BRINE MIGRATION STUDIES
IN THE WASTE ISOLATION PILOT PLANT (WIPP)*

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ABSTRACT

An experiment to quantify brine migration in multi-heater, full scale tests simulating repository environments is underway in the Waste Isolation Pilot Plant. The brine migration experiment is part of near field effects/waste package interactions tests that simulate near-reference repository conditions (18 W/m^2 thermal areal loading with 470 W per canister) for defense high-level waste (DHLW) in room A1 and near-field overtest conditions (1500 W per canister) in room B. After 265 days, 16.1 kg and 17.6 kg of water had been collected from two heated boreholes in room B. Heated boreholes in room A1 had yielded 1.1 kg and 1.3 kg after 105 days. These quantities of water are larger than our estimates for a hypothetical repository array of 2.16 kW canisters based on previous small scale test data and mechanistic brine transport models. They are also significantly larger than the quantities of brine that were reported for brine migration experiments in the Asse Mine of the Federal Republic of Germany. Mechanistic differences that depend on scale, thermal distribution, and site characteristics may account for this disagreement with other experiments and model calculations.

INTRODUCTION

A major advantage of rock salt as a medium for radioactive waste isolation is the absence of circulating groundwater within it. Groundwater is the primary medium for the potential transport of radionuclides from a repository to the biosphere. Water or brine can also accelerate the corrosion of container materials and leach radioactive materials from waste forms.

Typically, bedded rock salt is not completely dry. It contains approximately 0.1 to 1 wt% water as brine that migrates toward higher temperatures in temperature gradients such as those that are generated by heat-producing radioactive waste[1]. It is desirable to have realistic predictions of brine migration to resolve issues that have been raised in this regard and to provide quantitative data for performance assessments.

Previous efforts to quantify brine migration in salt have resulted from concern about the potential effects of brine on repository performance. Quantities of water as water vapor released from salt samples or collected in heated boreholes were measured and related to brine contained in the salt as the source of the water[1-9]. from these studies and mechanistic models were used to show that the migration of brine toward a heat-producing radioactive waste container is not likely to pose a significant problem for the isolation of radioactive waste in bedded salt[3]. That prediction was based on laboratory and relatively small scale field test data. The WIPP tests extend the test conditions of scale, geometry, and distributed thermal output to those that more nearly simulate an actual repository environment.

Experiments to quantify brine migration in multi-heater, full scale tests simulating repository environments are now underway in the Waste Isolation Pilot Plant (WIPP). The WIPP Project is a research and development facility to demonstrate the safe disposal of radioactive wastes in bedded salt. In situ testing in this facility addresses the technical issues of repository development, waste package performance, and plugging and sealing technology, as well as demonstrations of waste handling[10,11]. The brine migration experiments are part of the near field effects/waste package interactions tests[12] that simulate near-reference repository conditions (18 W/m^2 thermal area loading with 470 W per canister) for defense high-level waste (DHLW) in room A1 and near-field overtest conditions (1500 W per canister) in room B.

The experimental system and procedures for the WIPP brine migration experiments are given in this paper. Results to date are also presented. They are discussed in terms of brine transport in a full scale test geometry and compared with results from other brine migration tests.

APPARATUS AND PROCEDURE

A schematic diagram of the experimental system is shown in Fig. 1. The physical locations of

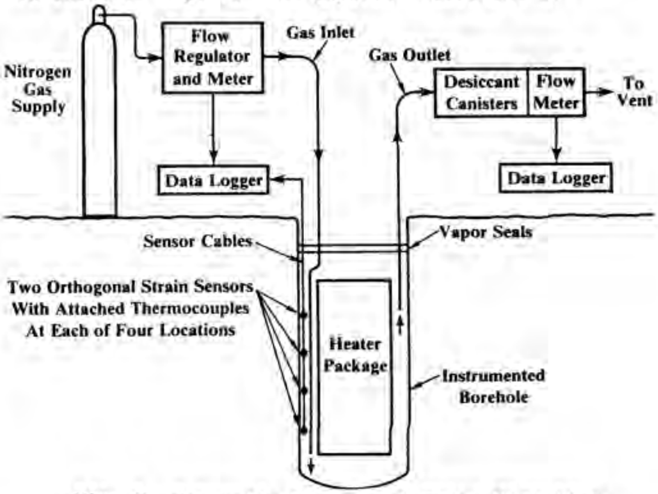

Fig. 1. Schematic Diagram of Brine Migration Experimental System.

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boreholes for this experiment among the WIPP near field effects/waste package interactions test is given elsewhere [12]. Electrical resistance heaters inside simulated DHLW canisters heat the lower sections of 0.76 to 0.91 m-diameter vertical boreholes in the floors of rooms A1 and B at the WIPP test facility. Boreholes A1041 and A1042 in Room A1 are 46.6 m apart. Boreholes B041 and B042 in Room B are 28.5 m apart. Borehole wall areas in the heated brine collection zones are 9.9 m^2 for borehole B041, and 7.4 m^2 for boreholes B042, A1041, and A1042. Borehole wall temperatures are measured with thermocouples. Strain at the borehole wall is measured with linear displacement gauges. Each displacement gauge measures relative displacements of two anchor points 20 cm apart. Borehole B041 has two displacement gauges near the top of the heater, one for horizontal and one for vertical displacement measurements. Borehole B042 has just one gauge for horizontal measurements near the top of the heater. Both boreholes in room A1 have one vertical and one horizontal gauge at each of four locations distributed on the salt walls between the bottom and the top of the heaters.

Each borehole is equipped with a separate nitrogen flow and water vapor collection and measurement system. Dry bottled nitrogen passes through a flowmeter, a molecular sieve desiccant, and then an inlet tube to the bottom of each borehole. A vapor seal (packer) above each heater-canister prevents significant gas and vapor leakage. Nitrogen and water vapor leave the borehole through an outlet tube in the cover plate. The gas mixture from each borehole in room B passes through a cold trap, a gas flowmeter, and molecular sieve desiccant canisters that absorb more than 90% of the water vapor in the flowing gas. For room A1, only desiccants are used. The weight gain of the desiccants added to the weight of water drained from the trap is the measure of the quantity of water that was released to each borehole between weighings. That quantity of water is assumed to be derived from brine that has migrated to the borehole.

The systems were initially designed to measure water release rates in the range of 0.0005 to 20 g/day using nitrogen flow rates from 10 to 1000 std. cc/min. The smallest measurable rate was determined by the smallest controllable nitrogen flow rate and the equilibrium water vapor pressure specified for the desiccant (0.001 Torr for sodium aluminosilicate 4A molecular sieve). The minimum allowable partial pressure of water was set at 0.02 Torr for 95% collection efficiency. The maximum measurable rate was fixed by the largest nitrogen gas flow rate allowable without risking vapor seal failure due to pressure buildup in the borehole. Pressure buildup could be appreciable due to pressure drop in the long (as much as 100 m) nitrogen return tubes between the boreholes in the heated rooms to the water collection and measurement systems outside the rooms. Input and return nitrogen flowmeter readings provide material balance data for monitoring the gas flow system.

Baseline data were taken first for unheated boreholes; then the heaters were turned on. Zero time (t = 0) for each experiment was chosen to be the clock time for the first set of baseline data. Baseline data were taken over a 4-day interval for room B and over a 7-day interval for room A1. Then, heater power was increased from zero to nominal values of 1500 W for room B and 470 W for room A1 within 2 minutes for each borehole. Initial nitrogen flow rates were set to keep the current water collection rates safely within the design range. Room B nitrogen flow rates were increased to the maximum allowable after the water collection rates rose rapidly. Desiccants were weighed several times each workday initially, and once each workday after the first few days. Temperature and displacement data were taken automatically at 15-minute intervals initially, and then at 4-hour intervals after several days.

RESULTS

Room B -- Near-Field Overtest Conditions

The cumulative quantities of water that were collected from each of the boreholes in room B are plotted in Fig. 2 versus time after baseline measurements began at 0.0 days. After 265 days, 17.6 kg of water had been collected from borehole B041, and 16.1 kg of water had been collected from borehole B042. Water collection was characterized by a small nearly constant rate before heater turn-on and a rapidly increasing rate after heater turn-on. During the first 4.2 days before the heaters were turned on, 22.4 g of water were collected from borehole B041 at an average rate of 5.4 g/day, and 19.3 g of water were collected from borehole B042 at an average rate of 4.6 g/day. After the heaters were turned on, the water collection rate increased to the maximum measurable rate within approximately 2 days for both boreholes in room B. Water was no longer being collected and measured at the rate that it was being released to the borehole. Some water collected as condensate in the return gas lines, and some water may have accumulated in the borehole. There is no reason to expect that water was lost from the water measurement systems.

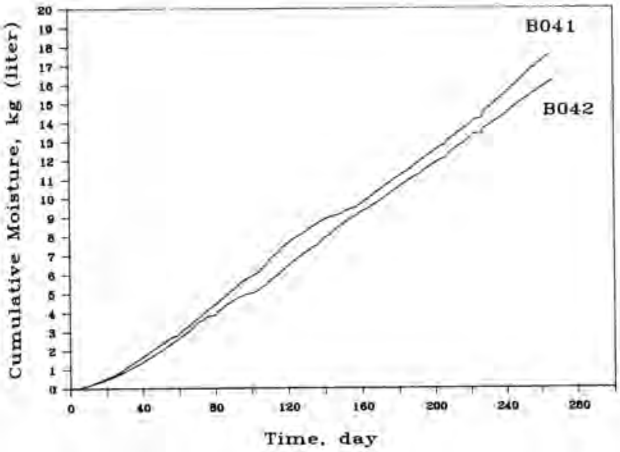

Fig. 2. Cumulative Quantities of Water Collected from Room B Boreholes.

Daily quantities of collected water remained unreliable as measures of water release rates to the room B boreholes until approximately 160 days after the measurements began. During that time, condensate was collected from the gas return lines from uncooled liquid traps and, after 68 days, from refrigerated liquid traps. After 105 days, larger diameter gas return tubing was put into service, and the maximum measurable water release rate was increased to approximately 100 g/day. At approximately 160 days, no evidence of condensate in the return tubing remained, and water collection rates became significantly less variable, as shown in Fig. 2.

Water collection rates remained relatively constant after 160 days at approximately 75 g/day for borehole B041 and approximately 65 g/day for borehole B042. Apparent discontinuities at 206 and 227 days in Fig. 2 were caused by unplanned fluctuations in cooling cycles for the cold traps. Again, no water was lost from the measurement systems.

Heater power was nominally 1500 W for the experiments in Room B. Several heater power interruptions and an interruption in power measurements occurred during the first 110 days of the room B experiment. Variations of water release rates that may have resulted from heater power interruptions were not detected, because the capacity of the water measurement systems was exceeded during that time interval. After 120 days, average heater power remained relatively constant within 10% of 1500 W.

Borehole wall temperatures at mid-heater height are plotted in Figs. 3 & 4. The borehole walls reached temperatures between 110 and 120°C approximately 260 days after heater turn-on. Temperature fluctuations before 120 days were due primarily to heater power fluctuations. After 120 days, noise in the measurement and data acquisition system and power interruptions to surrounding heaters may account for irregularities in the plots. A detailed analysis of room B data may yield that information.

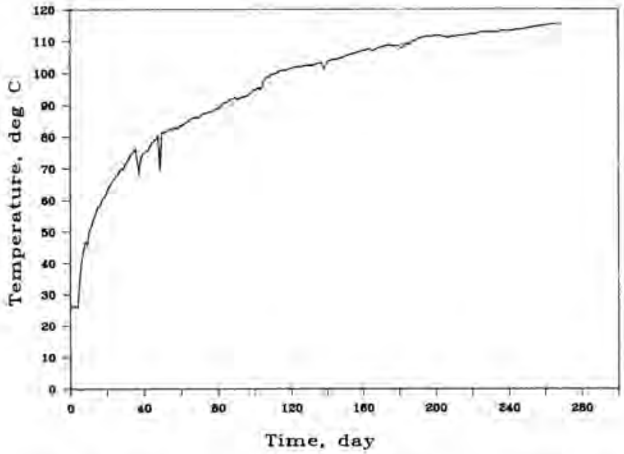

Fig. 3. Borehole Wall Temperatures at Mid-Heater Height for Borehole B041.

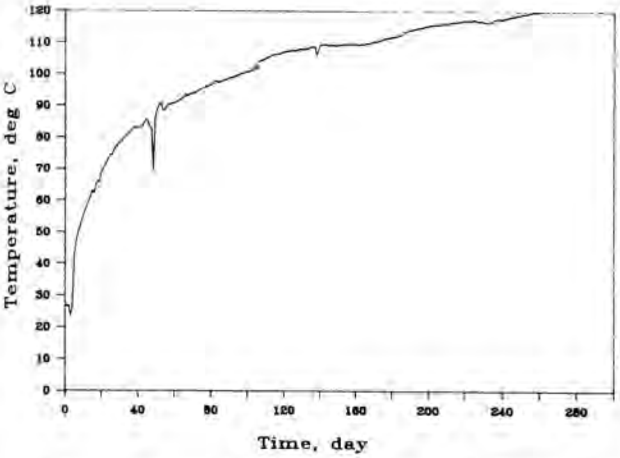

Fig. 4. Borehole Wall Temperatures at Mid-Heater Height for Borehole B042.

Vertical and horizontal strain measurements on the borehole walls are plotted in Fig. 5. Room B strain data after 100 days (t > 100) are unreliable due to maximum displacement and operating temperature limits of the gauges. The strain values are relative to an arbitrary zero and represent borehole wall displacements measured between fixed points 20 cm apart. Positive strain values are increased in the distance between the points. These plots show axial (vertical) expansion and circumferential (horizontal) contraction on the borehole walls near the tops of the heaters. Spikes near 80 days are due to an interruption of the data acquisition system. No rapid displacements were apparent after heater turn-on at 4 days and during heater power interruptions.

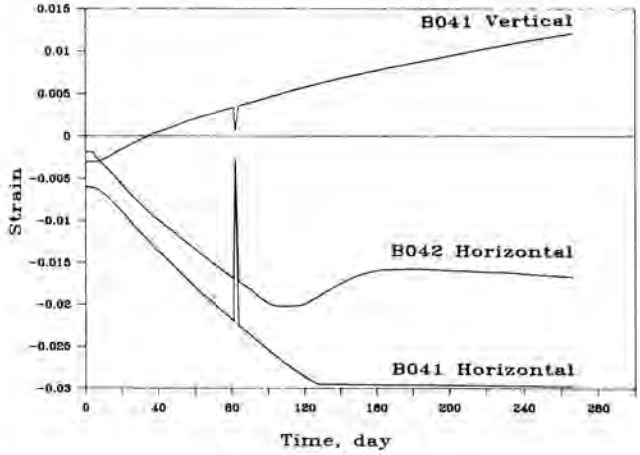

Fig. 5. Wall Strain in Boreholes B041 & B042.

Room Al -- DHLW Near-Reference Conditions

Cumulative water collection data are plotted in Fig. 6 for the boreholes in room Al. After 105 days, 1.3 kg of water had been collected from borehole A1041 and 1.1 kg from A1042. There were two transients characterized by large water collection rates, one immediately after initiating nitrogen flow and one approximately two days after heater turn-on. During the first 7.1 days before the heaters were turned on, 230 g of water were collected from borehole A1041, and 90 g of water were collected from borehole A1042. The water collection rates were nearly constant at 15 g/day and 7 g/day for boreholes A1041 and A1042, respectively during 2 days preceding heater turn-on. After heater turn-on at 7.1 days, the water collection rates remained at 15 g/day and 7 g/day for 2 days. Then the rates increased temporarily and decreased after 20 days to approximately 14 g/day for both boreholes. Thereafter, the water collection rates decreased gradually to approximately 9 g/day for both boreholes at 105 days.

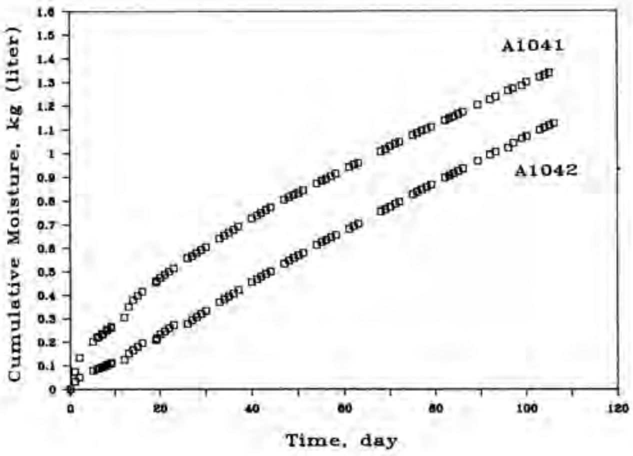

Fig. 6. Cumulative Quantities of Water Collected from Room Al Boreholes.

Apparent discontinuities at 19 and 26 days were caused by temporary use of refrigerated cold traps in the water collection systems during the two preceding weekends. Thereafter, the traps were not used. The traps were a precaution against loss of water from the system should there have been a rapid increase in the water collection rates.

At 103 days, the nitrogen flow rate for room Al boreholes was reduced by a factor of 1/4. The water collection rate remained well within the measurable range. No change in water collection rates was detected at the new nitrogen flow rate, confirming that the measured rates were determined by water transport rate processes in the boreholes.

Heater power measurements were nominally 470 W for the experiments in Room Al. No power interruptions of more than a few seconds duration occurred. Average heater power was relatively constant within 10% of 470 W.

Borehole wall temperatures at mid-heater height are plotted in Figs. 7 & 8. The wall temperatures increased to approximately 50°C after 105 days. The small temperature decrease near 80 days occurred during two power outages for all room Al heaters except those in the brine migration test boreholes.

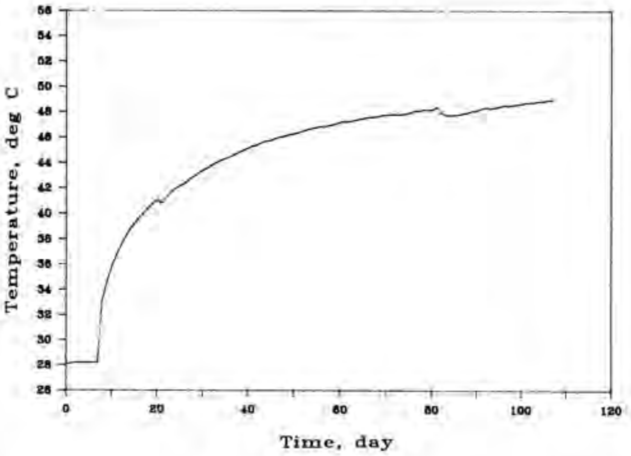

Fig. 7. Borehole Wall Temperatures at Mid-Heater Height for Borehole A1041.

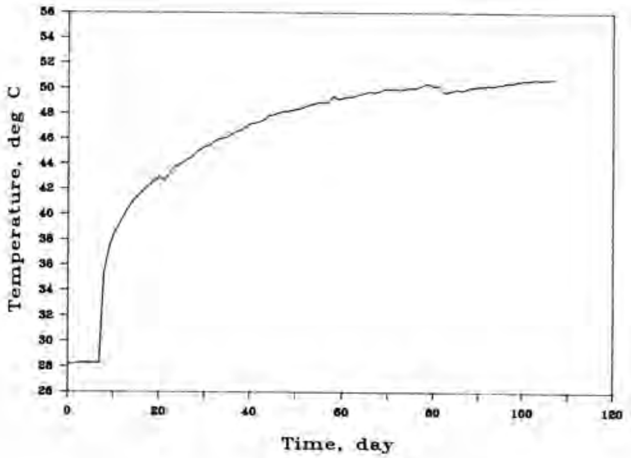

Fig. 8. Borehole Wall Temperatures at Mid-Heater Height for Borehole A1042.

Horizontal and vertical borehole wall strain data are plotted in Figs. 9 and 10 for borehole A1041. Strain data for borehole A1042 give identical results and are not included here. The strain values are relative to an arbitrary zero. These plots show gradual axial (vertical) expansion and circumferential (horizontal) contraction on the borehole wall at each of four equally spaced locations from the top to the bottom of the heater. The small perturbations in the curves near 80 days were concurrent with two power outages for nearby room Al heaters. Other perturbations may also be associated with events in the surrounding heater and instrumentation array. A detailed study of room A1 data may yield that information. No rapid strain changes were apparent immediately after heater turn-on.

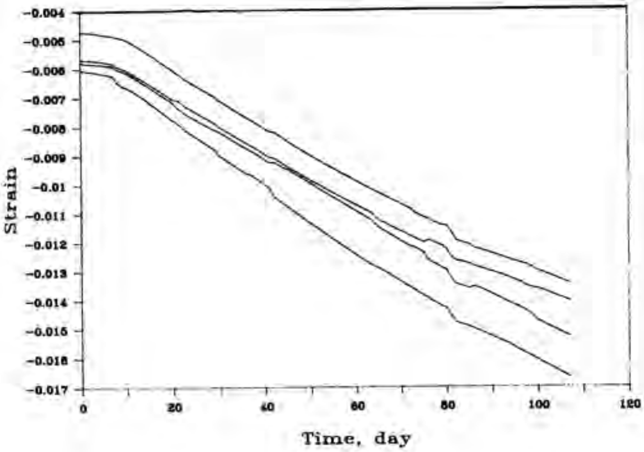

Fig. 9. Horizontal Strain on Borehole A1041 Wall.

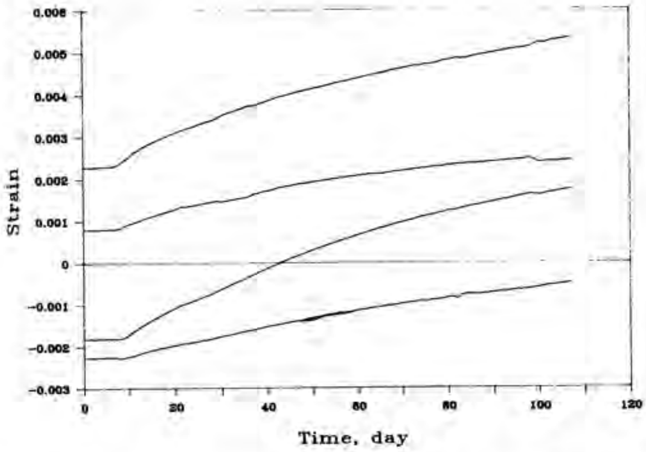

Fig. 10. Vertical Strain on Borehole A1041 Wall.

DISCUSSION AND CONCLUSIONS

Initial quantities of water that have been collected from heated boreholes in rooms A1 and B are larger than predictions from Shefelbein (Ref. 3) for a hypothetical repository array of 2.16 kW canisters with 37 W/m^2 thermal load. Vapor phase transport (0.23 wt % water in salt), fluid inclusion motion (0.23 wt % water), and stress-gradient transport (0.3 wt % water) were used as predictive models. Stress-gradient transport yielded the largest predicted water release: ∿0.3 kg during the first year after emplacement. Each borehole in room A1 (1.5 kW/canister) yielded >1 kg during the first 100 days, and the boreholes in room B each yielded >15 kg during the first 260 days in the WIPP experiments. While these quantities are relatively small compared with the initial repository void volume associated with a canister, they could be significant for canister corrosion. This experiment will be important in understanding the brine migration that occurs in a full-scale test as opposed to small scale experiments.

It is likely that sufficient water was initially present in the bedded rock salt within 1 m distance from the borehole walls to account for all of the water that has been collected in these experiments. At 1 wt % (2.17 vol %) water, a layer of salt that is less than 10 cm thick surrounding one of the boreholes in these experiments contains 17.6 kg (17,600 cm^3) of water, the largest quantity of water collected from one of the boreholes. At 0.1 wt % water, the water in less than 60 cm of salt would account for the same amount of collected water. Bedded salt in general and WIPP salt samples fall nominally within that water content range.

Another relatively large and long term experiment is underway in the Asse salt mine located in the Federal Republic of Germany[9]. Water content (available for migration at < 235°C) at the test sites was reported to be in the range of 0.01 to 0.10 wt %[9]. The design of that experiment was based on commercial high level waste at an areal heat loading of 37 W/m^2 using 3 kW heaters to achieve a maximum salt temperature of 210°C. The borehole wall area in the experimental zone at each test site is 2.7 m^2.

Quantities of water collected at the Asse test sites were considerably smaller than the quantities from the WIPP tests. During the first 10 months after heater turn-on at test site #2, only 0.095 kg of water were collected. Only 0.079 kg of water were collected at test site #4 during the first 3.5 months after heater turn-on[13].

Borehole wall area and water content of the salt are not sufficient as scale factors to reconcile the differences between the WIPP and Asse brine migration results. The WIPP/Asse ratio of test zone wall areas is approximately 3, and the WIPP/Asse water content ratio is approximately 10. Area and water content scaling factors alone suggest that 30 times more water would be expected from the WIPP experiments than from the Asse experiments. According to that scaling factor, approximately 3 kg of water would have been collected from Asse site #2 in 10 months and 2 kg from Asse site #4 in 3.5 months if the wall area and salt water content were the same as for the WIPP brine migration test. These values are significantly smaller than the 16-18 kg that were collected from boreholes in room B where the thermal conditions are most nearly equivalent to those for the Asse experiment.

Another difference between the WIPP and Asse early test results is the unmeasurably small water collection rate before the Asse test heaters were turned on [13]. In the Asse experiment, brine transport was negligible before the heaters were turned on. In the WIPP experiment, nearly constant water collection rates in the range of 4 to 15 g/day were measured during several days before heater turn-on. A non-thermal brine transport mechanism was operative in the WIPP test area. Brine was also observed to collect in adjacent covered boreholes (∿10 cm diameter) that were located adjacent to the test boreholes for ancillary experiments.

The unexplained differences between the Asse and the WIPP test results may be due to differences in the transport mechanisms for brine at the two sites. Compared with the bedded salt of the WIPP, the salt diapir of the Asse test site is likely to be characterized by tighter grain boundaries, more uniform grain size, and thinner, more generally discontinuous interbeds of clay and other minerals. Therefore the preferred flow paths for brine or water may be different and may present greater flow resistance than is the case at the WIPP test site.

Transport of brine to an unheated borehole was also observed in a previous small scale in-situ experiment[3]. One of the three boreholes was without heat for the first 124 days of experiment while adjacent boreholes were heated to 145°C (borehole salt wall temperature) in three steps. The water collection rate from the unheated borehole remained relatively constant and approximately the same as the rates from adjacent boreholes as they were heated to 90°C. At 145°C and higher, the rates from the heated boreholes exceeded the rate from the unheated borehole.

The larger water collection rates from room B compared with room A1 are consistent with previous[3] observations that the rates are larger for higher borehole wall temperatures. Rates were in the range 65 to 75 g/day from room B at 110 to 120°C wall temperatures; rates for both boreholes in room A1 were 9 g/day at 50°C wall temperatures.

Water collection rates from room A1 were independent of the partial pressure of water vapor in the boreholes. A four-fold decrease of nitrogen flow rate did not change the measured water collection rate. Therefore, the partial pressure of water vapor in the boreholes must have increased by a factor of 4. This result is consistent with water (or brine) transport mechanisms that are independent of the partial pressure of water vapor in the borehole.

Mechanistic interpretations of the results of this experiment are premature at this time; additional data analyses and experiments are needed. The relative contribution to collected water by Darcy flow of brine or water vapor through interconnected porosity should be evaluated. Zones of high clay content and other mineral inhomogeneities may contribute flow paths in addition to intergranular joints. Thermally generated temperature and stress gradients are potential driving forces in addition to hydrostatic pressure at the test horizon. Both flow paths and stress gradients may be modified by the movements and stress changes that accompany room closure. Calculations of temperature gradients in the test borehole walls are needed as inputs to mechanistic models for brine transport. The borehole wall strain measurements must be integrated with room closure data to sort out the potential role of strain as a driving force for brine transport. Brine migration experiments in uheated boreholes are needed to quantify and understand isothermal brine migration. Detailed stratigraphic analyses may help to complete the mechanistic picture and provide more specific data on water content.

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