Scale-Up Testing—Foam as a Remedial Amendment Carrier - 10040

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ABSTRACT

This paper describes results from intermediate-scale, two-dimensional testing of foam injection into sedimentary materials collected from the U.S. Department of Energy (DOE) Hanford Site area. The testing was performed to evaluate the effects of delivery pressure, injection rate, foam stability, foam quality, and formation heterogeneities on the migration of foam, water, remediation amendment, and contaminants within a sedimentary volume. Testing was accomplished in a test bed that is configured in the form of two thin rectangular boxes. Each of the boxes holds approximately 135 liters (255 kilograms) of sediment. Foam was injected into each box through a segment of polyvinyl chloride slotted well casing, and air was extracted from the boxes through a similar system. Four sets of tests were conducted, and three of those tests will be described here. During Test 1, both of the boxes were loaded in a homogeneous manner, while in Tests 2, 3, and 4, the boxes were loaded so as to contain two rectangular zones of heterogeneity. In addition, a zone of the sediment contained in the test bed used for Test 4 was augmented with uranium-rich calcite to produce a known concentration of uranium. The injection rate varied between the boxes during Test 1 but was the same for each box during the final three tests. The foam generation formula for Tests 1 and 2 consisted of an aqueous solution of anionic surfactant. The foam generation formula used in Test 3 consisted of an aqueous solution of anionic surfactant and contained 25,000 milligrams per liter (mg/L) of phosphate in the form of a 9:1 mixture of sodium phosphate and sodium tripolyphosphate. The foam generating formula used in Test 4 consisted of an aqueous solution of an anionic surfactant and a nonionic surfactant and also contained 5,000 mg/L of phosphate as the aforementioned mixture. Subsequent to each of the four tests, the test beds were disassembled, and samples of the sediments were taken and analyzed for a number of parameters, depending on the specific test.

INTRODUCTION

The production of nuclear fuels and weapons has resulted in contamination of vadose zone sediments at a number of locations across the U.S. Department of Energy (DOE) Complex. The deep vadose zone sites represent one of the most challenging remediation problems within the DOE Complex. These areas pose unique problems for remediation since much of the contamination is too deep for applying remedial techniques that have been used for nearer surface waste sites. Alternatively, chemical fixation technologies can be used as a means of in situ immobilization of metals and radionuclides. Chemical fixation by amendments including direct reaction, chemical-induced precipitation and coprecipitation, and sorption to precipitates is the most commonly used approach for metals and radionuclides in situ immobilization [1, 2, 3, 4]. Using water as a carrier for chemical fixation reagents spreads the contamination and accelerates its entering the groundwater. By applying foam as a carrier for the fixation reagents, those reagents can potentially be emplaced with minimal change in the resident moisture of the area of injection and achieve a more uniform distribution of the treatment amendments, minimizing the spread of the contamination. The use of foams as a carrier of reagents is truly a cutting-edge application of these materials. Searches of the scientific literature reveal the use of foams for environmental purposes has almost exclusively been applied as a means of enhancing the removal of contaminants not the delivery and reaction of treatment reagents. To enhance the state of the art of using foam as a method for delivering treatment reagents with the overall objective of developing a foam delivery technology to be used for the distribution of immobilization amendments to deep vadose zone sediments, Pacific Northwest National Laboratory (PNNL), in conjunction with MSE Technology Applications, Inc. (MSE),

is conducting a research project entitled Foam Delivery of Remedial Amendments to Deep Vadose Zone for Metals and Radionuclides Remediation. MSE's role within the research project was to conduct intermediate-scale, two-dimensional (2-D) tests to evaluate foam movement, reagent transport, and reagent reactivity within homogeneous and heterogeneous sedimentary materials collected from the DOE Hanford Site area. The results of these intermediate-scale tests will be used to bridge the gap between small-scale foam transport studies conducted at PNNL and a field-scale demonstration.

INTERMEDIATE-SCALE TESTING
The intermediate-scale laboratory testing and data analysis was completed at the MSE Test Facility in Butte, Montana. Testing was performed to evaluate the effects of delivery pressure, injection rate, foam stability, foam quality, and formation heterogeneities on the migration of foam, water, remediation amendment, and contaminants within a sedimentary volume.

Test Objectives
The overall objective of the project was to develop a foam delivery technology to be used for the distribution of remedial amendments to deep vadose zone sediments for the in situ immobilization of metal and radionuclide contaminants in those sediments.

The primary objectives of the intermediate-scale testing conducted at MSE were:

- investigate the effects of sediment heterogeneities on the ability of foam to propagate through a sedimentary volume;
- investigate the effects of sediment heterogeneities on the ability of the foam to carry a treatment amendment through the entire sedimentary volume; and
- determine the potential mobilization of a contaminant of concern (uranium) by the foam and the ability of the treatment amendment to immobilize that contaminant of concern within the sedimentary volume.

Injection Testing Approach
The scale-up testing was performed in a test bed that was comprised of two thin rectangular boxes designed to focus on 2-D flow. Each box had dimensions of 100 centimeters (cm) in length by 90 cm high by 15 cm wide and held approximately 135 liters (L) [255 kilograms (kg)] of sediment. The boxes were formed of steel sheeting with a front face of clear acrylic and a removable lid to allow for loading and sampling of the contained sediment. Each box of the test bed was designed to withstand an internal pressure of 61 kilopascals (kpa) [10 pounds per square inch (psi)] without excessive deformation and leaking. Foam was injected into the central section of each box through a segment of polyvinyl chloride (PVC) slotted well casing, and air was extracted from the boxes through a similar system. A frontal view schematic of the two boxes that comprised the test bed loaded in a homogeneous manner is shown in Fig. 1 and loaded in a heterogeneous manner in Fig 2.

Each box was accompanied by a foam generating system consisting of a pressurized air system, a solution pump, and a porous plate apparatus as shown in Fig. 3. Foam was produced by mixing one or more surfactants with a surrogate Hanford groundwater and forcing the resulting solution through the porous plate with air. The resulting foam was then captured and injected into the test boxes.
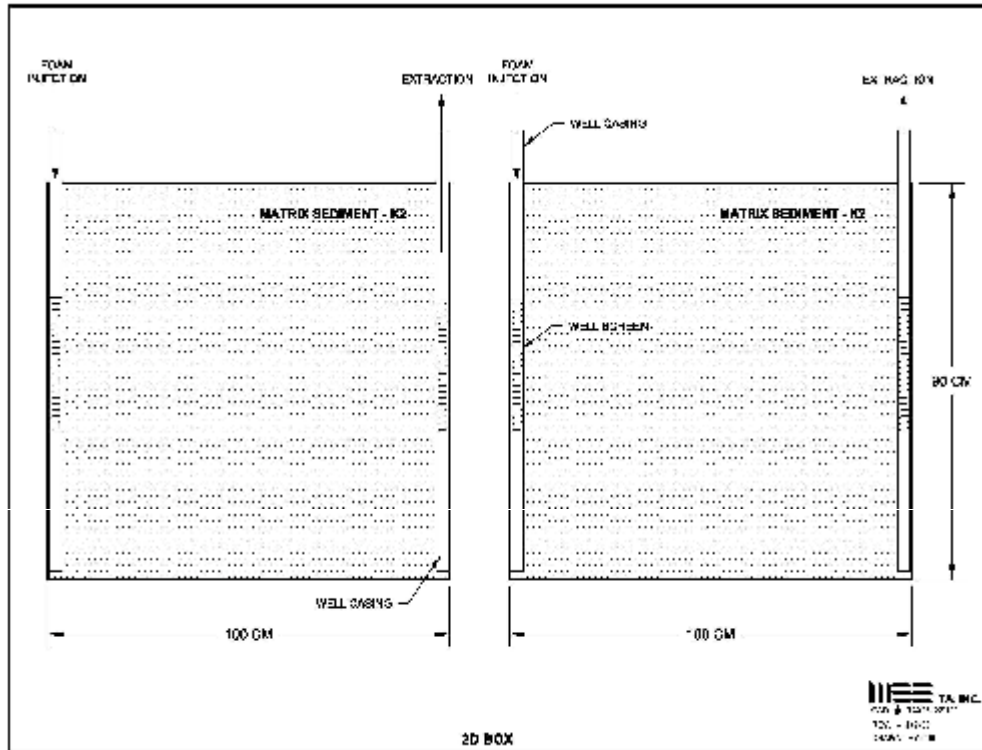
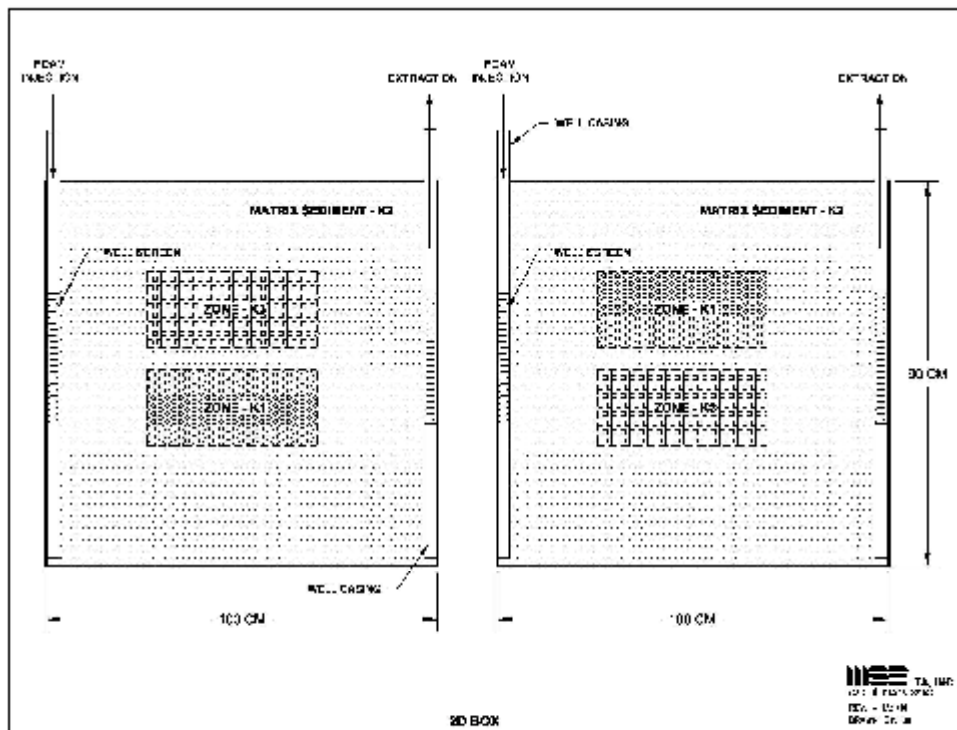Fig 1. Frontal view of a homogeneously loaded test bed.

Fig 2. Frontal view of a heterogeneously loaded test bed.

Fig 3. Porous plate foam generating apparatus.

Each test box also included five sample spigots and an instrument package consisting of nine pressure transducers and seven time-domain reflectometry (TDR) probes. These devices were incorporated into the back wall of each of the test boxes so they did not interfere with visual observations being made from the front of each box. The instruments were for determining the real-time pressure gradient and moisture distribution within each box during the testing sequences, and these were designed to communicate with a PC that was used as a data collection and retrieval system. The sample spigots were used to acquire samples of the foam as it traveled through the sediment. Fig. 4 shows the positions of these devices within the two test boxes loaded in a heterogeneous manner while Fig. 5 shows the instruments in the back of the test boxes.
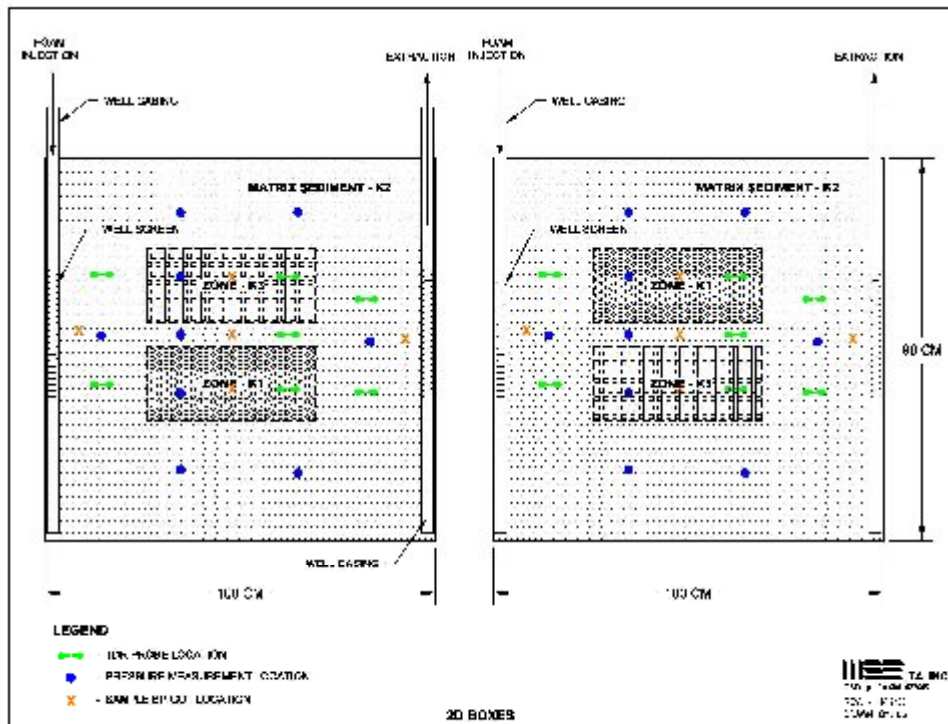
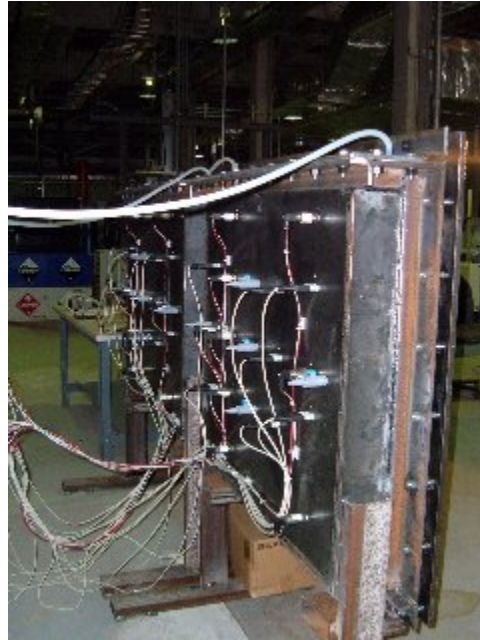Fig. 4. Instrument locations in a heterogeneously loaded test bed.

Fig. 5. Back of the test boxes showing the instrument locations.

Three sediments from the Hanford area were used for the tests. The first of these sediments (designated as K1) was quite coarse with particles ranging from 8 millimeters (mm) to less than 0.075 mm. The hydraulic conductivity of a packed sample of this sediment was 1.15 by 10^{-1} cm/second (s). The initial moisture concentration of the K1 sediment was approximately 3.5% by volume. The second sediment (designated K2) was also quite coarse with particles again ranging from 8 mm to less than 0.075 mm. The hydraulic conductivity of a packed sample of this sediment was 4.69 x 10^{-2} cm/s. The initial moisture concentration of the K2 sediment was approximately 5% by volume. The third sediment (designated K3) was coarse sand with particles ranging from 2 mm to less than 0.075 mm. The hydraulic conductivity of a packed sample of this sediment was 2.93 by 10^{-3} cm/s. The initial moisture concentration of the K3 sediment was approximately 9% by volume. The grain-size distribution of the three sediments is shown in Fig. 6.
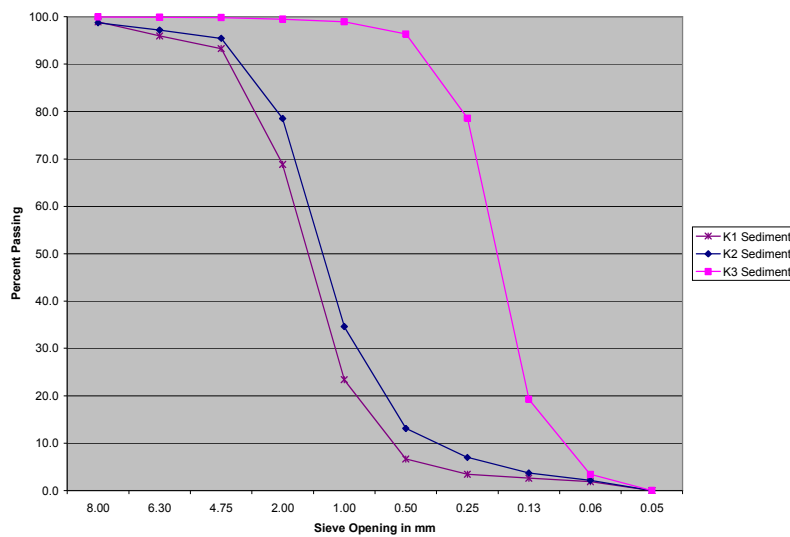

Fig. 6. Grain size distribution of test sediments.

Four sets of tests were conducted using both boxes for each test. Descriptions of those four test sets are listed below.

- Test 1: Both of the boxes were loaded in a homogeneous manner with only K2 sediment. Foam produced using a 0.5% solution of a biodegradable, anionic surfactant (CS-330) was injected into each of the boxes. The injection rate for the first box was 125 milliliters per minute (mL/min) while the injection rate for the second box was 250 mL/min. Air was extracted from each box at the same rate as foam was injected.

- Test 2: Both of the boxes were loaded so as to produce two rectangular heterogeneous zones (one zone with K1 sediment and one with K3 sediment) surrounded by K2 sediment. The first box had the zone with fine-grained K3 sediment nearer the top of the box while the second box had this zone nearer the bottom of the box. Foam produced using a 0.5% solution of CS-330 was injected into both boxes at a rate of 170 mL/min while air was extracted from both of the boxes at the same rate as foam injection.

- Test 3: Both boxes were again loaded in the same manner as was used in Test 2. Foam for the first box was produced using a solution with a concentration of 0.5% CS-330, and foam for the second box was produced using a solution with a concentration of 1.0% CS-330. Both of the foam production solutions contained a phosphate concentration of 25,000 milligrams per liter (mg/L) produced from a 9:1 mixture of sodium phosphate and sodium tripolyphosphate, respectively. Foam was injected into both boxes at a rate of 170 mL/min while air was extracted from both of the boxes at the same rate as foam injection.

- Test 4: Again, both sub-boxes were loaded in the same manner as was used in Test 2. However, uranium-rich calcite was added to the sediment in a specific location within each test box to produce a zone of uranium enrichment with a uranium concentration of approximately 300 mg/kg. Fig. 3 illustrates the location of these uranium-bearing zones. Foam for both boxes was produced using an aqueous solution with a concentration of 4% CS-330 and a 2% concentration of a nonionic surfactant known as NINOL 40-CO. The foam production solution for the first box contained a phosphate concentration of 2,500 mg/L produced from the aforementioned 9:1 mixture. The second foam production solution for the second box contained a phosphate concentration of 5,000 mg/L, again produced from the aforementioned 9:1 mixture. Foam was injected into both boxes at a rate of 175 mL/min while air was extracted from both boxes at the same rate.

The configuration of each of the boxes associated with each of the tests is shown in Table I. Each of the tests was run until liquid was extracted from the extraction zone of each box.

Table I. Testing Box Configuration.

Test	Sub-Box Orientation	Sediment Loading	Injection Extraction Rate (mL/min)	Treatment Reagent	Uranium-Bearing Zones
1	Left	Homogeneous	125	No	No
	Right	Homogeneous	250	No	No
2	Left	Heterogeneous	170	No	No
	Right	Heterogeneous	170	No	No
3	Left	Heterogeneous	170	Yes	No
	Right	Heterogeneous	170	Yes	No
4	Left	Heterogeneous	175	Yes	Yes
	Right	Heterogeneous	175	Yes	Yes

Subsequent to each of the four tests, the test boxes were disassembled, and samples of the sediments were collected from a grid-like pattern through each box. These samples were then analyzed for a number of parameters, depending on the specific test. The posttest analyzed parameters for each test are shown in Table II. In addition, a number of parameters including the foam quality and stability were tested via sampling throughout the duration of each test, and a number of operating parameters that included the injection pressure, the fluid and air injection rates, the extraction rate, and the internal pressure within each box were monitored throughout the duration of each test. Finally, the propagation of the foam wetting front was tracked through the sediment within the box during each test.

Table II. Posttest Measurements.

Test	Test Box Orientation	Sediment Moisture	Sediment Surfactant Concentration	Sediment Phosphate Concentration	Sediment Total Uranium Concentration	Sediment Leachable Uranium Concentration
1	Left	X				
	Right	X				
2	Left	X	X			
	Right	X	X			
3	Left	X	X	X		
	Right	X	X	X		
4	Left	X	X	X	X	X
	Right	X	X	X	X	X

TEST RESULTS
The initial concept of the four sets of injection tests was to progress from test to test while limiting the number of changes in the test parameters. However, the results of the first three tests illustrated that the foam developed from the single surfactant-based generating fluid was not of sufficient foam stability to propagate through the sediment in the test boxes. As such, a new foam generating fluid was developed by PNNL that was used in Test 4. Only the results of the first three tests will be reported here.

Test 1
As it was injected, the foam moved into the sedimentary masses and formed arcuate wetting fronts that expanded with time of injection to a point approximately 30 cm horizontally from the point of injection. Horizontal movement of the foam appeared to stop after this point. Throughout the test the movement of foam bubbles could be discerned within the sedimentary mass behind the arcuate wetting front. However, this movement and increased time of injection failed to enlarge the arcuate wetting front. The arcuate wetting front within the first box, which had an air injection rate of 125 mL/min, stopped moving horizontally after approximately 48 hours of injection while the front within the second box, which had an air injection rate of 250 mL/min, stopped moving horizontally after approximately 36 hours after the initiation of injection. Subsequent to the foam wetting front reaching the point of maximum horizontal movement, any movement of the foam wetting front in both boxes was difficult to discern but appeared to be generally downward toward the bottom of the box.

Liquid was extracted from the first test box after approximately 168 hours of injection into that box and 104 hours of injection into the second box. Table III contains information related to the operational conditions of Test 1.

Subsequent to the completion of Test 1, samples of the sediment from both of the test boxes were analyzed for contained moisture. Fig. 7 shows the results of these analyses.

Table III. Operational Conditions of Test 1.

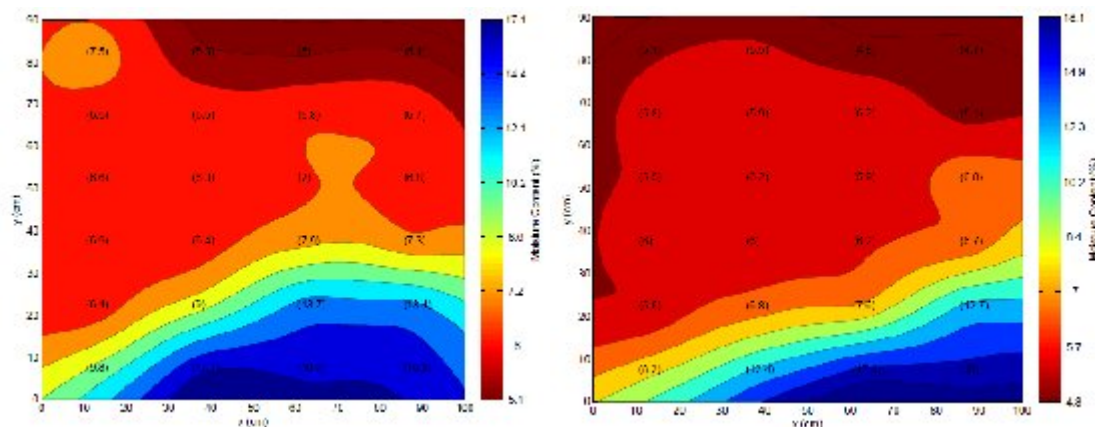| Test Box	Injection Pressure (psi)	Injected Foam Quality (%)	Injected Foam Stability (hr)	Injected Foam Bubble Size (mL)	Gas Flow Rate (mL/min)	Foam Solution Flow Rate (mL/min)	Gas Extraction Flow Rate (mL/min)
1	2.5	98	> 1	< 1	125	1.9	125
2	4.8	98	> 1	< 1	250	3.6	250

Fig. 7. Test 1 posttest gravimetric moisture percentages.

During Test 1, the pressure probes inserted into the back of both test boxes were operational. The data accumulated from those probes are shown in Fig. 8. A number of the early changes in pressure are due to operational changes being made to the test box while in operation. Both of the data plots denote several upset conditions during the initial portion of the test. The data captured during these times are not representative of the conditions of injection. However, once these upset conditions were overcome, the probes denoted a general increase in internal pressure in the boxes as the test proceeded with a greater increase in box 1 when compared to box 2. This increase has been observed by personnel of PNNL during other foam injection tests and has been attributed to the buildup of moisture within the sediments.
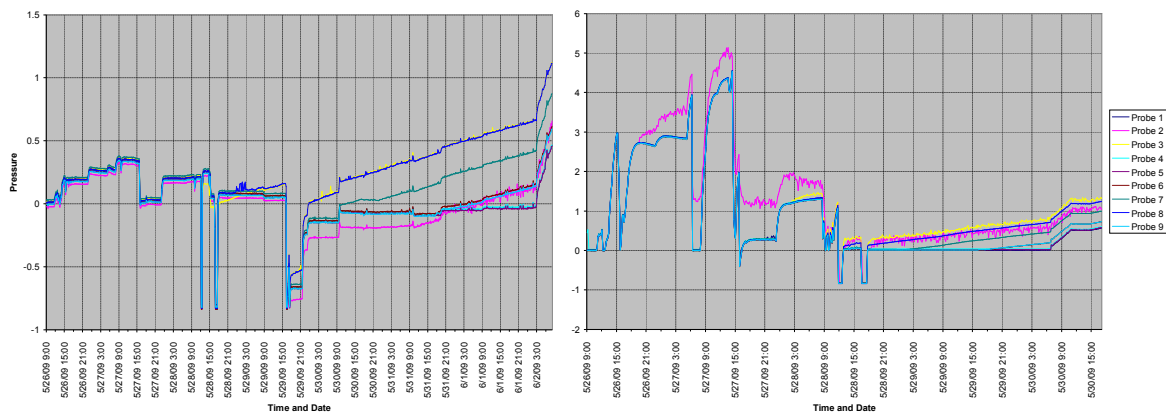

Fig. 8. Test 1 internal pressures.

The posttest moisture pattern within the sediments and observations made during the test revealed that subsequent to the foam reaching the point of maximum horizontal movement, a significant portion of the liquid from the foam injected into the box spread along the bottom of the box and subsequently moved upward into the sediment from that area. Other than the time required to reach the point of maximum horizontal movement, the difference in rate of injection for the two boxes did not produce distinguishable differences in the position of the foam wetting front.

The test boxes were designed for the foam wetting front to move across the width of each of the boxes and intercept the extraction section of the slotted PVC well casing from which foam or liquids would be extracted. The movement of the foam across the bottom section of the boxes did not allow the extraction system to remove foam or liquids from the box until the level of those materials rose within the box to the level of the slotted section of well casing. In addition, the section of the well casing below the slotted zone was hollow and allowed liquids to drain into the casing prior to removal. The design of the extraction systems for both boxes were changed prior to Test 2 in that the lower section of well casing was filled so to not allow any liquids or foam to drain into that portion of the system.

Test 2
Table IV contains information related to the operational conditions of Test 2.

Table IV. Operational Conditions for Test 2.

Test Box	Injection Pressure (psi)	Injected Foam Quality (%)	Injected Foam Stability (hr)	Injected Foam Bubble Size (mL)	Gas Flow Rate (mL/min)	Foam Solution Flow Rate (mL/min)	Gas Extraction Flow Rate (mL/min)
1	4.7	98	> 1	< 1	170	3	170
2	6.3	98	> 1	< 1	170	3	170

Liquid was extracted from the first test box after approximately 111 hours of injection into that box and after approximately 97 hours of injection into the second box. A portion of the difference in these values can be attributed to the foam injection to the second box being stopped during the test to correct a leak in that box.

The movement of foam in the sediments of the two boxes used for Test 2 was similar to that observed during Test 1. Again, the foam moved into the sedimentary masses and formed arcuate wetting fronts that expanded with time of injection to a point approximately 30 to 35 cm from the point of injection. Horizontal movement of the foam did not progress beyond that position in the test bed. The wetting front in both boxes stopped moving horizontally approximately 40 hours after the initiation of injection. Subsequent to that time, any movement of the foam wetting front in both boxes of Test 2 was difficult to discern but appeared to be generally downward toward the bottom of the box.

The movement of moisture through the sediments was influenced by the heterogeneous sedimentary zones. Throughout Test 2, the movement of foam bubbles could be easily observed within the coarse-grained sediments behind the arcuate wetting front. In addition, as the foam fronts contacted the fine-grained zones, the fine-grained sediment appeared to extract moisture into those zones by a process of wicking as no actual movement of the foam could be observed within the fine-grained zones. This collection of moisture by the fine-grained sediments is entirely within the accepted process by which moisture moves within vadose zone sediments.

Subsequent to the completion of Test 2, samples of the sediment from both of the test boxes were again analyzed for contained moisture. Fig. 9 shows the results of these analyses. These data (along with observations made during the test) revealed that the overall movement of foam through the sediment was similar to that observed during Test 1 (i.e., subsequent to the formation of an initial arcuate wetting front, a portion of the foam spread along the bottom of the box and moved upward into the sediment from that area). Unlike Test 1, the heterogeneous zones affected the posttest moisture data as the fine-grained sediments entrapped significant amounts of moisture
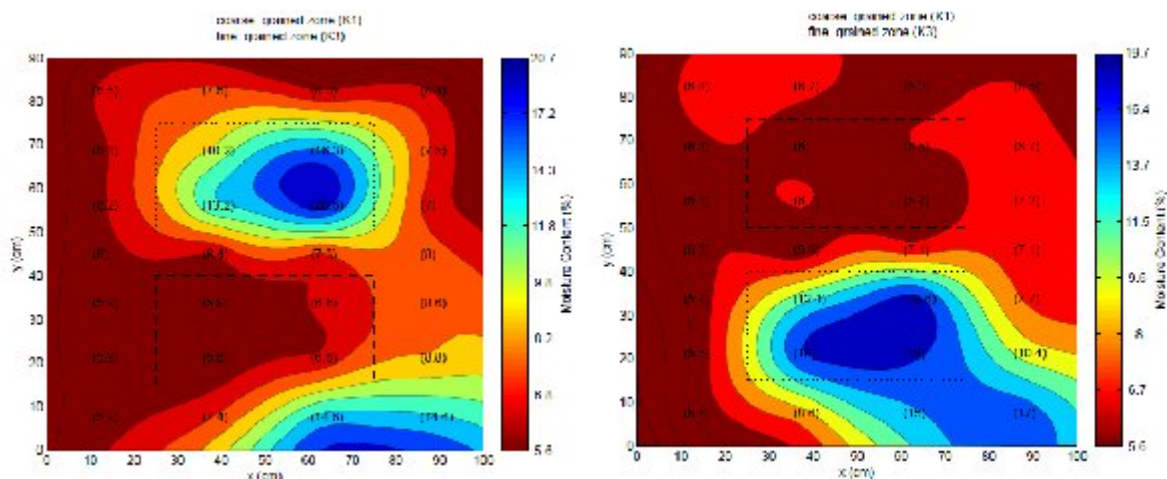

Fig. 9. Test 2 posttest moisture percentages.

Throughout the duration of Test 2, the color of the fine-grained heterogeneous zones varied. These zones initially had a homogenous, light tan color. As the test continued, those areas of the fine-grained zones nearest the flowing foam became darker in appearance, potentially due to the previously described wicking process. Later in the test, those portions of the fine-grained zones that initially darkened began to lighten, possibly as the contained moisture decreased. This drying of the fine-grained sediment may have been due to the movement of foam and gas used to form the foam through the test boxes.

Time-domain reflectometery data was collected from the probes associated with box 1 during the operation of Test 2. The results of that data collection are shown in Fig. 10. As can be seen from that figure, the TDR probes responded to changes in the volumetric water content of the surrounding sediments. Several of these changes in water content can be attributed to the arrival times of the foam wetting front at the positions of the probes. Previous studies of foam injection to vadose zone-like sediments have denoted a zone of increased moisture moving through the sediment in front of the actual foam front [5]. Probes 1 and 2 appear to have responded to such a zone of moisture by indicating a rapid increase and subsequent decrease in moisture after approximately 5 hours of injection. Probes 4 and 5 show increases in moisture content after approximately 25 to 26 hours of injection, which may be attributed to the arrival of the foam. However, these probes do not indicate a significant decrease in the moisture content after the foam arrival. Probe 3 was located in the fine-grained heterogeneous zone of box 1. The information collected by that probe denotes a slow increase in moisture content followed by a slow decrease in that measurement, both of which could be caused by the aforementioned wetting and drying sequence of the fine-grained sediments. Lastly, Probe 7 illustrates a rapid increase in the volumetric moisture content beginning after approximately 72 hours of injection that can be attributed to water accumulating near the bottom of the box.
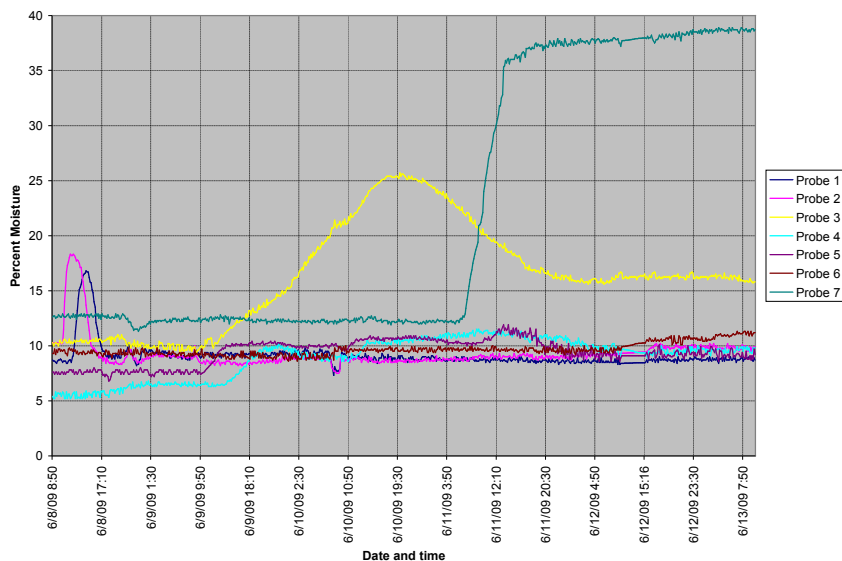
Fig. 10. Percent moisture by TDR in box 1 of Test 2.

During Test 2, the pressure probes inserted into the back of both test boxes were operational. The data accumulated from those probes is shown in Fig. 11. The rapid changes in pressure are again due to operational changes being made to the test box while in operation. Both of the data plots denote an increase in internal pressure in the boxes as the test proceeded. Probes 1, 4, and 9 are located near the horizontal centerline of both boxes, which is also in line with the injection and extraction zones of the boxes. These probes registered some of the lowest pressures within each of the boxes throughout the test duration. The higher pressure readings were denoted by the probes that were located peripherally to the horizontal centerline, with the probes located near the top of the box registering the highest readings. As such, the horizontal centerline should be the path of least resistance from pressure for the flow of the injected foam.
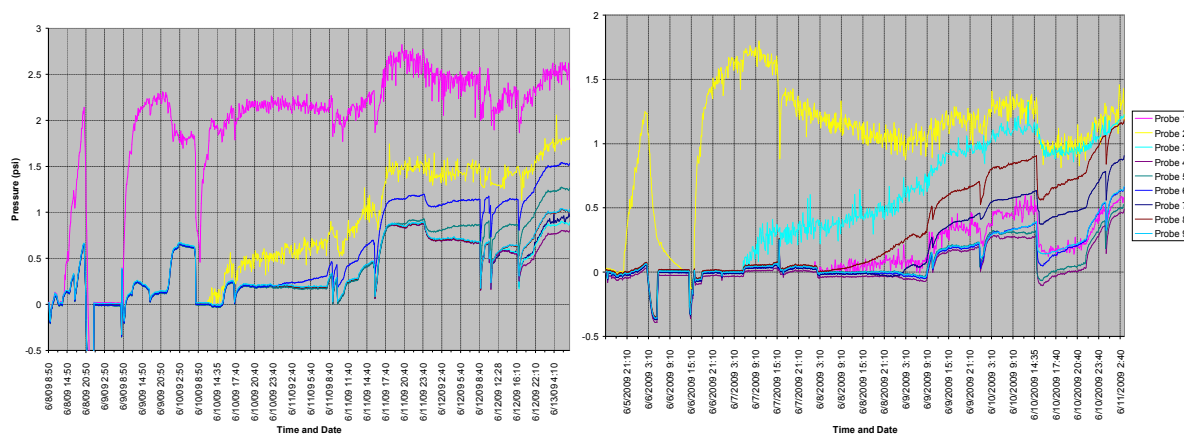

Fig. 11. Test 2 internal pressures.

After the completion of Test 2, the extraction systems of the boxes were again changed to include a suction tube placed within the curved section of PVC well casing so the open end of the suction tube was located adjacent to the slotted section of well casing. The extraction pump for each box pumped directly from this drop tube and thus removed any liquids very soon after they entered the extraction system.

Test 3

Table V contains information related to the operational conditions of Test 3.

Table V. Operational Conditions for Test 3.

Test Box	Injection Pressure (psi)	Injected Foam Quality (%)	Injected Foam Stability (min)	Injected Foam Bubble Size (mL)	Gas Flow Rate (mL/min)	Foam Solution Flow Rate (mL/min)	Gas Extraction Flow Rate (mL/min)
1	4.7	98	~ 30	< 1	170	3	170
2	6.3	98	~ 45	< 1	170	3	170

Liquid was extracted from the first test box after approximately 85 hours of injection into that box and 95 hours of injection into the second box. These values are less than the times required for the extraction of liquid from the test boxes associated with Test 2.

Observations made during Test 3 showed that (in general) the movement of foam through the test boxes was similar to that observed during Test 2. The foam moved into the sediments contained in the two boxes and formed arcuate wetting fronts that expanded with time of injection to a point approximately 25 to 30 cm from the point of injection. This point was reached approximately 35 hours after the initiation of injection. At that time, horizontal movement of the foam appeared to stop, and all the discernable movement of the front in both boxes was downward toward the bottom of the box from where the foam then spread toward the extraction end of each box. The downward movement of the foam during Test 3 was more evident than during Test 2.

As in the previous tests, the movement of foam bubbles in Test 3 could be observed within the coarse-grained, sedimentary materials behind the arcuate wetting front; however, again no foam movement could be observed within the fine-grained sediments. However, the foam movement was not as discernable as during Test 2. Tests of foam samples being injected during Test 3 revealed that the stability of the foam was significantly diminished from that of Test 2 (Table V). The lack of stability of the foam is believed to be the reason for the difficulty in observing the bubble movement during the Test 3. The lack of stability of the foams injected during Test 3 was probably due to the addition of the phosphate treatment reagents to the fluid used to generate the foams in Test 3.

The shapes of the wetting fronts and the posttest moisture data from Test 3 were again influenced by the heterogeneous sedimentary zones in much the same manner as was observed in Test 2. Moisture again wicked into the fine-grained zones and appeared to darken the color of those sediments as the fine-grained nature of those sediments entrapped significant amounts of moisture. Over time, this phenomenon decreased with the fine-grained sedimentary zones becoming lighter in color and potentially containing less moisture. The color changes in the fine-grained zone were more distinct in the second box than in the first box. The fine-grained zone of the first box was near the top of the test box while the fine-grained zone in the second box was near the bottom of the test box. As was expected, no wicking of moisture was observed within the coarse-grained zones. Moisture changes in the coarser grained zones appear to have been caused by direct contact with moving foam.

Subsequent to the completion of the third set of injection tests, samples of the sediment from the boxes were analyzed for contained moisture. The results of these analyses are shown in Fig. 12 for the first and second boxes of Test 3, respectively.
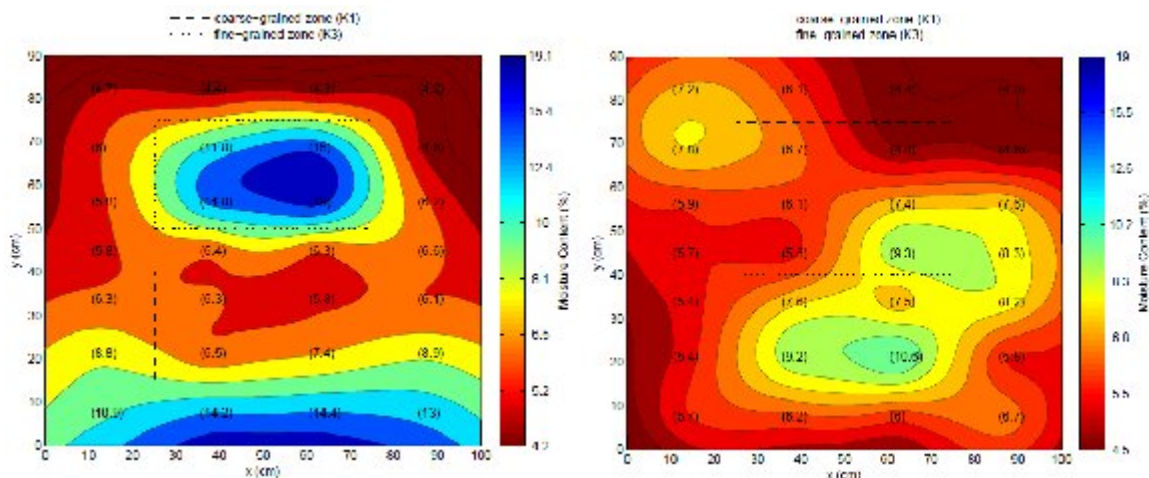
Fig. 12. Test 3 posttest moisture concentrations.

Time-domain reflectometery data was collected from the probes associated with both test boxes during Test 3. The results of that data collection are shown in Fig. 13 for test boxes 1 and 2, respectively. Probe 3 was located in the fine-grained heterogeneous zone of the first box, and probe 5 was located in the fine-grained zone of the second box. The information collected by probe 5 in the second box denotes the aforementioned wetting and drying sequence of the fine-grained sediments while the wet-dry phenomenon is not easily distinguished by the data collected by probe 3 of the first test box.
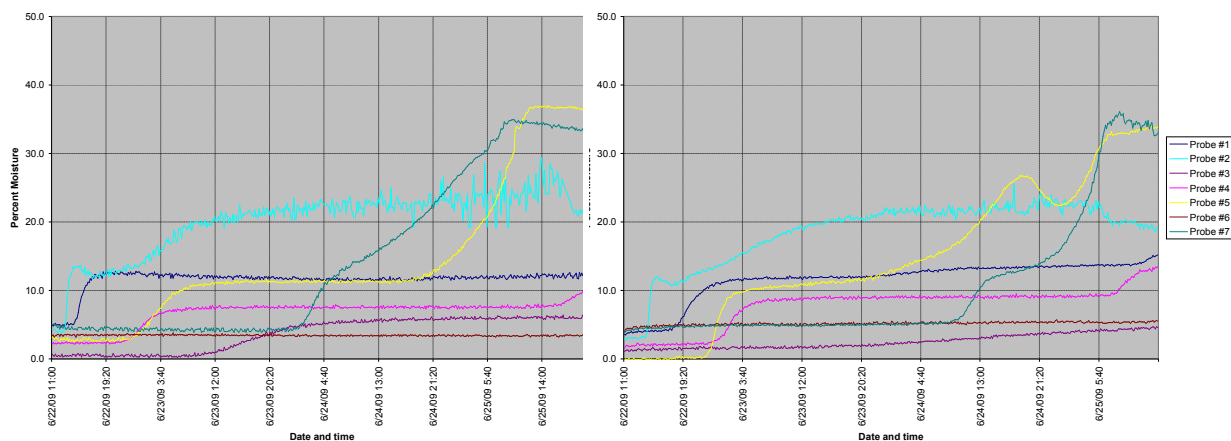

Fig. 13. Percent moisture by TDR in box 2 of Test 3.

The plots of the TDR data from both boxes show a number of rapid increases in moisture. These moisture changes are associated with the arrival of the foam and/or the wetting front at the locations of the specific TDR probes. See (for example) the moisture increases shown by probes 1 and 2 of box 1 within the first 5 hours of foam injection. In addition to the first arrival data, probes 5 and 7 within both test boxes exhibit large increases in moisture at these probe locations after approximately 36 hours of foam injection. These increases are produced by water accumulating near the bottom of the test boxes.

The surfactant concentration in the fluid emerging from the test boxes for Test 3 was depleted relative to the concentrations in the influent foam much as was the case for Test 2. This indicated that some of the surfactants had adsorbed onto the sediments. As such, sediment samples were analyzed to determine the adsorbed surfactant concentrations; that data is shown in Fig. 14 for test boxes 1 and 2, respectively.
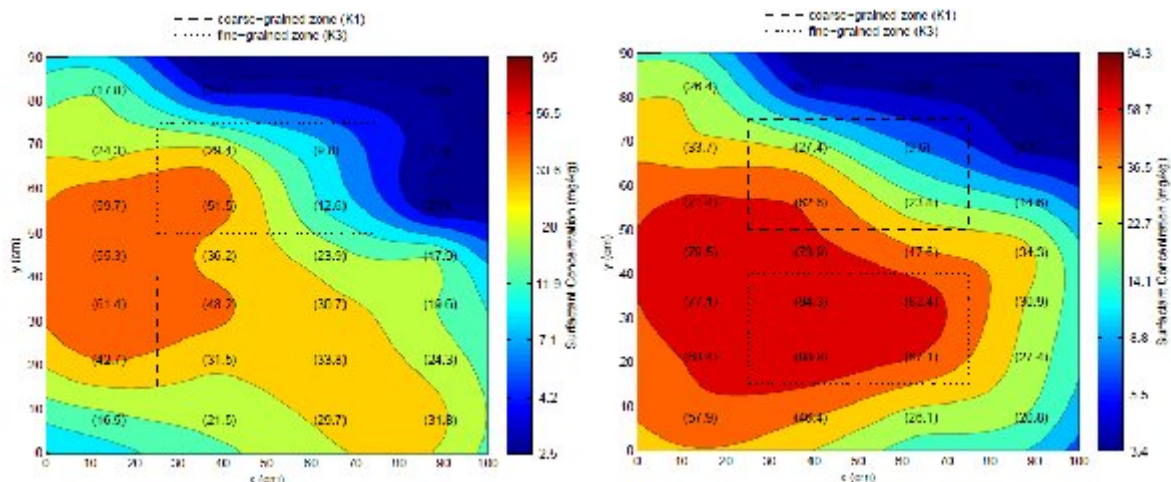
Fig. 14. Test 3 posttest surfactant concentrations.

The analytical method involved leaching the sediment samples with deionized water and subsequently analyzing the surfactant concentration within the leachate fluid. The surfactant concentration data indicate that higher concentrations of the surfactants in the first test box were generally associated with the materials near the injection zone with a finger-like projection extending from the injection zone toward the lower right-hand corner of the box. Within the second test box, the surfactant was largely contained within the fine-grained zone, which was also located near the bottom of the box, and adsorbed onto those sediments near the injection zone. In both test boxes, the adsorbed surfactant concentration generally followed the flow paths of the injected foam/moisture but was adsorbed fairly rapidly as the concentrations of surfactant fall off steeply away from the zones of injection and the lower, fine-grained zone.

The solution used to produce the foam for the third set of tests contained 25,000 parts per million (ppm) of phosphate as a 9:1 mixture of tribasic sodium phosphate and sodium tripolyphosphate, respectively. To determine the adsorbed concentrations of phosphate associated with the sediments within the test boxes, samples of the sediments were collected and analyzed for available phosphate. The analytical method involved extracting the phosphate from the sediments with a dilute acidic solution and analyzing the solution for phosphate using conventional analytical methods. The concentration of available phosphate associated with each of the sediment types used to fill the boxes was determined prior to the sediment coming in contact with the foam producing solution. The results of those analyses are:

  – K1 – available PO4 = 4.9 ppm;
  – K2 – available PO4 = 4.8 ppm; and
  – K3 – available PO4 = 6.3 ppm.

The results of the available phosphate analyses for the sediments collected from the test boxes of Test 3 are shown in Fig. 15 for test boxes 1 and 2, respectively.

During Test 3, the pressure probes inserted into the back of both test boxes were operational. The data accumulated from those probes are shown in Fig. 16 for test boxes 1 and 2, respectively. The rapid changes in pressure are again due to operational changes being made to the test box while in operation. In general, both of the data plots denote an increase in internal pressure in the boxes as the test proceeded. The data from all the probes associated with the first test box show very similar trends with probe 3 denoting the highest internal pressure of all the probes in the box. The data accumulated from test box 2 did not exhibit a reduction in pressure near the end of the test.
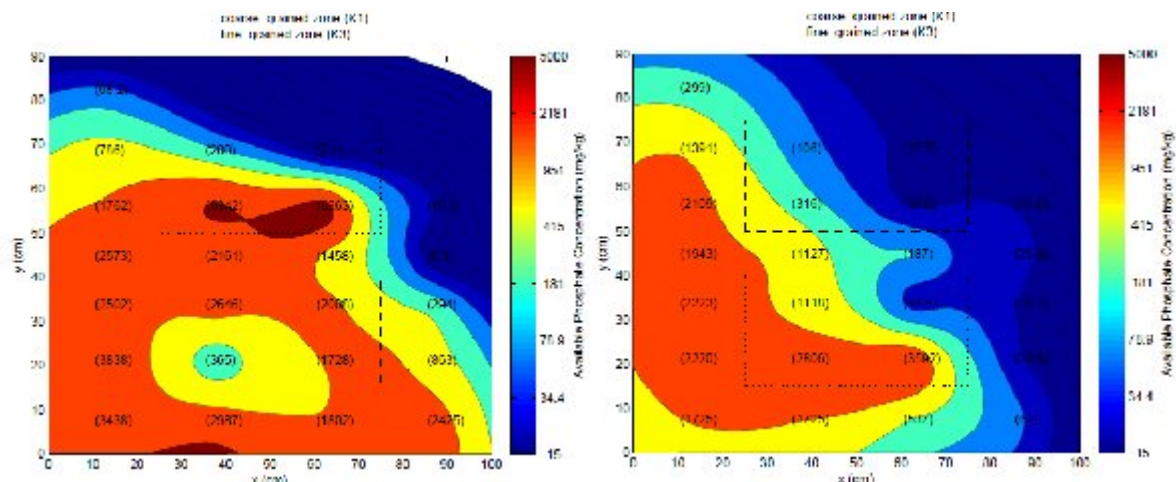
14

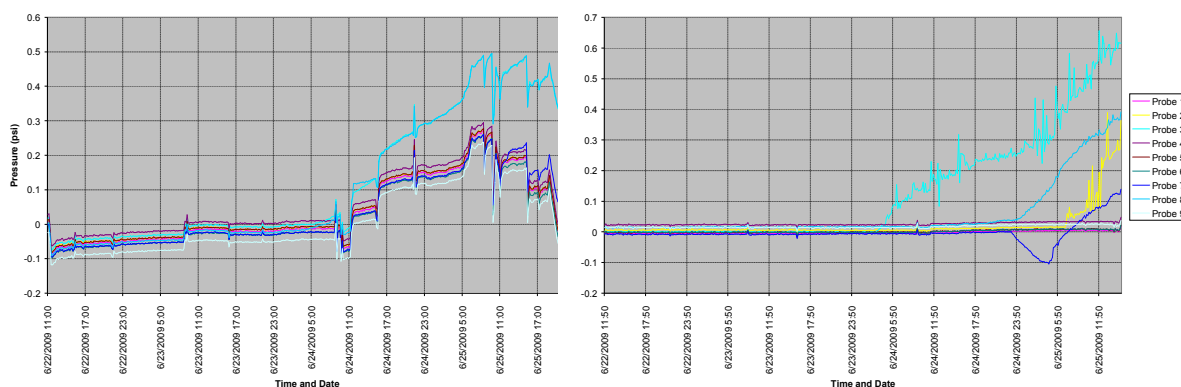Fig. 15. Test 3 posttest available phosphate concentrations.

Fig. 16. Test 3 internal pressures.

After the completion of Test 3, the extraction systems of the boxes were again changed. These changes included an increase in the screened section to include the lower 60 cm of the system and three suction drop tubes placed at approximately 30, 60, and 90 cm from the top of each box. The extraction pumps for each box pumped directly from these drop tubes and thus removed any liquids as they entered the extraction system.

CONCLUSIONS
The movement of foam through the sediments was quite similar for all three of the first three injection tests. In each of those tests, the foam wetting front produced an arcuate form that moved into the sediment for only a relatively short distance. Subsequent foam movements were largely downward toward the bottom of the boxes. The addition of phosphate treatment reagent to the foam in Test 3 exacerbated the downward movement.

Foam stability values as well as values of other parameters determined from samples of the injected foam acquired during the first three tests of the injection series showed relatively low denominations, with the values from Test 3 lower than the first two tests.

In addition, data generated from the sediments analyzed subsequent to the injections enhanced the perception that the bubbles of the foam broke down rapidly as the foam passed through the sediment thus releasing the surfactant solution to the sediment. The released solution increased the moisture content of

the sediment and of the foam mass passing through the sediment, which allowed gravity to increase the downward movement of the foam. As such, the foam generating fluid used during Tests 1, 2, and 3 did not produce foam with sufficient stability to propagate farther than approximately 30 cm in a horizontal direction through a vadose zone-like sedimentary mass. The addition of the phosphate-based reagent to the foam generating fluid for Test 3 decreased the foam stability from that seen in the first two tests. The addition of the phosphate reagent used during Test 3 probably played a part in decreasing the foam stability throughout that test. As such, the foam generating fluid formula used in Test 3 did not produce foam of sufficient stability to carry a viable quantity of phosphate reagent through a sizable mass of sediment.

RECOMMENDATIONS

It is recommended that new foam generating fluid formulas and foam generating methods and systems be developed that increase the stability of the produced foam. These new foam generating formulas should then be subjected to further studies and tests, both at bench and intermediate scale. These studies should focus on enhancing foam stability and increasing the ability of the foam to carry treatment reagents for greater distances within a vadose zone sedimentary mass. Additionally, the effect of the foam stability on the reactability of the treatment reagent needs to be investigated. Also, the length of time that additional intermediate-scale tests are conducted needs to be lengthened to determine the effects on the adherence of the surfactant components of the foam generating fluids.

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