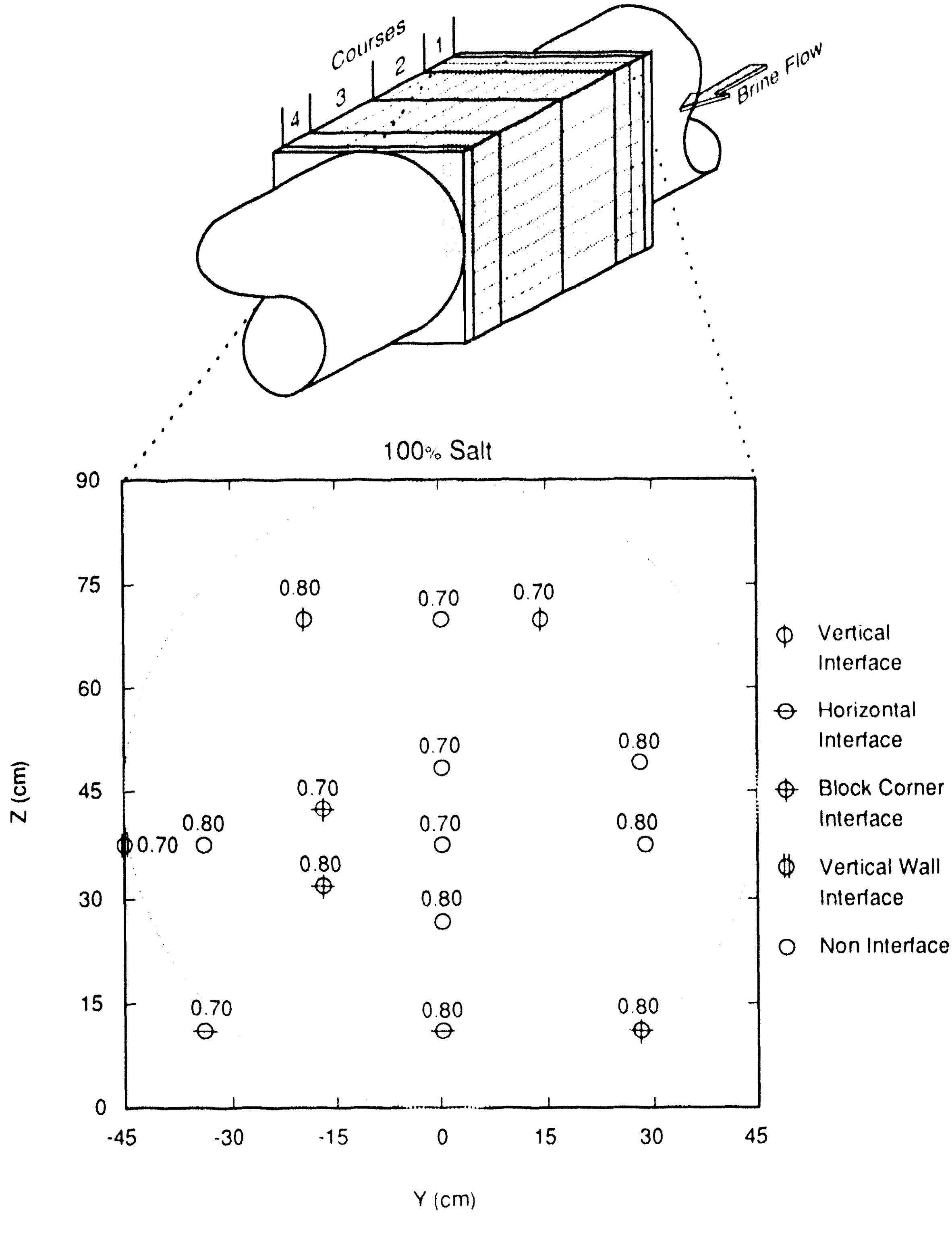

Figure 5-14. Clay content (wt) map of sample plane 8.

6.0 CONCLUSIONS

The results of brine flow tests on the seal in MCE33 show that the permeability of the salt and salt/bentonite seal was of the order of 2 to 3 x 10^{-4} darcy. This number is about two orders of magnitude higher than comparable concrete seals located at the WIPP.

The disassembly of seal MCE33 provided 212 core samples. Water content in the seal and clay content in the 100% crushed salt block endcaps were measured. The water contents from the salt endcaps correspond to saturations of about 14 to 65%, with the higher saturations occurring near the base of the seal. Gravity dainage probably caused a reduction in the saturation of these samples during disassembly of the seal. Water contents in the 50%/50% salt bentonite blocks are fairly uniform throughout the core of the seal and probably correspond to saturations of nearly 100%.

Clay content analyses suggest that the original salt used for this testing probably contained about 0.7 to 1.0% clay by weight. This can be seen as a "background" clay concentration uniformly distributed throughout both ends of the seal. A threefold increase over this background clay content was measured at the block/wall interface at the front of the seal near the bottom. This increase probably corresponds to a migration of bentonite from the center of the seal to plug potential piping failure at that location.

The use of 50%/50% salt/bentonite material may provide an acceptable alternative to short-term seal components. The migration of bentonite to a region of potential piping failure shows that this material may possess favorable sealing characteristics that can be used in combination with other seal materials or systems. Additional study of the mobility of saturated bentonites under structurally confined conditions should be undertaken prior to specifying this material in actual WIPP seal designs.

7.0 REFERENCES

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APPENDIX A: CORE SAMPLE LOCATIONS AND CONTENT ANALYSES

Table A-1. Data from Salt Cores Collected at Sample Plane 1

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
6- 22	1.52	0.93	0.00	0.00	47.63
6- 23	1.28	0.90	0.00	0.00	62.87
6- 24	1.86	1.00	0.00	0.00	30.48
6- 25	3.61	0.91	0.00	0.00	15.24
6- 26	4.00	0.91	0.00	-7.62	10.16
6- 27	1.18	0.80	0.00	0.00	78.74
6- 28	3.33	0.77	0.00	33.02	15.24
6- 29	2.60	0.91	0.00	31.75	33.02
6- 30	2.12	1.00	0.00	29.21	48.26
6- 31	1.63	0.93	0.00	16.51	62.87
6- 32	2.98	0.86	0.00	-26.67	15.24
6- 33	2.40	1.08	0.00	-30.48	30.48
6- 34	2.23	0.88	0.00	-30.48	46.99
6- 35	1.67	0.97	0.00	-15.24	63.50

Table A-2. Data from Salt Cores Collected at Sample Plane 2

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
6- 1	1.53	0.96	7.62	0.00	47.63
6- 2	1.24	0.86	7.62	0.00	62.87
6- 3	1.90	0.89	7.62	0.00	30.48
6- 4	3.33	0.82	7.62	0.00	15.24
6- 5	3.96	0.82	7.62	-7.62	10.16
6- 6	1.20	0.76	7.62	0.00	78.74
6- 7	2.83	0.92	7.62	33.02	15.24
6- 8	2.05	0.88	7.62	31.75	33.02
6- 9	1.93	1.01	7.62	29.21	48.26
6- 10	1.52	0.87	7.62	16.51	62.87
6- 11	2.68	0.84	7.62	-26.67	15.24
6- 12	1.68	1.23	7.62	-30.48	30.48
6- 13	1.76	0.93	7.62	-30.48	46.99
6- 14	1.34	0.81	7.62	-15.24	63.50
6- 15	1.03	0.78	7.62	0.00	88.90
6- 16	1.67	1.01	7.62	-43.18	41.91
6- 17	3.57	1.50	7.62	0.00	0.00
6- 18	1.18	0.73	7.62	17.78	76.20
6- 19	1.28	0.77	7.62	-165.10	73.66
6- 20	5.03	3.18	7.62	44.45	0.00
6- 21	3.69	1.95	7.62	-43.18	0.00

Table A-3. Data from Salt/Bentonite Cores Collected at Sample Plane 3

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
4- 1	13.91	NA	17.78	0.00	47.63
4- 2	11.92	NA	17.78	0.00	64.14
4- 3	13.77	NA	17.78	0.00	79.38
4- 4	12.27	NA	17.78	-9.53	78.74
4- 5	12.77	NA	17.78	-10.16	69.22
4- 6	12.38	NA	17.78	-18.42	64.14
4- 7	14.78	NA	17.78	-27.31	78.74
4- 8	10.42	NA	17.78	-33.66	74.30
4- 9	13.60	NA	17.78	-36.83	59.69
4- 10	15.31	NA	17.78	-10.80	58.42
4- 11	13.83	NA	17.78	-18.42	53.34
4- 12	14.52	NA	17.78	-9.53	48.26
4- 13	14.58	NA	17.78	-8.89	36.83
4- 14	9.02	NA	17.78	-30.48	45.72
4- 15	13.17	NA	17.78	-23.50	35.56
4- 16	14.48	NA	17.78	-16.51	29.21
4- 17	14.63	NA	17.78	-31.75	30.48
4- 18	14.57	NA	17.78	31.75	20.32
4- 19	13.78	NA	17.78	-21.59	16.51
4- 20	14.46	NA	17.78	-10.16	10.16
4- 21	14.56	NA	17.78	7.62	16.51
4- 22	14.09	NA	17.78	21.59	17.78
4- 23	13.90	NA	17.78	30.48	22.23
4- 24	14.65	NA	17.78	29.21	47.63
4- 25	11.32	NA	17.78	14.61	52.71
4- 26	12.32	NA	17.78	7.62	58.42
4- 27	12.90	NA	17.78	15.24	63.50
4- 28	12.93	NA	17.78	27.94	74.93
4- 29	12.67	NA	17.78	20.32	80.01
4- 30	14.43	NA	17.78	41.91	57.15
4- 31	10.69	NA	17.78	41.91	36.83
4- 32	12.92	NA	17.78	10.16	3.81
4- 33	13.09	NA	17.78	-26.67	2.54
4- 34	14.20	NA	17.78	-44.45	41.91

Table A-4. Data from Salt/Bentonite Cores Collected at Sample Plane 4

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
4- 35	12.92	NA	30.48	0.00	47.63
4- 36	13.59	NA	30.48	0.00	64.14
4- 37	14.44	NA	30.48	0.00	79.38
4- 38	13.61	NA	30.48	-9.53	78.74
4- 39	11.61	NA	30.48	-10.16	69.22
4- 40	11.63	NA	30.48	-18.42	64.14
4- 41	13.00	NA	30.48	-27.31	78.74
4- 42	11.94	NA	30.48	-33.66	74.30
4- 43	12.36	NA	30.48	-36.83	59.69
4- 44	9.92	NA	30.48	-10.80	58.42
4- 45	11.55	NA	30.48	-18.42	53.34
4- 46	13.24	NA	30.48	-9.53	48.26
4- 47	13.52	NA	30.48	-8.89	36.83
4- 48	10.62	NA	30.48	-30.48	45.72
4- 49	13.36	NA	30.48	-23.50	35.56
4- 50	13.34	NA	30.48	-16.51	29.21
4- 51	13.00	NA	30.48	-31.75	30.48
4- 52	12.72	NA	30.48	-31.75	20.32
4- 53	12.39	NA	30.48	-21.59	16.51
4- 54	13.15	NA	30.48	-10.16	10.16
4- 55	12.69	NA	30.48	7.62	16.51
4- 56	12.07	NA	30.48	21.59	17.78
4- 57	13.22	NA	30.48	30.48	22.23
4- 58	13.93	NA	30.48	29.21	47.63
4- 59	14.09	NA	30.48	14.61	52.71
4- 60	14.29	NA	30.48	7.62	58.42
4- 61	13.90	NA	30.48	15.24	63.50
4- 62	11.99	NA	30.48	27.94	74.93
4- 63	13.89	NA	30.48	20.32	80.01
4- 64	13.11	NA	30.48	41.91	57.15
4- 65	11.85	NA	30.48	41.91	36.83
4- 66	11.02	NA	30.48	10.16	3.81
4- 67	11.23	NA	30.48	-26.67	2.54
4- 68	12.11	NA	30.48	-44.45	41.91

Table A-5. Data from Salt/Bentonite Cores Collected at Sample Plane 5

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
2- 1	15.04	NA	51.44	15.88	42.55
2- 2	14.13	NA	51.44	8.89	38.10
2- 3	12.99	NA	51.44	24.13	31.75
2- 4	12.44	NA	51.44	22.23	25.40
2- 5	10.98	NA	51.44	15.24	21.59
2- 6	12.64	NA	51.44	8.26	26.67
2- 7	12.80	NA	51.44	30.48	20.96
2- 8	13.53	NA	51.44	7.62	16.51
2- 9	12.11	NA	51.44	38.74	31.75
2- 10	11.03	NA	51.44	24.13	5.08
2- 11	13.22	NA	51.44	0.00	41.91
2- 12	14.45	NA	51.44	8.89	5.08
2- 13	13.75	NA	51.44	39.37	10.80
2- 14	15.69	NA	51.44	-6.35	38.10
2- 15	14.96	NA	51.44	-12.70	32.39
2- 16	15.32	NA	51.44	-6.35	26.67
2- 17	13.08	NA	51.44	-22.86	21.59
2- 18	12.94	NA	51.44	-6.99	16.51
2- 19	14.07	NA	51.44	-13.34	22.23
2- 20	13.43	NA	51.44	-20.96	38.10
2- 21	13.35	NA	51.44	-13.34	10.80
2- 22	11.83	NA	51.44	-6.35	5.08
2- 23	13.57	NA	51.44	-29.21	10.80
2- 24	14.42	NA	51.44	-38.10	15.88
3- 1	13.15	NA	51.44	-29.21	31.75
3- 2	11.78	NA	51.44	-38.10	36.83
3- 3	13.33	NA	51.44	0.00	53.34
3- 4	14.61	NA	51.44	-21.59	58.42
3- 5	12.95	NA	51.44	15.11	62.87
3- 6	12.83	NA	51.44	6.35	80.01
3- 7	12.54	NA	51.44	30.48	73.66
3- 8	11.40	NA	51.44	38.74	59.06
3- 9	13.27	NA	51.44	30.48	63.50
3- 10	15.00	NA	51.44	-22.86	68.58
3- 11	13.57	NA	51.44	-11.43	73.66
3- 12	13.86	NA	51.44	44.45	26.67
3- 13	12.06	NA	51.44	44.45	2.54
3- 14	12.41	NA	51.44	-21.59	2.54
3- 15	14.10	NA	51.44	-43.82	15.24

Table A-6. Data from Salt/Bentonite Cores Collected at Sample Plane 6

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
5- 1	13.66	NA	64.77	15.88	42.55
5- 2	14.29	NA	64.77	8.89	38.10
5- 3	14.07	NA	64.77	24.13	31.75
5- 4	13.38	NA	64.77	22.23	25.40
5- 5	13.67	NA	64.77	15.24	21.59
5- 6	13.92	NA	64.77	8.26	26.67
5- 7	15.78	NA	64.77	30.48	20.96
5- 8	14.52	NA	64.77	7.62	16.51
5- 9	11.24	NA	64.77	38.74	31.75
5- 10	13.51	NA	64.77	24.13	5.08
5- 11	10.71	NA	64.77	0.00	41.91
5- 12	12.50	NA	64.77	8.89	5.08
5- 13	9.00	NA	64.77	39.37	10.80
5- 14	15.07	NA	64.77	-6.35	38.10
5- 15	14.95	NA	64.77	-12.70	32.39
5- 16	9.35	NA	64.77	-6.35	26.67
5- 17	13.52	NA	64.77	-22.86	21.59
5- 18	11.59	NA	64.77	-6.99	16.51
5- 19	11.49	NA	64.77	-13.34	22.23
5- 20	12.41	NA	64.77	-20.96	38.10
5- 21	12.88	NA	64.77	-13.34	10.80
5- 22	9.04	NA	64.77	-6.35	5.08
5- 23	13.07	NA	64.77	-29.21	10.80
5- 24	14.74	NA	64.77	-38.10	15.88
5- 25	14.15	NA	64.77	-29.21	31.75
5- 26	7.14	NA	64.77	-38.10	36.83
5- 27	14.68	NA	64.77	0.00	53.34
5- 28	14.74	NA	64.77	-21.59	58.42
5- 29	14.20	NA	64.77	14.61	62.87
5- 30	13.04	NA	64.77	6.35	80.01
5- 31	13.17	NA	64.77	30.48	73.66
5- 32	11.50	NA	64.77	38.74	59.06
5- 33	15.13	NA	64.77	30.48	63.50
5- 34	10.93	NA	64.77	-22.86	68.58
5- 35	14.89	NA	64.77	-11.43	73.66
5- 36	13.73	NA	64.77	44.45	26.67
5- 37	12.60	NA	64.77	44.45	2.54
5- 38	13.30	NA	64.77	-21.59	2.54
5- 39	10.91	NA	64.77	-43.82	15.24
5- 40	14.25	NA	64.77	-47.63	87.00

Table A-7. Data from Salt Cores Collected at Sample Plane 7

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
7- 1	2.52	1.22	85.09	0.00	10.80
7- 2	3.40	0.91	85.09	0.00	26.04
7- 3	3.27	1.09	85.09	0.00	36.83
7- 4	3.17	0.94	85.09	0.00	47.63
7- 5	2.25	1.07	85.09	0.00	68.58
7- 6	3.18	1.64	85.09	27.94	10.80
7- 7	4.32	0.92	85.09	28.58	36.83
7- 8	2.86	0.99	85.09	27.94	48.26
7- 9	2.66	1.05	85.09	13.97	68.58
7- 10	3.52	1.21	85.09	-33.02	10.80
7- 11	3.39	0.84	85.09	-33.02	36.83
7- 12	3.87	1.33	85.09	-16.51	31.12
7- 13	4.22	0.92	85.09	-16.51	41.91
7- 14	2.74	0.88	85.09	-19.05	68.58
7- 15	3.55	1.04	85.09	-45.72	36.83

Table A-8. Data from Salt Cores Collected at Sample Plane 8

Box- Sample No.	Moisture Content (%)	Clay Content (%)	Distance East of Seal Front (cm)	Distance North (-) of Hole Axis (cm)	Distance Above Seal Floor (cm)
7- 16	3.12	0.80	88.27	0.00	10.80
7- 20	2.35	0.71	88.27	0.00	68.58
7- 21	4.05	0.75	88.27	27.94	10.80
7- 22	4.29	0.78	88.27	28.58	36.83
7- 23	3.33	0.78	88.27	27.94	48.26
7- 24	2.33	0.73	88.27	13.97	68.58
7- 25	4.63	0.71	88.27	-33.02	10.80
7- 26	3.97	0.76	88.27	-33.02	36.83
7- 27	4.01	0.76	88.27	-16.51	31.12
7- 28	3.24	0.73	88.27	-16.51	41.91
7- 29	2.31	0.79	88.27	19.05	68.58
7- 30	3.61	0.73	88.27	-45.72	36.83

APPENDIX B: MCE33 BRINE RECIRCULATION DATA

Table B-1. MJE33 Brine Recirculation Data

Date	Time	Days from Recirculation Startup	Extracted Volume (L)	Cumulative Extracted Volume (L)	Calculated Flow Rate (ml/day)
9/2/87	12:00	0.00	4.11	4.11	
9/8/87	12:00	6.00	3.65	7.76	608.33
9/14/87	12:00	12.00	3.58	11.34	596.67
9/21/87	9:10	18.88	3.04	14.38	441.74
9/25/87	10:40	22.94	3.25	17.63	800.00
10/2/87	9:00	29.88	4.05	21.68	584.37
10/9/87	12:50	37.03	4.16	25.84	581.03
10/14/87	8:30	41.85	2.82	28.66	585.13
10/16/87	9:30	43.90	1.17	29.83	573.06
10/23/87	9:37	50.90	4.25	34.08	606.72
10/30/87	9:00	57.88	4.13	38.21	592.17
11/6/87	8:45	64.86	3.87	42.08	552.97
11/13/87	8:30	71.85	4.37	46.45	625.22
11/20/87	8:59	78.87	4.15	50.60	591.16
11/25/87	8:35	83.86	2.95	53.55	591.97
12/4/87	9:00	92.88	5.02	58.57	556.70
12/11/87	10:30	99.94	3.40	61.97	481.42
12/18/87	9:30	106.90	3.78	65.74	542.51
12/22/87	10:56	110.96	2.00	67.74	492.64
12/30/87	9:30	118.90	3.60	71.34	453.38
1/6/88	10:00	125.92	3.21	74.55	457.21
1/13/88	9:10	132.88	3.00	77.55	430.71
1/20/88	8:45	139.86	3.00	80.55	429.64
1/27/88	8:45	146.86	3.00	83.55	428.57
2/3/88	8:33	153.86	2.85	86.40	407.63
2/10/88	8:52	160.87	2.71	89.11	386.41
2/17/88	10:00	167.92	2.73	91.84	387.39
2/24/88	9:25	174.89	2.56	94.40	366.99
3/2/88	9:00	181.88	2.65	97.05	464.04
3/9/88	9:15	188.89	2.42	99.47	345.20
3/16/88	9:15	195.89	2.40	101.87	342.86
4/13/88	10:45	223.95	4.28	106.15	449.00
4/27/88	9:16	237.89	4.13	110.27	559.28

Table B-1. MCE33 Brine Recirculation Data (continued)

Date	Time	Days from Recirculation Startup	Extracted Volume (L)	Cumulative Extracted Volume (L)	Calculated Flow Rate (ml/day)
5/4/88	10:00	244.92	2.16	112.43	671.71
5/5/88	18:00	246.25	0.24	112.67	784.39
5/18/88	10:00	258.92	3.66	116.33	900.72
6/2/88	10:00	273.92	4.25	120.58	1021.30
6/16/88	9:00	287.88	3.84	124.42	1145.72
7/1/88	13:00	303.04	4.12	128.54	1274.26
7/15/88	12:00	317.00	3.77	132.31	1406.57
7/27/88	12:00	329.00	3.20	135.51	1542.08
8/10/88	12:00	343.00	3.74	139.25	1681.33
8/24/88	12:00	357.00	3.83	143.08	1824.42
9/7/88	12:00	371.00	3.87	146.95	1971.37
9/21/88	12:00	385.00	3.65	150.60	2121.96
10/5/88	12:00	399.00	3.67	154.27	2276.24
10/21/88	12:00	415.00	4.24	158.52	2434.75
11/4/88	12:00	429.00	3.88	162.39	2597.15
11/21/88	12:00	446.00	4.62	167.01	2764.16
12/9/88	12:00	464.00	4.74	171.76	2935.92
12/27/88	12:00	482.00	4.38	176.14	3112.05
1/13/89	12:00	499.00	3.97	180.10	3292.16
2/8/89	12:00	525.00	5.63	185.74	3477.89
2/24/89	12:00	541.00	3.74	189.47	3667.36
3/9/89	12:00	554.00	2.88	192.35	3859.71
3/23/89	12:00	568.00	3.21	195.56	4055.27
4/7/89	12:00	583.00	3.40	198.96	4254.23
5/2/89	12:00	608.00	5.08	204.03	4458.26
5/22/89	12:00	628.00	3.93	207.96	4666.23
6/6/89	13:00	643.04	2.98	210.94	4877.17
6/19/89	10:30	655.94	2.61	213.55	5090.72
6/30/89	12:15	667.01	2.58	216.13	5306.86
7/20/89	14:00	687.08	4.68	220.81	5527.67
8/3/89	12:00	701.00	3.34	224.15	5751.82
8/17/89	12:00	715.00	3.39	227.54	5979.36
8/31/89	12:00	729.00	1.80	229.34	6208.70
9/19/89	12:00	748.00	3.53	232.87	6441.57
10/3/89	12:00	762.00	3.05	235.91	6677.48

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