PNNL-12001

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Low-Pressure, Single-Point Grout Injection for Tank Heel Sludge Mixing and In Situ Immobilization

Greg A. Whyatt
Chuck R. Hymas

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Prepared for the U.S. Department of Energy
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SUMMARY

This report describes tests conducted in an approximately 9-ft (2.7 m) diameter test tank situated outside the 336 building in Hanford's 300 area. The tests were performed to measure the ability of jets of grout slurry to mobilize and mix simulated tank sludge. The technique is intended for in situ immobilization of tank waste heels.

In situ grouting is one potential method for final closure of waste storage tanks. At the Savannah River Site, Tanks 17 and 20 are being closed by simply adding the grout to the tank without any jetting action. While this approach may be sufficient for some applications, it is preferable to mobilize the sludge and mix it with the grout to provide the best immobilization of the residual waste. It has been proposed that an in situ grouting technique be used to immobilize waste in Tank TH-4 at the Oak Ridge National Laboratory (ORNL). To support TH-4 closure, a demonstration of Multi-Point Injection (MPI), a proprietary technology of Ground Environmental Services was conducted in a 15-ft (4.6 m) diameter tank under the direction of ORNL. The demonstration successfully mixed and grouted a layer of sand placed on the bottom of the tank. The tests described in this report were conducted to examine an alternate in situ grouting approach.

The experimental approach described in this report differs from the MPI approach in several ways. MPI uses multiple injection points with numerous small-diameter fixed nozzles that are driven at very high pressure. In contrast, the current approach uses a single, rotated, larger-diameter nozzle driven at lower pressure. Due to the larger diameter, the potential for plugging is reduced and the effective radius around an injection point over which the jet is effective in mobilizing sludge from the tank bottom can be made larger. The greater effective range from the injection point eliminates the need for a large number of injection points and corresponding tank dome penetrations. Because the technique is implemented using lower pressure, the jets do not have the cutting capability of the high pressure jets. Also, the lower pressure allows less expensive and more readily available pumping equipment to be used.

A total of three grout injection tests were conducted in a 9-ft (2.7 m) diameter tank. In each case, a 2-in. (5.0 cm) layer of kaolin clay paste was placed on a dry tank floor to simulate a sludge heel. The clay was covered with 4 inches (10.2 cm) of water. The grout slurry, consisting of Portland cement, class F fly ash, and water, was prepared and delivered by an offsite vendor. In the third test, the sludge in half of the tank was replaced by a layer of 20x50 mesh zeolite, and bentonite clay was added to the grout formulation. A concrete pumping truck provided by an offsite vendor pumped the grout through the nozzle. The nozzle sizes and injection parameters for each test are shown in Table S.1.

After injection, the grout was allowed to set and then the entire grout monolith was manually broken up and excavated using a jack hammer. Intact pieces of clay were visually apparent due to a sharp color contrast between the grout and clay. Remaining clay deposits were collected and weighed and suspended clay pieces within the monolith were photographed.

The mobilization performance of the grout jets exceeded expectations. The jet flow rates were selected based on past experience with sludge mobilization with

Table S.1. Nozzle Sizes and Injection Parameters

	Test #1	Test #2	Test #3
Nozzle Size (inside diameter, inches)	0.875	0.5	0.875
Average Flow (gpm)[a][b]	138	65	122
Average Discharge Pressure (plateau pressure, psi)[c]	146	307[d]	117
Duration of Injection (minutes)	5.0	10.0	5.9

(a) The pump used in testing produces a maximum pressure and flow toward the end of each piston stroke and a minimum between piston strokes.
(b) The average flow is determined based on tank dimensions, the change in level, and the duration of grout injection. Due to the pulsing nature of the flow, the minimum and maximum flows vary around the average flow value.
(c) The average discharge pressure is taken as an average of the pressure plateaus and thus represents an average maximum injection pressure.
(d) Excludes some low pressure readings during the ramp up in pressure during the first minute of injection.

the intent of leaving a small undisturbed sludge deposit at some range from the nozzle. However, in all tests, sludge mobilization occurred to the far wall. In the first test, a few very thin floor deposits remained but the mass in these deposits accounted for only 0.075% of the mass of clay initially added to the tank. The second test had even fewer deposits. The third test, despite a reduction in the flow rate of the jet compared to Test #1 had no floor deposits at all. The zeolite added in Test #3 was mobilized and mixed throughout the grout monolith. Mobilization predictions were made based on past research on the ability of supernate jets to mobilize and mix sludge for retrieval from Hanford double-shell tanks. The enhanced performance of the grout jets is believed to be due to several factors including the higher density of the grout relative to supernatant[a], the fact that the grout is initially more dense than the fluid it is jetted into[b], the pulsing nature of the output from the concrete pump[c], and in Test #3, the erosive effect of the larger particulate (zeolite) being suspended in the slurry.

The test results indicate the larger-diameter rotated nozzle approach is very promising. Extrapolation of the current results to placement of a single rotated nozzle at the center of an 18-ft (5.5 m) diameter tank (the size of TH-4) is believed to be straightforward. In addition, the current system should be scaleable to allow waste heels in larger tanks such as the 50-ft (15 m) diameter GAAT tanks or the 75-ft (23 m) double-shell and single-shell tanks at Hanford to be treated using a single injection point. Additional testing at larger scale is needed to confirm this prediction. Prior to actual application, the waste properties must be known or at least bounded to allow confidence in prediction.

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[a] The higher density has the effect of increasing the force exerted by the jet on the sludge.
[b] The higher density of the grout jet relative to surrounding fluid reduces the rate of velocity decay of the jet.
[c] While average flow rate was used in predicting performance, the pressure readings indicate that the maximum flow may exceed the average flow rate by approximately 50%. This higher flow would have a longer mobilization range than the average flow rate.

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1.0 Introduction

This report describes tests conducted in an approximately 9-ft (2.7 m) diameter tank situated outside the 336 building in Hanford's 300 area. The tests were performed to measure the ability of jets of grout slurry to mobilize and mix simulated tank sludge.

In situ grouting is one potential method for final closure of waste storage tanks. At the Savannah River Site, Tanks 17 and 20 are being closed by simply adding the grout to the tank without any jetting action. While this approach may be sufficient for some applications, it is preferable to mobilize the sludge and mix it with the grout to provide the best immobilization of the residual waste. At the Oak Ridge National Laboratory (ORNL) in Tennessee, it has been proposed to use a jet grouting approach to immobilize waste in one of the gunite and associated tanks (GAATs), Tank TH4. As part of this effort, a test of Multi-Point Injection, a proprietary technology of Ground Environmental Services was conducted in Duncan, Oklahoma, in a 15-ft (4.6 m) diameter tank with sand in the bottom. The test involved the use of high-pressure pumping equipment used in oil well fracturing to pump grout at nominal pressures of 5000 psi[(a)] (34.5 MPa) through alternating sets of thirty-two, 0.0945-in. (0.24 cm) diameter nozzles. While this approach successfully mixed the sand with the grout, the test required 8 injection points[(b)], experienced plugging of 50% of the nozzles[(c)], and required relatively expensive pumping capability.

Previous correlations developed for sludge mobilization with supernatant jets predict that the distance over which a jet maintains effectiveness in mobilizing sludge can be increased using a single, larger diameter, rotating nozzle operated at much lower pressure. Benefits of the operation at lower pressure with larger nozzles are expected to include less nozzle plugging, the ability to use more readily available and less expensive pumping capacity, and fewer injection points being required to treat a tank.

The testing described here used non-hazardous mixtures of clay and water to simulate tank sludge and a grout slurry composed of Portland cement, class F fly ash, and water. In one test, the sludge in half of the tank was replaced by a layer of 20x50 mesh zeolite, and some bentonite clay was added to the grout formulation. In each case, the grout slurry was prepared offsite and then delivered and pumped into the test system by offsite vendors.

This work was funded by the EM-50 Tank Focus Area through the PNNL Retrieval Process Development and Enhancements Project.

[(a)]Actual measured pressure and flow data were declared proprietary by GES. GES indicated target values of 350 to 400 gpm through thirty-two, 0.24 cm nozzles at a pressure of 6000 psi. The velocity head of the initial jet is calculated at 3847 psi (slurry density =1.74 g/cm^3) for 400 gpm. However, half of the nozzles plugged during the test which may have increased the velocity head on the unplugged nozzles to 11,800 psi for 350 gpm if plugging was complete. In the absence of actual test data, a nominal 5000 psi will be used here for purposes of discussion.

[(b)]For tank TH-4, the addition of 8 injection points was considered an acceptable approach.

[(c)]It is expected that the plugging rate could be reduced to 10% or less by addition of a special filter but the appropriate filter could not be obtained for the test.

2.0 Background

In situ jet grouting is one proposed method for in situ immobilization of a tank heel. Jet grouting would involve inserting one or more vertical pipes into the tank to supply pressurized grout to horizontal nozzles located near the tank bottom. The jets of grout impact on the sludge waste heel in the tank and mix the grout with the sludge. Once all the waste is mixed with the grout, the grout flow is turned off and the mixture is allowed to solidify. This is followed by final tank closure, which may involve filling the remainder of the tank with concrete or other fill material.

Resuspension of the waste heel using submerged jets of grout slurry is analogous to the mobilization of double-shell tank sludge at Hanford using jet mixer pumps. Mobilization of sludge by mixer pumps has been studied at PNNL and other DOE sites (see Powell et al. 1997). This previous work has been used to guide the planning of the jet grouting tests described herein. However, there are aspects of jet grouting that may limit the applicability of the mixer pump work. These aspects include the high density and non-Newtonian rheology of the grout slurry and the shorter duration of the grout injection. In addition, the jet grouting is performed at higher discharge pressures than have been used in the mixer pump tests, which are typically conducted at less than 50 psi. The theory that guides sludge mobilization by mixer pumps and a consideration of the differences between jet grouting and mixer pumps is given in the next section.

A test of Multi-Point Injection, a proprietary technology of Ground Environmental Services was conducted in Ducan, Oklahoma, in a 15-ft diameter tank with sand in the bottom. The test involved the use of high-pressure pumping equipment used in oil well fracturing to pump grout at nominal pressures of 5000 psi through a large number (2 sets of 32) of 0.0945-in (0.24 cm) nozzles. The current experimental approach differs from the MPI approach in several ways including:

1) The current approach uses much lower pressure (<350 psi compared to approximately 5000 psi).
2) MPI uses numerous fixed nozzles[a] while the current approach uses a single rotating nozzle.
3) The pumps required to implement the MPI approach, designed for use in oil well fracturing, are more expensive and less common than the pumps used in this work which are normally used for concrete pumping and are readily available for rental.
4) The nozzles at 0.5-in and 0.875-in diameters are much larger and less prone to plugging than the 0.0945-in (0.24 cm) diameter nozzles used in the MPI approach.
5) The greater effective range of the larger diameter nozzle in mobilizing sludge reduces the number of injection points needed to mobilize sludge from a given area of tank floor.
6) At close range, the very high velocities at the nozzle exit in the MPI approach have cutting capability which must be considered in implementation to prevent cutting of the tank walls by jets positioned near the tank wall.

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[a] In the Duncan Oklahoma demonstration the injectors were manually rotated a few degrees with the pumps shut down to ensure complete coverage. During injection, the nozzles do not move.

2.1 Theory and Data from Tank Sludge Mobilization Testing

Many tank sludges in radioactive waste storage tanks were formed when solids precipitated during the rapid neutralization of an acidic solution with excess sodium hydroxide to form a high-pH slurry. When this slurry is transferred to a storage tank, the solids settle and consolidate over time forming a cohesive sludge. In double-shell tanks at Hanford, it is planned to use mixer pumps to mobilize and mix the sludge to allow retrieval of the sludge from the tanks. The mixer pumps consist of an oscillating submerged pump with nozzles that produce turbulent jets of tank fluid to mobilize and mix the tank sludge. As a result, previous work has been conducted investigating the ability of low density, low pressure (< 100 psi) jets to mobilize sludge for retrieval from double-shell tanks at Hanford (Fow et al. 1987; Fow et al. 1988; Whyatt et al. 1988; Powell et al. 1990; Powell 1991[a]). The work performed in this area produced correlations based in part on the velocity decay along the centerline of a rounded turbulent free jet for which the form of the equation is

$$U_x = K\,U_o D/x$$

Where U_x = maximum velocity of jet, at a distance x from the nozzle
U_o = velocity at the nozzle exit
D = diameter of the nozzle
x = distance from the nozzle
K = constant

At some distance from a jet mobilizing sludge, the velocity will decay to the point where the sludge can resist the erosive force of the jet. The ability of a purely cohesive sludge to resist mobilization can be related to the sludge shear strength. The tensile strength is believed to be a better measure of the cohesive nature of a sludge because frictional forces can increase the shear strength without increasing the resistance to mobilization by a jet. However, shear strength is used because it is less difficult to measure than tensile strength. The equation for velocity decay in the jet is adapted into an empirical equation for the distance over which the jet is effective in mobilizing sludge.

$$ECR = K\,U_o D\ ^{-n}$$

Where

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[a] Fow, C. L., P. A. Scott, G. A. Whyatt, and C. M. Ruecker. 1987. Pilot-Scale Retrieval Tests Using Simulated NCAW. 7W21-87-15. Pacific Northwest Laboratory, Richland WA. Technical report for Westinghouse Hanford Company.

Fow, C. L., G. A. Whyatt,T. D. Powell. 1988. Evaluation of a Triangular Arrangement of Mixing Pumps for Waste Retrieval from Double-Shell Tanks. 7W21-88-1. Pacific Northwest Laboratory, Richland WA. Technical report for Westinghouse Hanford Company.

Whyatt, G. A., C. L. Fow, T. D. Powell, P.A. Scott. 1988. FY1988 Bench-Scale Sludge Mobilization Testing. 7W21-88-05. Pacific Northwest Laboratory, Richland WA. Technical report for Westinghouse Hanford Company.

Powell M. R., Fow, C. L., G. A. Whyatt, P. A. Scott and C. M. Ruecker, 1990. Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization. Pacific Northwest Laboratory, Richland WA. Technical report for Westinghouse Hanford Company.

Powell, M. R., February 1991. The Current Status of DST Sludge Mobilization Research. PNL Technical report for Westinghouse Hanford Company.

ECR = "effective cleaning radius" the distance over which the jet mobilizes sludge
= shear strength
K, n = empirical constants used to fit data
U_0 = velocity at nozzle exit
D = diameter at nozzle exit

Figure 2.1 shows a summary of data collected while testing sludge mobilzation in a 3-ft diameter tank using a variety of different sludge simulants. The ECR/U_0D ratio for kaolin can be seen in the plot to be slightly less dependent on shear strength than the bulk of the other data. This is believed to be because the kaolin clay gains some shear strength through frictional interactions at higher strength. This makes the mobilization performance of the kaolin clay less dependent on the exact value of the shear strength. It also implies that the kaolin clay may be easier to mobilize than a purely cohesive sludge simulant, such as bentonite, with the same shear strength. The scatter in the data and the potential nature of the sludge needs to be considered when applying the correlations.

Figure 2.2 shows the data collected in the 3-ft diameter tank without the kaolin/water data included. Three potential correlations are provided on the plot, the first is a best fit to the data from cohesive sludges, the second is a conservative line drawn as a floor under the data to ensure conservative predictions, and the third is the regressed line from data collected in a 6-ft diameter tank (which is 1/12 scale relative to a million-gallon double-shell tank at Hanford) using a sludge consisting of silica flour mixed with a concentrated soda ash solution. The shear strength of this sludge simulant was approximately 10 $kdyne/cm^2$. Because the data were collected in a narrow range around a single shear strength, there is more uncertainty in the dependence of ECR/U_0D on shear strength for these data.

Figure 2.3 provides the data specific to the sludge used in these grouting tests which consisted of kaolin clay and water. The nominal shear strength of the clay used was 15 $kdyne/cm^2$. This figure indicates that for a kaolin clay shear strength of 15 $kdyne/cm^2$ a value of ECR/U_0D of approximately 0.055 s/cm is obtained.

The scatter in Figures 2.1 through 2.3 provide some indication of the variabiliy in potential results that may be obtained with variation in sludge properties and with random variations between tests. In addition to this scatter, when predicting grout mobilization performance, there are several factors which introduce uncertainty into predictions. First, the grout slurry is somewhat more dense than the mobilizing fluid used in mixer pump experiments. The higher density is beneficial in terms of the forces exerted on the sludge and early in the process, on the rate of velocity decay for the jet[(a)]. The higher density is clearly a beneficial effect.

Second, in the mixer pump experiments, the test was typically run for a longer period of time, allowing low erosion rates to affect the ECR, while in the grout experiment the injection time is shorter. The shorter time available to mobilize in the

[(a)] Early in the injection the grout jet is more dense than the supernatant over the sludge and, as a result, the velocity decay prior to reaching the sludge is less than if the grout were jetted into a fluid of equal density.

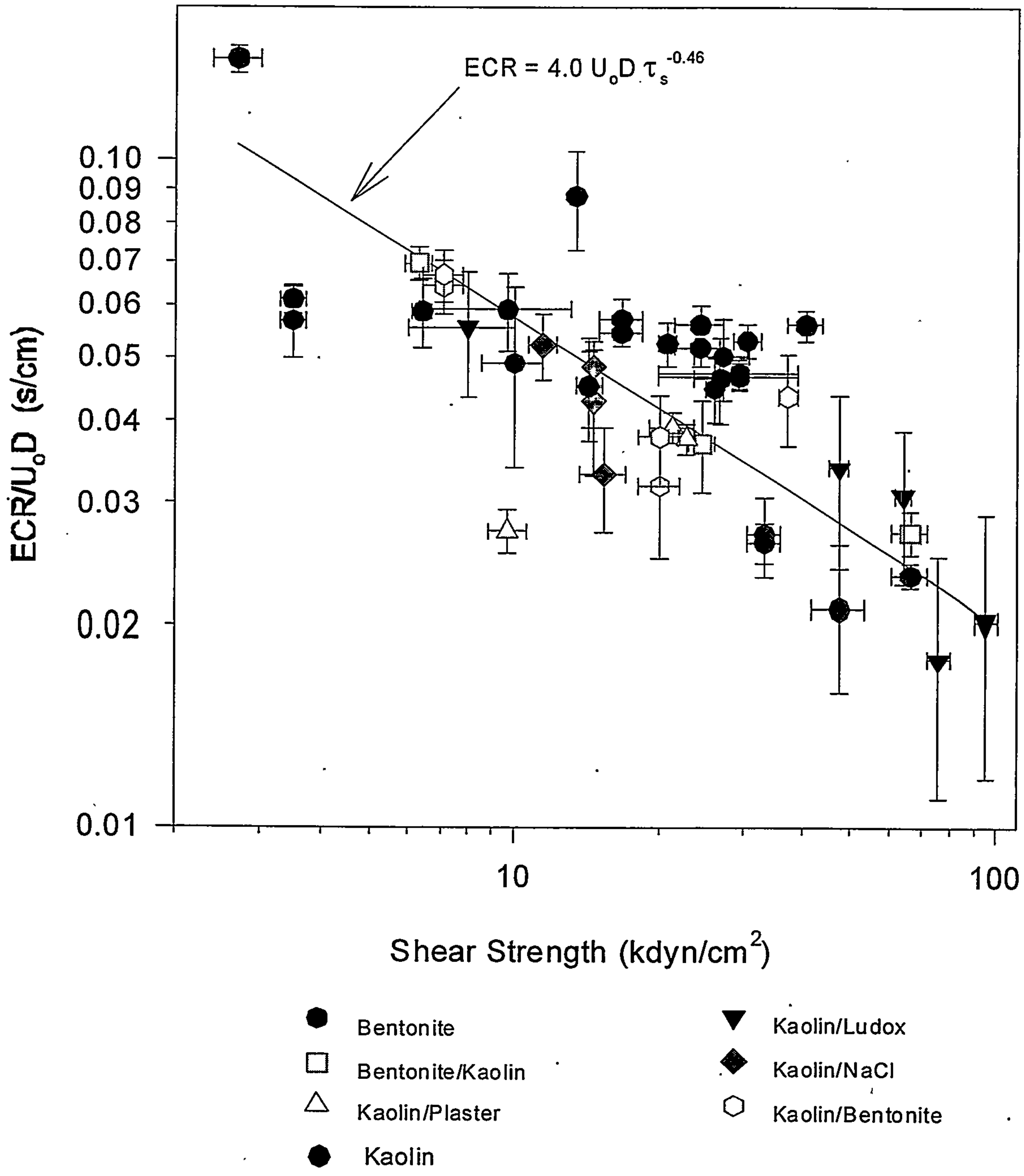

Figure 2.1. Sludge Mobilization Data Collected in 3-ft Diameter Tank (Powell et al. 1997)

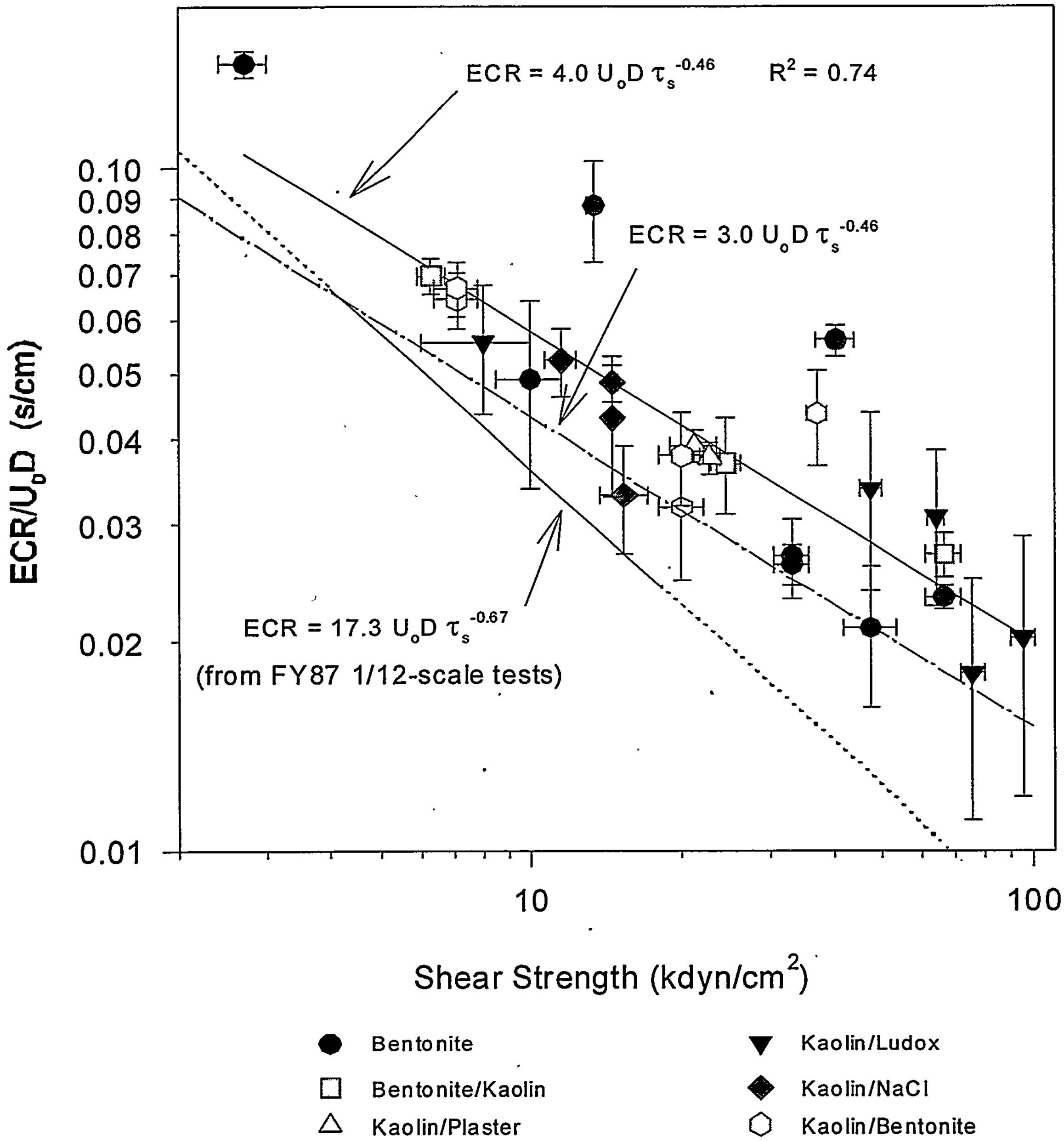

Figure 2.2. Cohesive Sludge Mobilization Data (Powell et al. 1997)

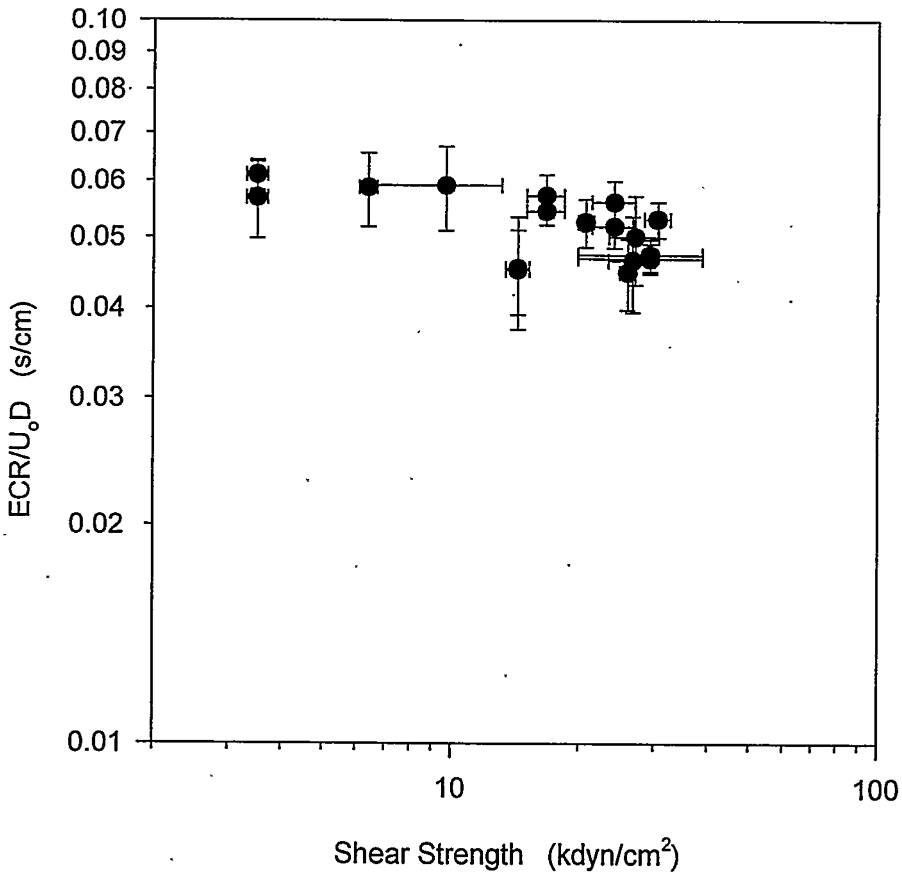

Figure 2.3. Sludge Mobilization Data for Kaolin Clay Simulant. At 15 kdyn/cm^2 the ECR/U_0D is approximately 0.055 s/cm. (Powell et al. 1997)

grout injection test would be expected to have some detrimental effect on the ECR obtained.

Third, the viscosity is higher and non-Newtonian compared to the low-viscosity Newtonian rheology of the tank supernatants. The effect that this may have is unclear but is probably detrimental to the ECR obtained.

2.2 Implications of Sludge Mobilization Relationship to Nozzle Selection

The previous section indicates that the distance over which a fluid jet is effective in mobilizing sludge is proportional to the product U_0D. If the effective mobilization distance of the jet for a given sludge is held constant (by maintaining a constant U_0D product) then the tradeoff between pressure and flow rate of the injected grout slurry can be evaluated. For purposes of this comparison, the velocity head at the nozzle exit is taken to be representative of the required pressure although in practice the pumping pressure would need to be sufficient to overcome frictional pressure drops in the piping system as well. Figure 2.4 shows the pressure and flow required to maintain a constant U_0D value of 4.22 ft^2/s. This corresponds to 11.7 gpm through a 0.24 cm (0.094 inch) nozzle which is believed to be the approximate condition for the nozzles during the MPI demonstration. Figure 2.4 illustrates the rapid increase in pressure requirement as the nozzle size is reduced. The same plot is repeated in Figure 2.5 to illustrate the tradeoff in the range encompassing the 0.5-in and 0.875-in nozzles tested in this effort.

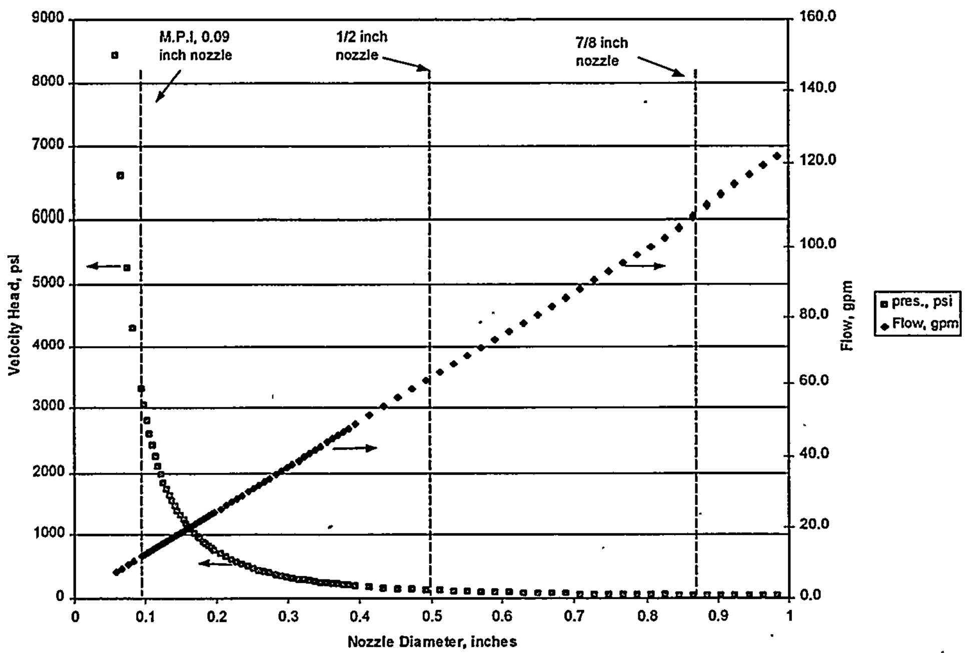

Figure 2.4. Corresponding Pressure and Flow for Various Nozzle Sizes to Achieve a U_0D value of 4.22 ft^2/s. This U_0D value corresponds to 11.7 gpm through a 0.094-in (0.24 cm) nozzle which is believed to be the approximate condition for the nozzles during the MPI demonstration.

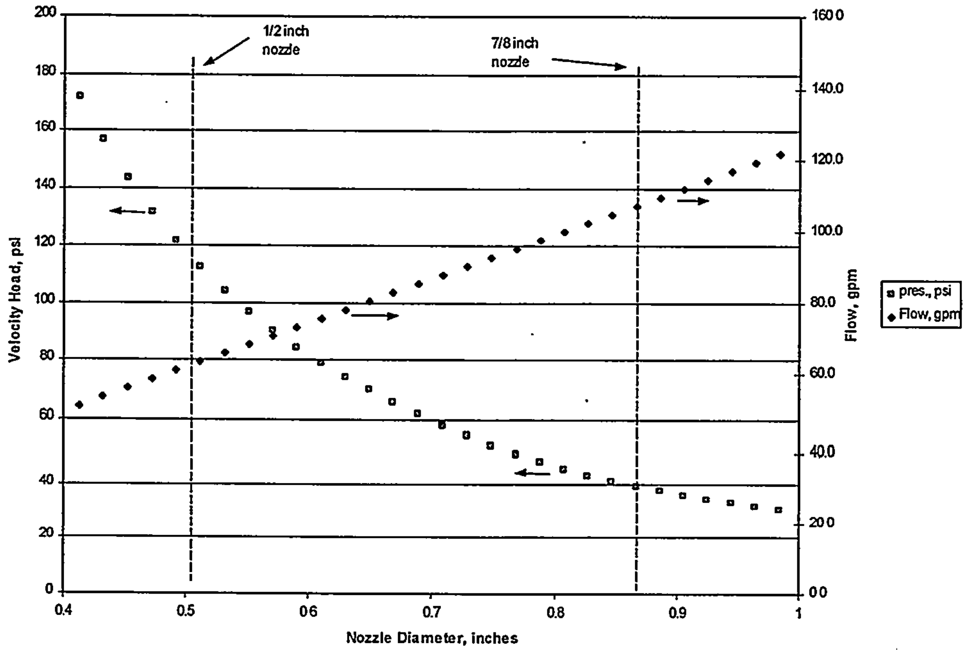

Figure 2.5. Corresponding Pressure and Flow for Various Nozzle Sizes to Achieve a U_0D value of 4.22 ft^2/s. The plot is identical to Figure 2.4 except that the scale is selected to illustrate the region encompassing the 0.5-inch and 0.875-inch nozzles tested in the current work.

3.0 Test Configuration and Equipment Description

The pumping capacity for this testing was provided by a concrete pumping truck with a Schwing America model BPL 500 pump. The pump curve from Schwing indicates that the pump has a maximum pressure output of 859 psi and the maximum flow is 243 gpm (maximum pressure and flow not obtained simultaneously). The pump is powered by the truck engine.

The grout was pumped through a 2-in diameter flexible hose provided by the vendor and delivered to a hard-piped system consisting of 2-in schedule 80 piping. A schematic of the hard-piped portion of the test system is shown in Figure 3.1. The schedule 80 piping was used to allow the piping system to withstand the maximum pressure output of the pump. However, the pressures actually experienced during testing did not require the heavy wall construction.

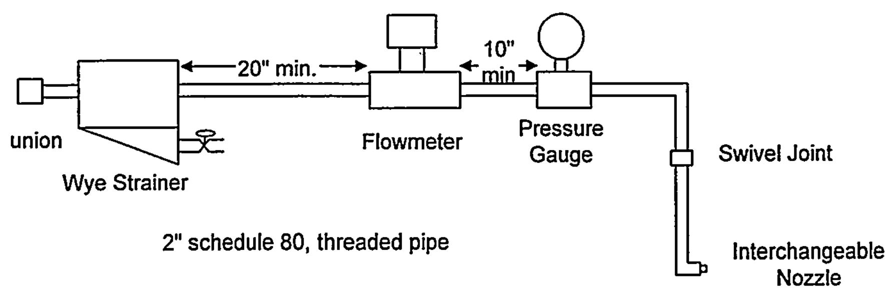

Figure 3.1. Schematic of Hard-Piped Portion of Test System

The hard-piped portion of the system consisted of a 2-in union followed by a wye strainer. The wye strainer was included to prevent large particles (gravel, etc., from previous operations of the cement truck or pumper) from entering the piping system, protecting the flow meter from damage. The pressure drop across the strainer screen was too high when pumping the grout which resulted in a rupture of the screen. In an actual application, it is recommended that the flowmeter be replaced with a non-intrusive flowmeter such as a magnetic flowmeter which would eliminate the need for a strainer.

The flowmeter used was a turbine flowmeter with tungsten carbide shaft and bearings. It has a flow range of 40 to 400 gpm with accuracy of 1% of reading. The body is 316L stainless steel and is rated for 5000 psi. A readout connected to the meter provided flow in gallons per minute as well as totalized flow in gallons. The flow-meter was installed with 10 pipe diameters of straight pipe upstream and 5 pipe diameters downstream to avoid flow disturbances. After the strainer screen ruptured, the flowmeter turbine tended to become jammed with small gravel pieces. The gravel is present in the system as a result of contamination from previous concrete pumping and hauling performed by the cement truck and pump.

The pressure gauge used has a range of 0 to 1000 psi with 0.5% accuracy. The pressure is transmitted through a diaphragm to prevent clogging of the sensor with grout or particulate.

A schematic of the test configuration showing the mud mixing gun positioned in the 9-ft diameter tank is shown in Figure 3.2. The mud mixing gun consists of 2-in schedule 80 pipe with a mounting bracket to mount the gun on the side of a tank. Due to the lightweight nature of the tanks being used, the gun was mounted to a heavy steel frame positioned next to the tank to prevent movement. The gun was used with interchangable parabolic nozzles with tungsten carbide inserts in sizes of 0.5-in ID and 0.875-in ID. The gun contains a rotating joint which allowed the jet to be manually rotated. Manual stops were added to the mixing gun to allow consistent oscillations through a 107 degree arc. This arc was traversed in a nominal time of 10 seconds. The mud mixing gun has a maximum cold working pressure of 2000 psi.

The tank used was typical of tanks used for watering livestock. The sides of the tank were extended vertically by use of a plastic wall salvaged from an above-ground swimming pool. The wall extension was attached to the tank using rivets and the gap between the plastic liner and the tank wall was sealed using bentonite clay. The inside diameter of the tank after installation of the liner was 106.4-in (average of 106.5, 106.25, 106.5, 106.25). A schematic of the test tank setup is shown in Figure 3.2. The clay simulant was spread to a depth of approximately 2-in across the entire tank, the clay was covered with an additional 4-in water and then the grout was injected. In the third test, half of the clay was replaced with a 20x50 mesh zeolite. A total of 4 yd^3 (808 gal) of grout was ordered for each test. Thus, the amount of grout injected into the tank was slightly less than 808 gallons (4 yd^3) due to losses to the cement truck surfaces, and due to material being in the hopper and pipelines at the time the pump was shut down.

A photo showing the cement truck discharge into the hopper of the pumping truck is shown in Figure 3.3. Figure 3.4 shows the cement truck and pump truck arrangement. Figure 3.5 shows the mixing gun supported on the steel frame with a handle consisting of a piece of pipe to allow manual rotation. Figure 3.6 illustrates typical surface appearance of the jetting action from early in the jetting sequence (photo is of test #2). Figure 3.7 illustrates typical surface appearance of the jetting action near the end of an injection sequence (taken from near the end of test #1).

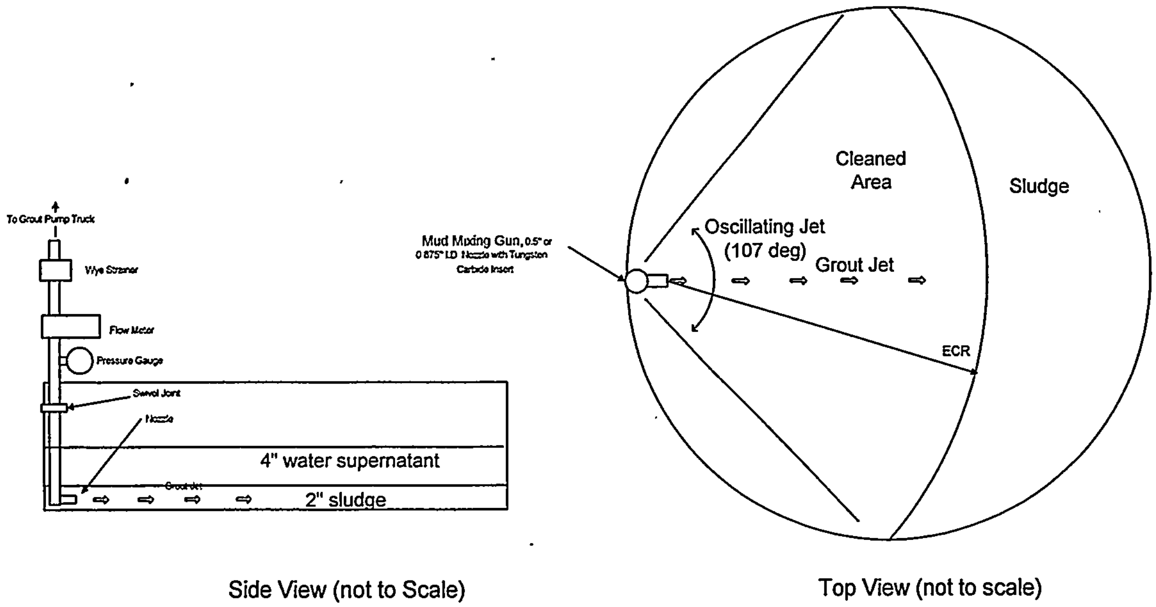

Figure 3.2. Schematic of Test Configuration Showing Nozzle Positioned in 9-ft Diameter Tank

Figure 3.3. Cement Truck Positioned to Discharge to Pumping Truck

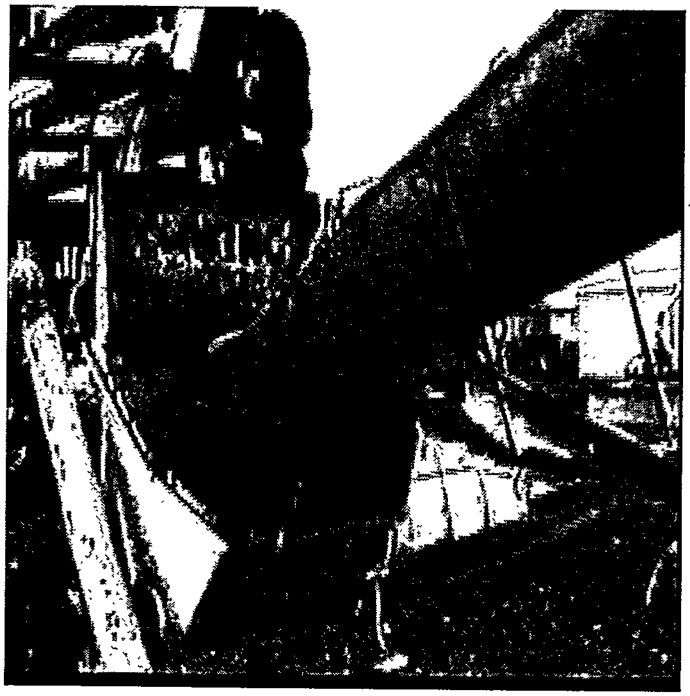

Figure 3.4. Discharge Configuration Between Cement Truck and Pump Truck. Hopper contained a 5 mesh screen to remove gravel.

Figure 3.5. Mixing Gun with Rotation Stops. Gun is supported by heavy steel frame and is rotated using the pipe in foreground.

Figure 3.6. Example of Jetting Action Early in Injection Test #2. Mixing gun is to the left. Second vertical pipe is discharge from wye strainer and was not used.

Figure 3.7. Typical Surface Appearance of Jetting Action Near End of Injection. Photo taken near end of Test #1.

4.0 Test Observations

Before the grout injection tests were performed, the concrete pump was used to pump water through the test system. Sand was placed in the tank and the system pressurized to approximately 117 psi with the 0.5-in nozzle and to 49 psi with the 0.875-in nozzle. These flows are able to push the sand layer around the tank to form a sand bar just inside the far side of the tank. Changes made as a result of the water test included the following:

1) due to some leakage of water from the piping to flexible hose connection, the connection was reconfigured to take place at ground level to remove the weight of the hose from the connection
2) mechanical stops were added to the mixing gun so that the extent of the rotation would be consistent between rotations and between different tests
3) a piping joint which shifted slightly due to the reaction force was welded to prevent movement

The sand was then thoroughly cleaned from the tank prior to adding materials for the first grouting test. A summary of the individual tests is provided below.

TEST #1

Clay sludge simulant was thoroughly mixed in batches using a Littleford mixer and staged into 5 gallon plastic pails with lids. The total mass of clay sludge simulant included 683 lb of dry EPK pulverized kaolin clay (Feldspar Corp., Edgar, Florida) and 400.8 lb water. The kaolin clay paste was dumped from the plastic buckets and spread by hand onto a completely dry tank floor to form an approximately 2-in. thick layer. As soon as the 2-in. layer was completed, water was added to bring the total level to 6 inches.

Test #1 used the 0.875-in. nozzle. The grout consisted of the following ingredients:

Portland Cement	1947 lb
Class F Flyash	5840 lb
Water	3539 lb

The volume of grout prepared was 4 yd^3 and except for losses to the walls of the cement truck and hopper and the grout in the lines when the hopper was empty, the full grout volume was delivered to the tank. The grout was pumped at an average pressure[a] of 146 psi (measured just prior to the nozzle) while the maximum pressure recorded was 169 psi. The flow was interrupted briefly at 1 min 15 seconds into the test because the concrete truck was not keeping up with the pump truck. This was quickly remedied and the test resumed with steady pumping through the end of the test.

Approximately half way through the test, a 1 gallon sample of the grout was taken from the cement truck discharge to determine the density and viscosity. The density was measured in triplicate using a 100 ml density cup to provide an average of 1.708 g/ml. The rheology was evaluated in duplicate using a Fann viscometer starting and ending at 600 rpm. The rheogram is plotted in Figure 4.1.

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[a] The pressure dips between piston strokes and reaches a plateau during the piston stroke. The plateau pressure is recorded and an average of the plateaus is then calculated.

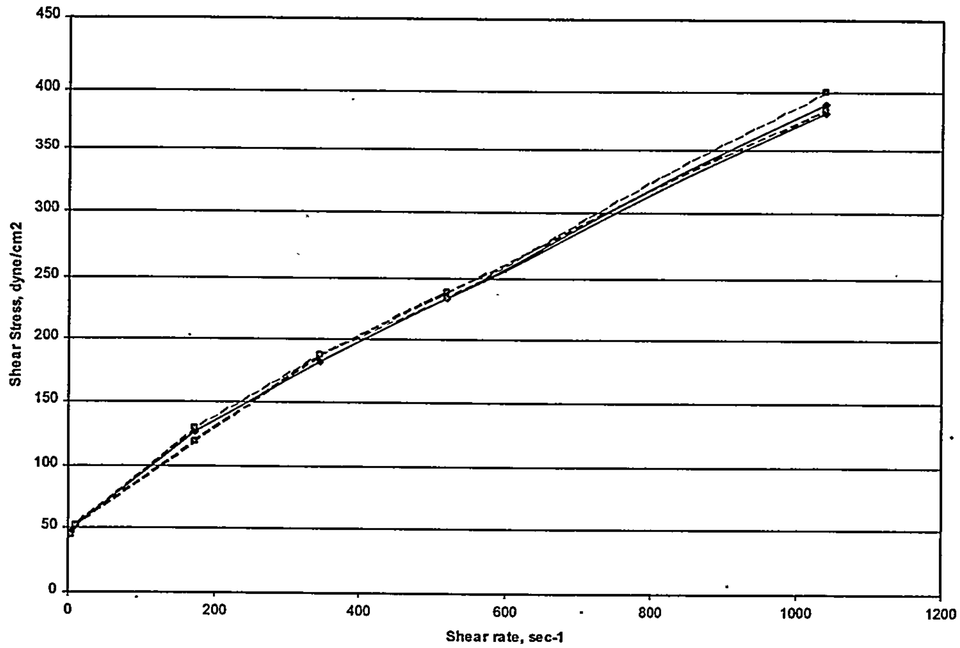

Figure 4.1. Duplicate Rheograms for Grout Sample Taken During Test#1

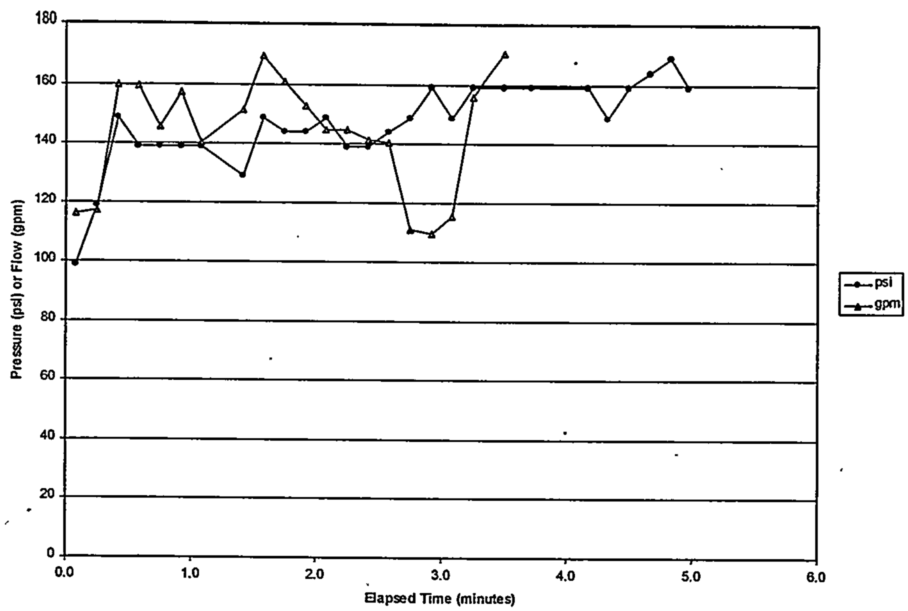

Figure 4.2. Flow and Pressure Data from Test #1

The flow and pressure data during the first grout injection test are shown in Figure 4.2. The short pump shutdown at 1 minute 15 seconds is excluded from the elapsed time in the plot. About 3/4 of the way through the test, the flowmeter stopped reading. After the test, this was determined to have been caused by a rupture of the wye strainer screen which allowed some roughly 1/8-in gravel particles to lodge between the body of the flow meter and the turbine. The average flow rate from the flowmeter while it was operational was 143 gpm. Based on the tank diameter (106.4-in), the increase in level (18-in) and the elapsed pumping time (4 min 58 seconds), a total of 3.4 yd^3 was transferred at an average flow of 138 gpm which is in good agreement with the flowmeter data.

Test #1 Post-Injection Observations

Very soon after the injection was completed, a thin layer of water separated from the grout. Within 48 hours, the separated water and some additional rain water either evaporated or was absorbed. A concrete penetrometer indicated that compressive strength was >700 psi, the maximum capability of the penetrometer. The grout was excavated 4 days after being poured. No shrinkage cracks were evident. The grout was too hard to effectively dig with a pick and shovel but could easily be broken by an electric jackhammer. Excavation started at the injection point and then proceeded at increasing radii. The entire grout mass was manually broken into pieces, inspected, and removed from the tank. The presence of any unmixed kaolin clay was noted. In general, there were no undisturbed regions of the kaolin clay remaining on the floor of the tank. A couple deposits which had been significantly eroded from the initial height of 2-in were located. In addition, a few small clay chunks which had not completely broken down were found suspended within the grout. The ability to locate small pieces of clay within the grout was excellent due to the high contrast of the gray cement with the white kaolin clay. These small pieces were sufficiently small and rare that a sampling approach based on chemical analysis to determine uniformity would not likely have been able to detect them.

A few small deposits of clay remained in isolated locations on the floor of the tank. Where these deposits were thick enough to collect and weigh, a weight was recorded. The wet weight of clay recovered is summarized in Table 4.1.

Table 4.1. Weights of Kaolin Recovered During Test #1

Radial Location in Tank - Measured from center of mixing gun pipe.	Wet Kaolin Weight Recovered (g)
Up to 60 inches	16.6
60 inches to 78 inches	41.2
78 inches to 86 inches	36.0
86 inches to far wall	273.9

The total mass of unmixed clay represents only 0.075% of the total added to the tank. It was initially planned to measure the shear strength of clay deposits recovered from the test. However, too little material remained to allow a measurement. Photos of the excavation and deposits observed are shown in Figures 4.3 through 4.7.

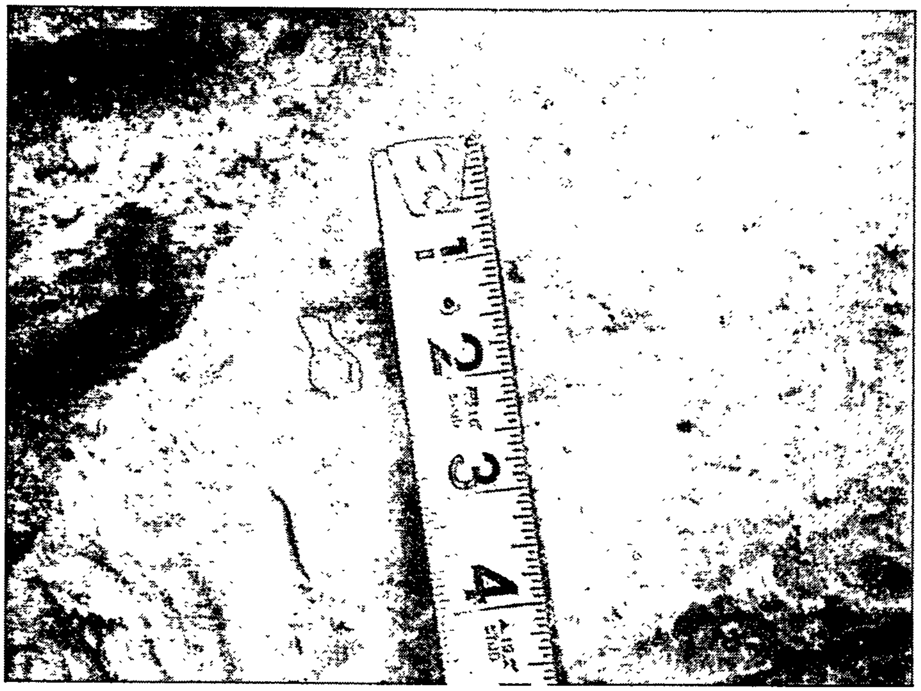

Figure 4.3. Largest Mobilized Kaolin Fragment Located During Test #1 - Approximately 3/4-in in Largest Dimension. A number of smaller <1/4-in fragments were also found.

Figure 4.4. Thin Streaks of Kaolin Clay. Deposit was initially in contact with the floor. Several similar deposits were seen. Layer is approximately 1/16-in. thick.

Figure 4.5. More Significant Floor Deposit Prior to Far Wall. View shows surface that was in contact with the tank floor (see side view of deposit below).

Figure 4.6. Same Deposit in the Preceding Figure Viewed from the Side. The deposit was reduced in thickness from about 2-in initial thickness to approximately 1/4-in thick.

Figure 4.7. Most Significant Deposit Located Along the Wall Farthest from the Jet. The mass was collected and recorded in Table 4.1 under "86 inches to far wall" heading.

TEST #2

The compositions and masses of the clay sludge simulant and cement slurry ordered for this test were the same as in Test #1. The clay was placed in a 2-in thick layer with 4-in thick water cover as in Test #1. However, the nozzle diameter was 0.5-in rather than the 0.875-in nozzle used in Test #1.

During preparation of the clay, six samples were taken for evaluation of the shear strength. The average shear strength of the six clay samples measured using a square bladed vane was 15.54 kdyne/cm^2 with a 95% confidence interval on the mean of $\pm$1.23 kdyne/cm^2. This agrees well with the target value of 15 kdyne/cm^2.

A plot of pressure verses time is shown in Figure 4.8. The initial ramp up in pressure in the first minute was an intentional action on the part of the pump operator who had been instructed that a 10-second ramp up in pressure was acceptable. Neglecting the first minute, the grout was pumped at an average pressure[a] of 308 psi. The wye strainer screen which ruptured during the first test was left out of the system for this test. Small gravel particles with an approximately 1/8-in diameter jammed the flow meter within the first 10 seconds of operation so no flow meter data are available. Based on the tank diameter (106.4-in), the increase in level (17-in) and the elapsed pumping time (10 min 2 seconds), a total of 3.2 yd^3 was transferred at an average flow of 65 gpm.

As in Test #1, an approximately 1 gallon grout sample was taken approximately half way through the test. The grout density was measured as 1.709 g/cm^3 using a 100 ml density cup (average of 3 measurements). The rheology was investigated as before using a Fann viscometer, and the rheogram is shown in Figure 4.9.

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[a] The pressure dips between piston strokes and reaches a plateau during the piston stroke. The plateau pressure is recorded and an average of the plateaus is calculated.

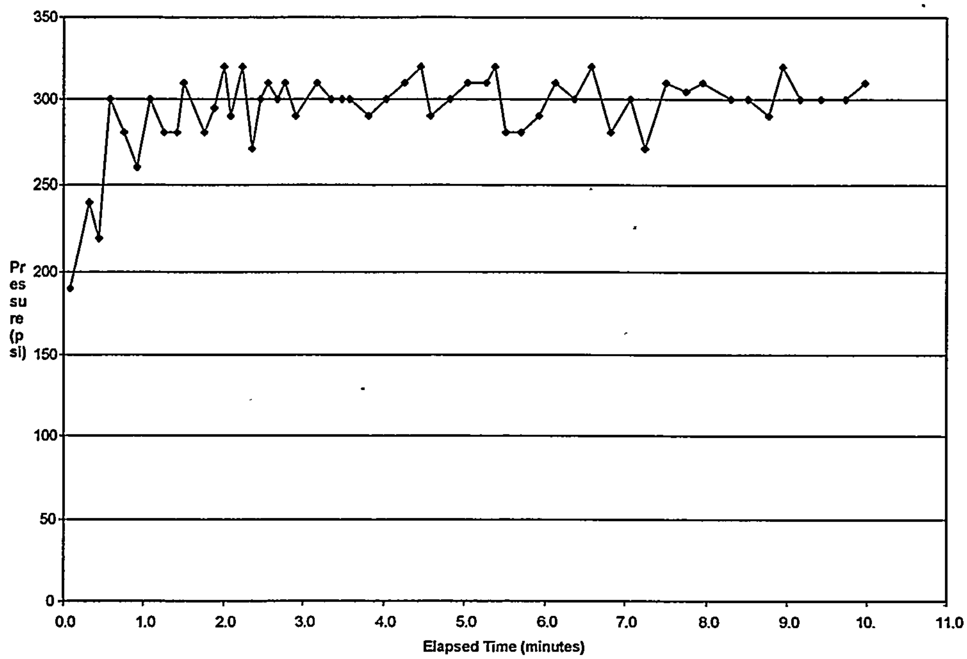

Figure 4.8. Pressure verses Time for Test #2

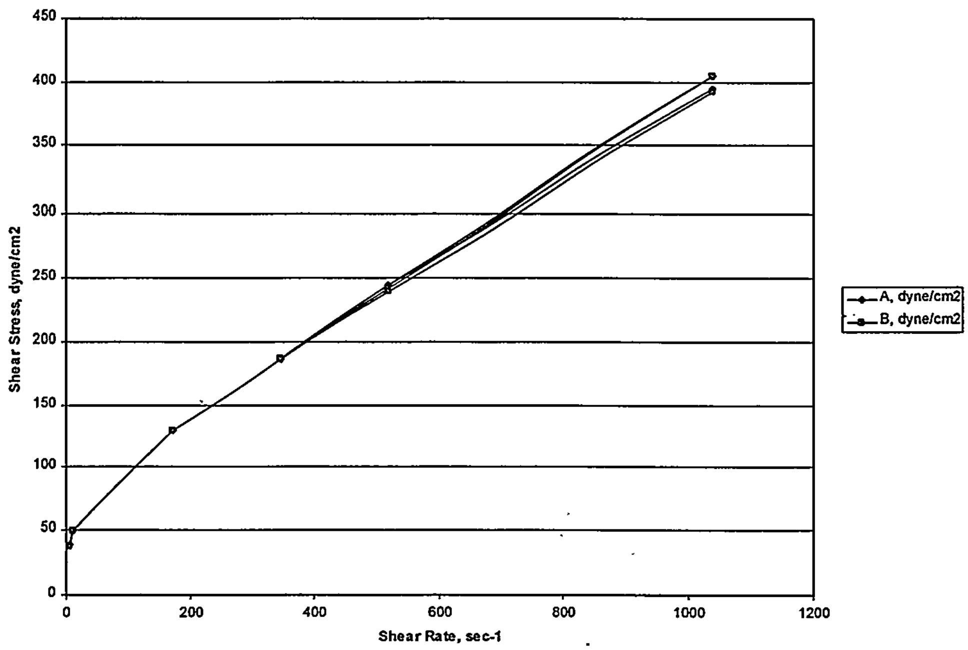

Figure 4.9. Grout Rheology During Injection Test #2

Test #2 Post-Injection Observations

The grout was excavated 2 days after being poured. As before, a jackhammer was used to excavate the grout at the injection point first and then at successively greater distances from the injection point. No significant sludge deposits were located in the grout pour. The largest deposit was against the far wall in a sheltered area formed by the bottom of the side wall extension and the tank floor. This deposit was recovered and weighed 13.3 grams. There were a number of locations with very thin layers of clay attached to the floor. These layers were just thick enough to give some color but were too thin to be recovered and weighed. Compared to the first test, there were qualitatively fewer floating clay specks which had not fully broken down and there were no major deposits on the floor. Photos from the excavation are shown in Figures 4.10 through 4.14.

Figure 4.10. Several Volcano-Like Structures Observed Prior to Excavation. These were observed at the point where the mixing gun was withdrawn. They are slightly elevated over the flat grout surface and appear to have occurred due to settling causing a flow of liquid up through the center of the structure.

Figure 4.11. Grout Being Jackhammered for Inspection. Grout was removed at successively greater distances from injection point.

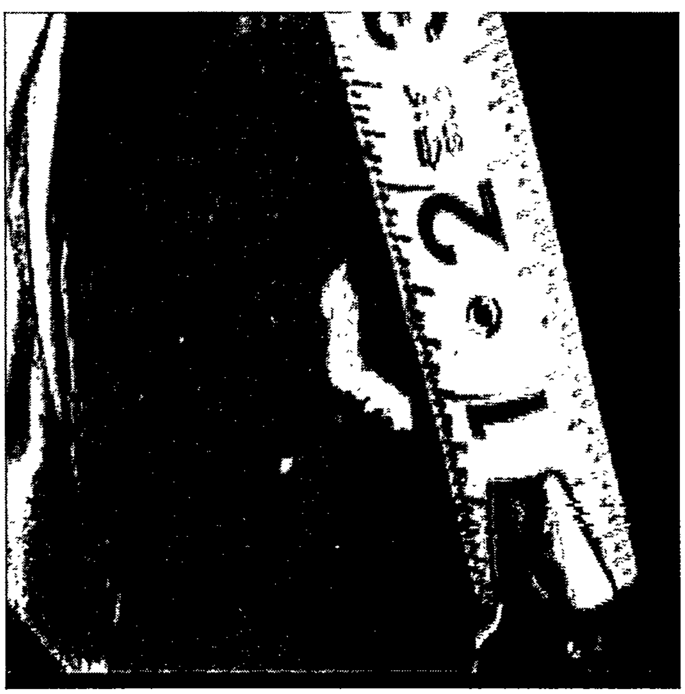

Figure 4.12. Small Piece of Kaolin Clay Suspended in Grout. Clay had not fully broken down. Several smaller suspended pieces were also seen. The number of suspended pieces in Test #2 was qualitatively less than in Test #1.

Figure 4.13. Very Thin Floor Deposit. Scratches with screwdriver illustrate the thin nature of the deposit. Several such deposits were found.

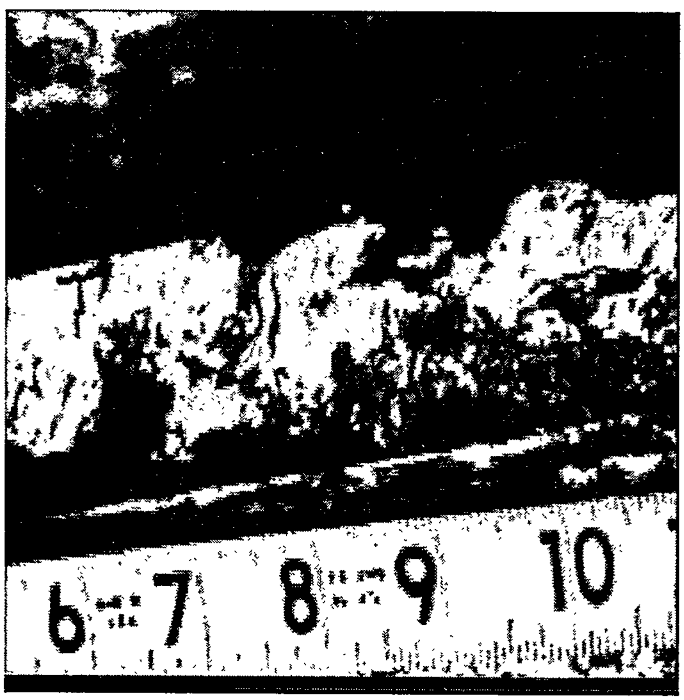

Figure 4.14. Deposit from Crevice Below Wall Extension Along Far Wall. This deposit accounted for the majority of the mass recovered in Test #2.

TEST #3

This test used half of the amount of clay in Test #1 to cover the west half of the tank to a depth of 2-in. Three samples were taken from the batches of clay and the shear strength measured as 14.76, 17.73, 18.22 kdyne/cm^2. The average of the three measurements is 16.9 kdyne/cm^2.

In the west half of the tank, 300 lb of 20x50 mesh Mol-Siv Zeolite (IE-96) was used to create a layer approximately 2.6 inches thick (after wetting). Water was added to provide a total height of 6-in in the tank.

The injection point was located at the north wall of the tank on the line separating the clay and zeolite materials. The flowmeter and wye strainer were removed from the system for this test. The 0.875-in nozzle was used for the test.

To minimize settling, one 100-lb bag of bentonite clay was added to the 4 yd^3 cement slurry batch. Prior to selecting the amount of bentonite to add, lab tests were performed to verify that the amount added would prevent settling of the zeolite particles. At the vendor's site, the dry bentonite clay was placed in the cement truck and the mixed cement slurry was then added and the truck turned for 200 revolutions. Some fraction of the bentonite clay was not adequately mixed up in the grout and was caught on a 5 mesh screen covering the hopper of the concrete pump. The material caught on the screen was not quantified but was small relative to the 100 lbs added. The screen was sufficiently plugged to push some grout up over the top of the screen so that some of the cement slurry was not screened.

A 1 gallon sample was taken half way through the discharge of the grout and poured through a No. 5 sieve. A total of 29.8 g bentonite (dry wt) was retained. Extrapolated to 4 yd^3 of grout, this would imply 53 lb of the initial 100 lbs of bentonite existed as small balls of bentonite in the slurry prior to passing through the pump and being injected into the tank. However, it is not known how representative the single 1-gallon sample may be of the total batch. The slurry (minus the sieved material) was then evaluated for density and viscosity. The average of density measurements on four sub-samples was 1.67 g/cm^3. The rheogram was performed on two subsamples and is shown in Figure 4.15. The discharge pressure during the injection is shown in Figure 4.16. Based on the tank diameter (106.4-in), the increase in level (19-in) and the elapsed pumping time (6 minutes), a total of 3.6 yd^3 was transferred at an average flow of 122 gpm.

Test #3 Post-Injection Observations

The test pour from Test #3 was excavated in the same manner as were the previous two pours except that excavation was accomplished over a period lasting from 16 to 21 hours post-injection. This was done to facilitate the sieving of samples to recover zeolite from the grout. The samples were taken immediately to the laboratory and were processed during a period 18 to 24 hours post-injection.

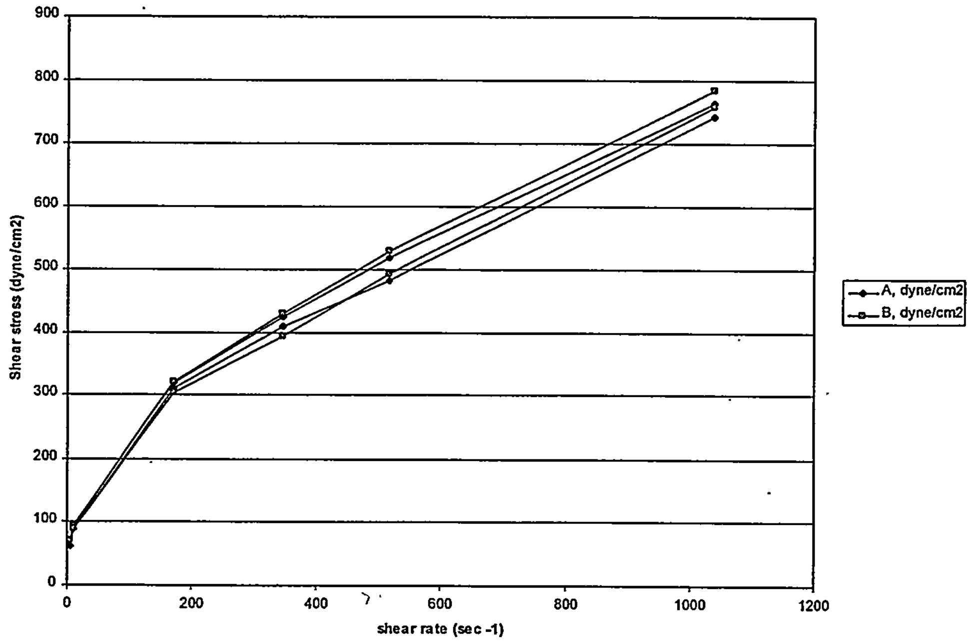

Figure 4.15. Rheogram for Grout Slurry in Test #3. Sample sieved on No. 5 sieve prior to measurement.

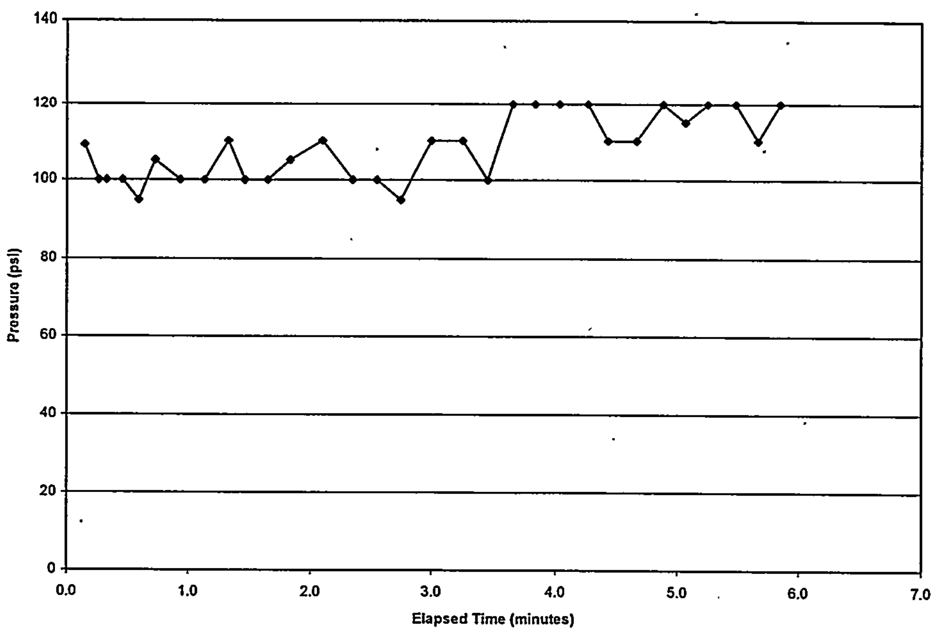

Figure 4.16. Discharge Pressure During Test #3

The surface of the poured grout was wet at the start of excavation and dried as the work proceeded. The grout was firm enough at the start of excavation to stand on without leaving indentations on the surface. The jackhammer was still the tool of choice although some progress could be made initially using a pointed sharpened shovel. There were several approximately 3-inch diameter volcano-like structures in the grout surface which appeared to have been where water was flowing to the surface prior to set. A few of these were seen in Test #2 but Test #3 had more of these structures.

As in the previous tests, no unmobilized bulk sludge layer remained at the end of the test. In fact, in Test #3, there were no floor deposits at all. Test 3 also had fewer of the small, non-broken down kaolin clay specks than in previous tests. There was no visual evidence of non-uniform zeolite distributions.

Samples were obtained from seven locations with five samples from different elevations each for a total of 35 samples. The sample locations are shown in Figure 4.17.

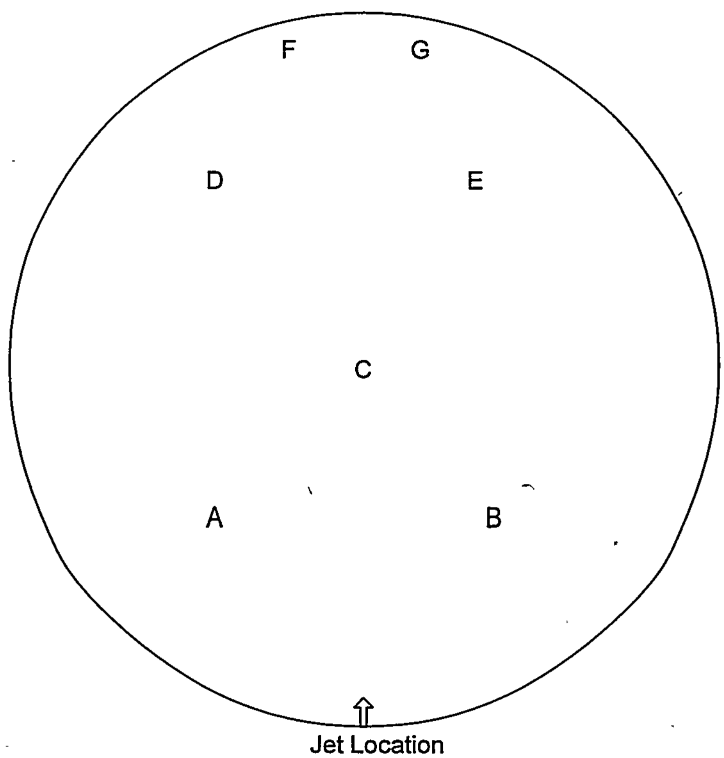

Figure 4.17. Approximate Sample Locations in Test #3.

The five samples taken at each location were numbered with A-1 being from the top inch of grout, A-3 being at the center, A-5 being from the bottom inch, and A-2 and A-4 being evenly spaced between the other samples. The samples were taken by chipping and scraping with a pocket knife into a plastic sample container with a lid. As soon as a group of five samples at a given location was obtained, the samples were removed from the test tank and taken to the lab for analysis. In the laboratory, the samples were slurried with water and sieved through a 65 mesh screen (0.0082-in opening) to recover the zeolite. The zeolite was dried in air and weighed to determine the weight fraction of zeolite in each grout sample. The first concern with this approach is that if the grout curing has progressed too far, chunks of grout may be counted as zeolite particles. To evaluate this concern, the zeolite content results were plotted in order of the analysis performed, which corresponds to increasing cure time prior to analysis (Figure 4.18).

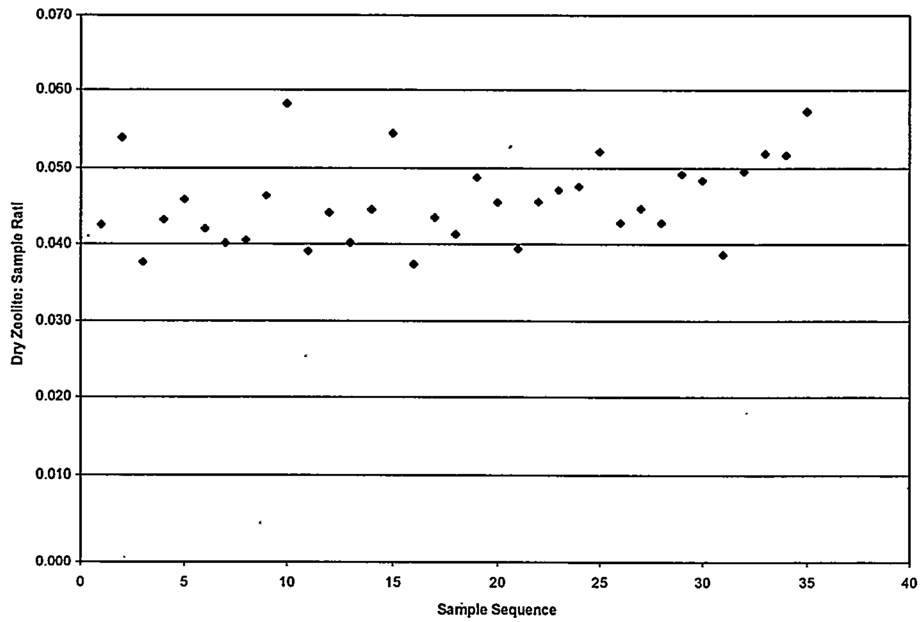

Figure 4.18. Zeolite Content Plotted Against Analysis Sequence. Samples higher in the sequence were cured for a longer time prior to being slurried and sieved for analysis of zeolite content.

Figure 4.18 does not show any clear trend in zeolite content results with analysis sequence. The data indicate a spread in results between roughly 0.04 and 0.06 wt fraction dry zeolite. Much of this scatter is believed to be due to analytical inaccuracies rather than actual variation in concentrations. Similar scatter was seen in labortory mixed samples. The data were evaluated to determine if there was evidence of non-uniformity related to either position or elevation within the tank. A comparison by location is shown in Figure 4.19. The error bars in the plot are the 95% confidence intervals on the mean based on the samples at that location. The data points are shown in Figure 4.20. There is no evidence of variation with position within the tank. Figure 4.21 provides a comparison relative to elevation within the tank. This plot indicates that the zeolite content may be slightly lower at the top surface of the grout. This may be related to a higher water content at the top surface of the grout (recall that the surface was wet when excavation was started.) There is a less convincing case to be made that there may be a slight elevation in zeolite content at the tank bottom (Figure 4.21). Any trend is even more questionable examining the actual data points (Figure 4.22). Photos from the excavation of Test #3 are shown in Figures 4.23 through 4.25.

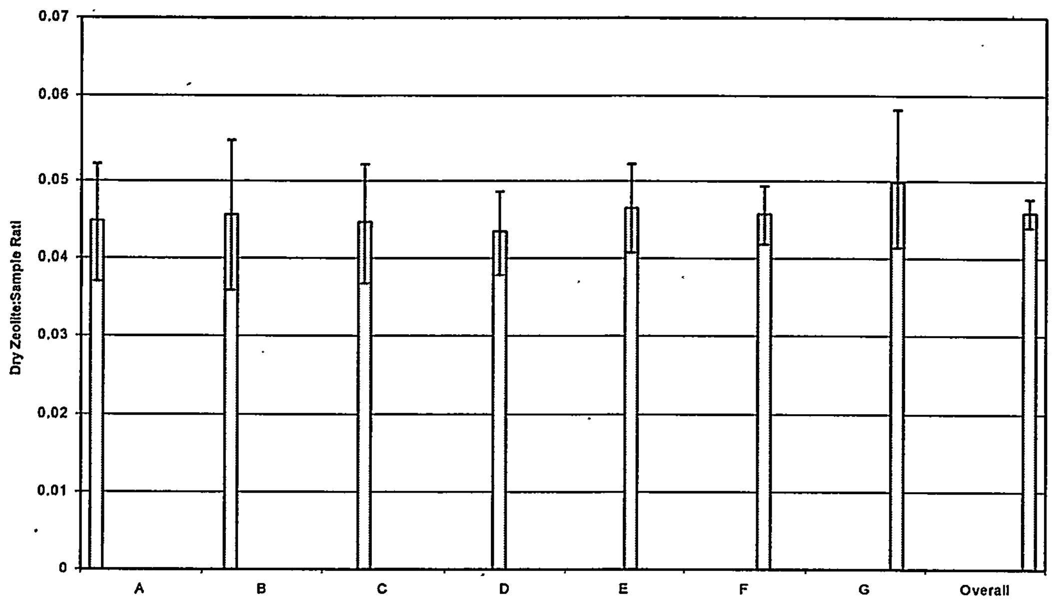

Figure 4.19. Variation in Zeolite Content by Position. Error bars are 95% confidence limits on mean determined from samples at each location.

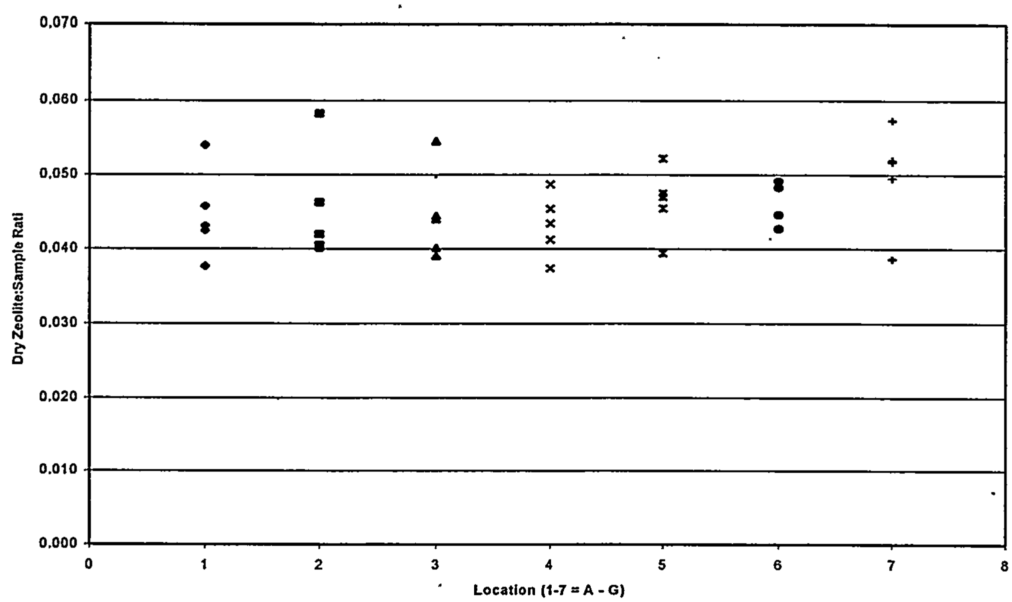

Figure 4.20. Variation in Zeolite Content by Position - Data Points

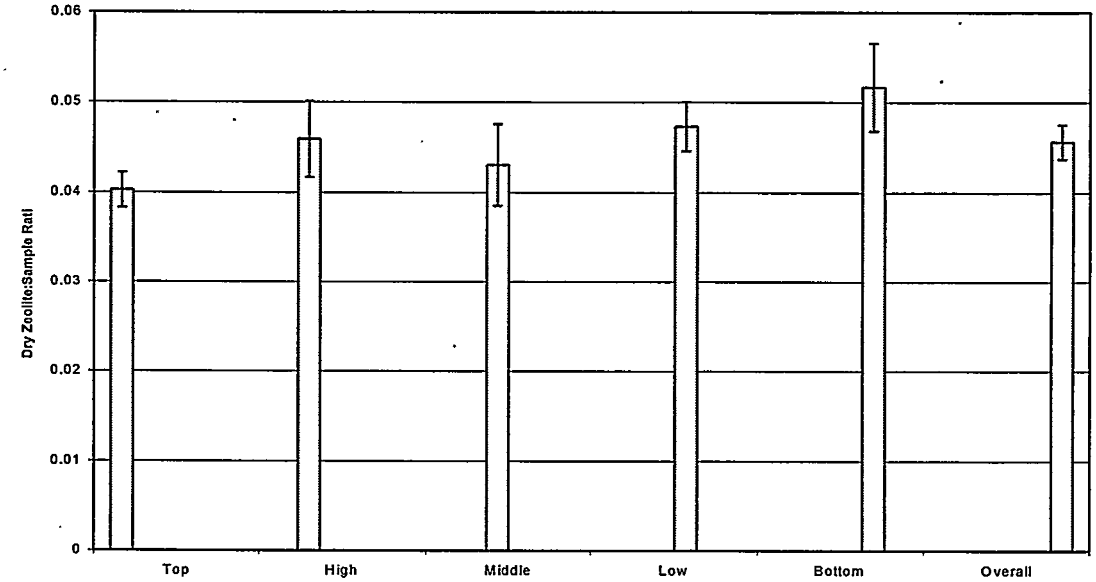

Figure 4.21. Variation in Zeolite Content by Elevation. Error bars are 95% confidence limits on mean determined from samples at each elevation.

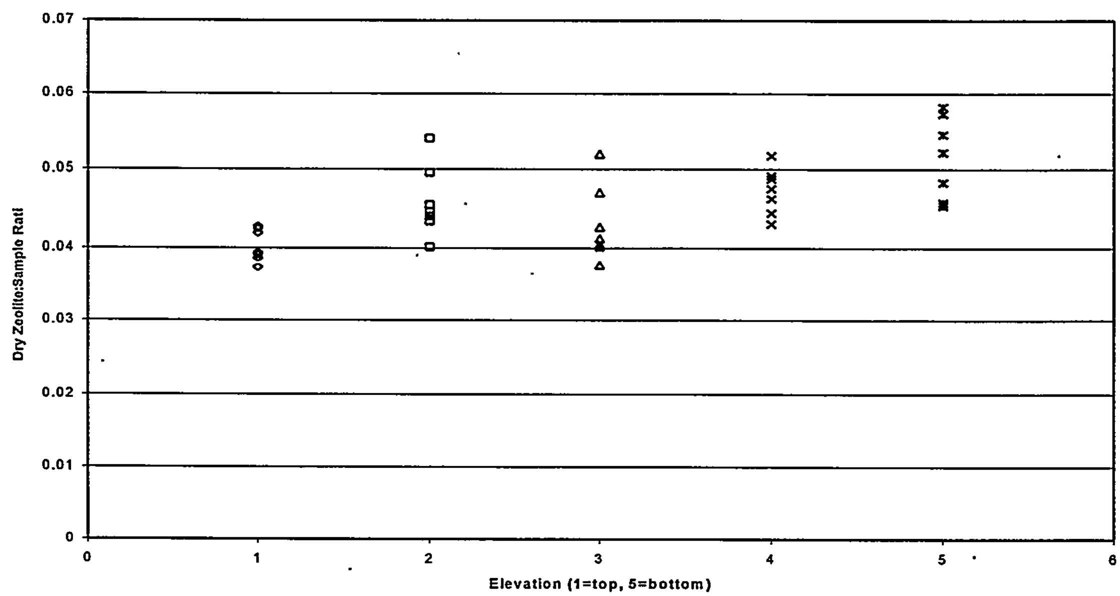

Figure 4.22. Variation in Zeolite Content by Elevation - Data Points

Figure 4.23. Volcano-Like Structure in Grout Surface. More of these structures were seen in grout surface during Test #3 compared to previous tests.

Figure 4.24. Small Piece of Kaolin Clay Suspended in Grout

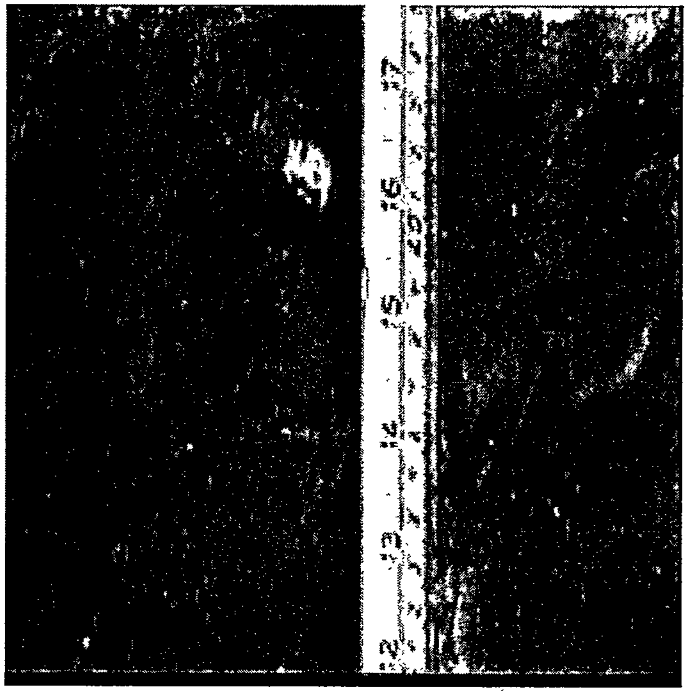

Figure 4.25. Piece of Kaolin Clay Suspended in Grout

4.1 Discussion

A summary of the key parameters for each of the three tests is summarized in Table 4.2.

Table 4.2. Summary of Key Test Parameters

	Test #1	Test #2	Test #3
Nozzle Size (inside diameter, inches)	0.875	0.5	0.875
Average Flow (gpm)[(a)(b)]	138	65	122
Average Discharge Pressure (plateau pressure, psi)[(c)]	146	307[(e)]	117
Duration of Injection (minutes)	5.0	10.0	5.9
U_0D (ft^2/s)[(d)]	5.37	4.43	4.75
Predicted Sludge Mobilization ECR (ft) [(f)]	9.0	7.4	8.0
Slurry Density (g/cm^3)	1.71	1.71	1.67

(a) The pump used in testing produces a maximum pressure and flow toward the end of each piston stroke and a minimum between piston strokes.
(b) The average flow is determined based on tank dimensions, the change in level, and the duration of grout injection. Due to the pulsing nature of the flow, the minimum and maximum flows would vary around the average flow value.
(c) The average discharge pressure is taken as an average of the pressure plateaus and thus represents an average maximum injection pressure.
(d) Calculated based on the average flow.
(e) Excludes low values during ramp-up in pressure over first minute of operation.
(f) Calculated from ECR/U_0D = 0.055 s/cm for 15 $kdyn/cm^2$ target. Actual sludge shear strengths were Test #1 - not measured, Test #2 15.5 $kdyn/cm^2$, Test #3 16.9 $kdyn/cm^2$. Predictions do not take into account the increased density, or pulsing flow effect relative to sludge mobilization experience.

The first observation is that despite the predicted cleaning distances being 9.0, 7.4, and 8.0 feet, the sludge was effectively mobilized to the far wall of the 8.9-ft diameter tank. This greater than expected mobilization performance is believed to be due to the greater density of the grout slurry relative to the tank supernatant and due to the pulsing nature of the flow. The plateau pressures are higher than can be explained based on the average flow values. If the plateau pressure is taken as the velocity head of the nozzle at maximum flow (this neglects the frictional pressure drops between the gauge and the nozzle and would tend to overestimate flow for this reason), the maximum flow in Tests #1, #2, and #3 is indicated to be 53%, 54%, and 57% higher than the average flow value. Because this pulsation results in higher maximum flows which should be beneficial, it is not recommended that the pump output be dampened to eliminate pressure and flow oscillations. The concrete pump used was a dual piston pump. If a 3-piston pump is readily available, this would provide a steadier pumping without sacrificing the maximum flow and pressure. Of course, in an actual application, the system would be run near the pressure and flow capability of the system, while in testing it is often desirable to operate at reduced the flow and pressure to determine the limits of adequate operation.

The second observation is that Test #1 had more residual clay than Test #2 although the U_0D product in Test #1 was higher. It is believed that the enhanced cleaning in Test #2 relative to Test #1 is primarily due to the duration of flow. Because the volume of grout injected was held constant, the duration of injection was twice as long in Test #2 which used the smaller nozzle. Doubling the duration at a U_0D value 80% of the previous test appeared to provide more time for deposits to erode away and for suspended pieces to break down. In optimizing the performance of a system where the volume to be injected is limited, there may be a tradeoff between the high U_0D values attainable using a larger diameter rotated jet compared to the longer duration of injection using a smaller diameter rotated jet. There may also be an advantage to the longer duration of injection using a single rotated jet compared to a shorter duration of injection from numerous fixed nozzles of similar characteristics. In any case the optimum performance in a grouting application would be obtained by fully utilizing the available volume in the tank to maximize the duration of flow.

Test #3 did not have any remaining floor deposits and very few suspended pieces of intact clay. However, the U_0D product was less than Test #1 which did have small floor deposits and had a greater number of suspended clay pieces. It is believed that the enhanced performance seen in Test #3 was due to the substitution of zeolite for half of the clay. The presence of the larger zeolite particles increased the ability of the grout to scour and erode the clay surface. This hypothesis is supported by civil engineering research on the erosion of cohesive soils in river beds by water containing suspended sand. Bhasin et al. (1969) performed a suite of laboratory experiments which included a cohesive clay and a rounded Ottawa sand between 20 and 30 mesh. In a few tests, Ottawa sand between 50 and 70 mesh size was also added. Based on the series of experiments, it was concluded that "*The erosion rate increases with an increase in the amount of sand in the eroding flow.*" Subsequent work done by Kamphuis (1988) used a coarser sand sized between 1.4 and 2.0 mm and determined that the flow with sand suspended in it "*...removed the cohesive material at a much higher rate than the clear water could under the same shear stresses.*" The sand acting as an active eroding agent is also consistent with earlier work performed by Kamphuis (1983) using a consolidated clay and an eroding fluid containing sand with a median diameter of 2 mm. In this work, it was found that "*A fluid containing sand will cause erosion of a consolidated cohesive bed at much lower fluid velocities or shear stresses than if the fluid were clear.*"

Based on these observations, it may be desirable to add sand or other particulate to a grout formulation if some type of suspendable particulate is not present in the tank. This could also be accomplished by adding the particulate directly to the tank prior to injection.

Because the jet cleaned all the way to the opposite wall in each case, the range over which the mobilization can be achieved was not experimentally established. The reasons for the mobilization distance exceeding initial predictions include:

1) The pulsing flow which provides a maximum U_0D that is higher than the average.
2) The increased density of the jet relative to the supernatant early in the injection decreases the velocity decay with distance.
3) The increased density of the mobilization jet compared to sludge mobilization experiments which increases the force exerted on the sludge.
4) In Test #3, the presence of a larger particulate which aids the erosion of the clay.

Of these, the effects of 1 and 3 can be quantified using the current correlations. The effect of increased density on mobilization was examined by Powell et al. (1995) and predicted to vary with the $4/9^{th}$ power of density. The pressure readings indicate a maximum flow roughly 50% greater than the average flow. If these factors are used to adjust the predicted 9 ft ECR in Test #1, the result is

$$ECR = 9 \text{ ft } (1.7/1.1)^{(4/9)}(1.5\ U_o/U_o) = 16.4 \text{ ft}$$

The effects of the initial jet density difference and presence of erosive particles would increase the attainable ECR further. If this expectation is correct, it is reasonable to expect that the system could be modified to acheive higher U_0D values and could be applied to relatively large tanks such as the 50-ft diameter GAAT tanks using a single injection point. In some applications, the ability to use existing dome penetrations rather than adding a number of new penetrations is a significant advantage. As an example of the scale-up, consider a 50-ft tank with the following assumptions:

- Rotating nozzle at center of 50-ft diameter tank (ECR= 25 ft)
- injected grout density 1.7 g/cm^3
- sludge similar to kaolin simulant used in these tests
- velocity head of 300 psi at nozzle exit
- ignore the beneficial pulsation in cement pump flow.

Bernoulli's equation can then be used with the equation

$$ECR = 0.055 \text{ s/cm } (U_oD)\ (1.7/1.1)^{(4/9)}$$

to determine the nozzle size and flow. This results in a nozzle diameter of 0.91 inches and a flow of 329 gpm (98 yd^3/hr). This pressure and flow is well within that attainable using a single concrete pumping truck (although larger than that used in the current testing). Data on the Schwing web page indicates that their larger mobile concrete pumps have maximum flows just over 200 yd^3/hr (674 gpm) and maximum pressures of approximately 1100 psi (not simultaneous).

Extrapolation to very large tanks such as the 75-ft diameter single- and double-shell tanks at Hanford may also be practical. Using similar assumptions as above, the nozzle would be 1.37-in diameter and the flow 740 gpm. This is near the maximum flow for a large concrete pump.

Additional testing at larger scale to establish the maximum cleaning radius would be needed prior implementation. Also, in larger tanks with high domes, the reaction force of the nozzle needs to be considered and it may be necessary to provide two opposing jets operating simultaneously to neutralize this force. Also, the jet rotation would need to be automated. Finally, although no detailed evaluation of the pump performance relative to the pump curve was performed during testing, it is suspected from the testing experience that the actual pump performance was less than indicated by the pump curve. The current testing did not require the full capability of the pump so any under-performance was not an issue in the testing. However, it is recommended that prior to application of the approach to an actual tank, the selected grout formulation and truck be tested first to verify that the desired pressure and flow are attainable using the grout rather than rely on the pump curve provided for the pumping of concrete.

Finally, prior to design of a system, it would be helpful to identify quantitative success criteria (in terms of % of waste mobilized or the range of waste loadings in the grout, etc.) based on the performance requirements of the grouted waste form. This would allow a quantitative statement as to what constitutes an acceptable in situ grouting result.

5.0 Conclusions

Testing of grout injection at pressures of about 300 psi or less through 0.5-in and 0.875-in nozzles resulted in sludge mobilization over a greater distance than initially predicted based on sludge mobilization work with simulated tank supernatant. A single oscillated nozzle located at one side of a 9-ft diameter tank was capable of fully mobilizing a sludge simulant from the floor of the tank. Only a few clay pieces which had not fully broken down were found suspended in the grout.

The greater than expected performance is believed to be due to the greater density of the slurry and the pulsating nature of the flow from the concrete pump. It is estimated that the maximum flow may be 50% greater than the time averaged flow. Unfortunately, the experimental setup did not allow determination of the maximum instantaneous flow during a piston stroke. However, it would be conservative to use time-average flow data for the pump for design purposes.

A 20x50 mesh zeolite was fully mobilized from the floor of the tank and uniformly mixed throughout the grout mass. The zeolite content in the top inch of grout was slightly lower than the tank average. This is believed to be due to some settling prior to set of the grout and is consistent with a small amount of separated water at the surface of the grout.

Based on this testing, it is concluded that in situ stabilization of a tank heel consisting of sludge or zeolite is feasible using a single injection point and a rotated nozzle. The optimum position for a single injection point would be at the center of the tank. The current testing demonstrated that a single nozzle can mobilize sludge at least across a 9-ft diameter tank without difficulty. It is believed that extrapolation of the approach to a single injection point at the center of an 18-ft diameter tank is very straightforward. Compared to small fixed nozzles operated at very high pressure, the approach using larger, rotated nozzles at lower pressure has the advantage that it may be scaled to larger tanks without introducing a large number of injection points. In fact, it is predicted that a 50-ft diameter tank such as the GAAT tanks at ORNL could be treated with a rotated jet placed through a single injection point located at the center of the tank. Scale-up of the process may be possible to allow application to a 75-ft diameter tank such as the single-shell and double-shell tanks at Hanford using a single injection point. Additional testing at larger scale is needed to verify scaling relationships prior to actual application in larger tanks.

6.0 References

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