# Grout Selection and Characterization in Support of the Colloidal Silica Barrier Deployment at Brookhaven National Laboratory

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**Abstract:** Small and large-scale laboratory colloidal silica (CS) testing was performed in support of the Brookhaven National Laboratory (BNL) Linear Accelerator Isotope Producer (BLIP) grouting project. The laboratory testing consisted of two phases: the selection of a CS variant that best reduced the permeability of the BNL soils, and the injection of the selected CS into large sand tanks to determine in situ values of hydraulic conductivity in addition to developing soil-water characteristic curves for grouted samples excavated from the tanks. Nine CS variants having different colloid particle size ranges were identified and tested using injection columns and flexible wall permeameters. From this testing, an optimal CS variant was selected to advance to the second laboratory testing phase. The selected CS grout was injected into sand tanks placed in a load cell to simulate injection at depth. Results indicate that the selected CS variant was successful at reducing the saturated hydraulic conductivity of the BNL soils by four to five orders of magnitude. The soil-water characteristic curves developed for the grouted soils were unique and supported the use of the CS material site as a grout at the BNL site to isolate activated soils in the vadose zone.

**Introduction:** The BLIP creates radioisotopes, which are crucial to nuclear medicine for both research and clinical use. During operation, a proton beam impinges a target to produce the required isotopes. High-energy neutrons and protons created in the process pass through the subsurface target complex and into the surrounding soils. These high-energy particles are absorbed by the soil, creating numerous radioactive isotopes from the naturally occurring elements, including tritium and sodium-22, which are mobile and have impacted the groundwater that exists approximately 8 meters below the activated soils. To minimize the transport of contaminants to the aquifer from infiltrating atmospheric water, flow through the activated soils in the vadose zone necessitated reduction. To achieve this reduction, emplacement of a viscous liquid barrier into the activated soils was selected by BNL as the preferred alternative, where a low viscosity grout is injected into the soil matrix to form a unique groundwater flow barrier in the unsaturated zone.

Selection of an acceptable CS grout variant was the next step in the process, critical to the success of the project. CS grout was selected as the preferred grout type due to its initial low viscosity and high solids content, along with its ability to maintain its properties in radiation fields. A series of laboratory tests were conducted to select a CS variant that best reduced the BNL soil's saturated hydraulic conductivity. Once the CS testing was completed, the project proceeded to the field at BNL where the grout was emplaced into the activated soils.

**Laboratory Testing:** Nine different CS variants (blind labeled MSE 1 through MSE 9) were selected for laboratory testing, based on percent solids, particle size, and particle size distribution. Several of the

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variants had narrow particle size ranges, while others had wider ranges of particle sizes. The CS variant testing involved a series of consecutive tests including drain-in tests, gel time determination, column injection testing, and saturated hydraulic conductivity testing on grouted BNL soils. The drain-in tests were used to identify CS variants that gel prematurely in the presence of native BNL soil. Gel tests were conducted on all variants by adding an electrolyte solution to determine if gelation occurred and at what electrolyte molarity a reasonable gel time could be expected. Two CS variants failed the gel testing phase and were removed from the test list.

Groups of four sand columns were injected with CS grout from each of the remaining seven variants. The columns were packed with native BNL sand that was dried and re-wetted to duplicate the actual soil moisture conditions (5% by weight) at the BLIP. The sand in each of the columns was packed volumetrically to 90% of the Standard Proctor Test for the BNL soil. The column injection apparatus assembly is shown in Figure 1. Grout was injected into each column until 2.5-pore volumes of grout were collected in each of the overflow containers. The grouted sand columns were visually inspected weekly to determine if the CS grout had strengthened or cured within the columns. The columns were allowed to cure for 28 days before the saturated hydraulic conductivity tests were initiated.

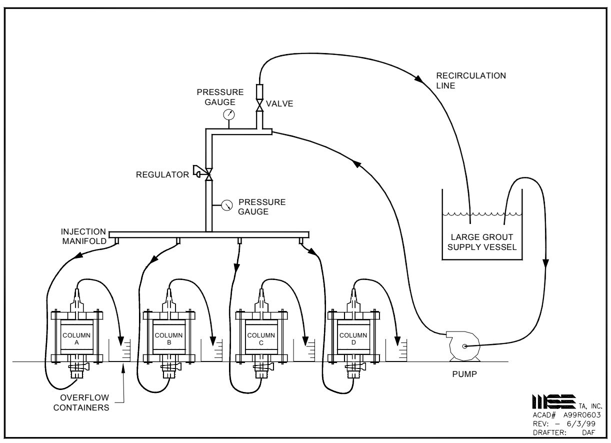


***Figure 1. Schematic of column injection apparatus.***

***Table 1. Geometric mean of hydraulic conductivity results.***

| Grout Sample | Geometric Mean of Hydraulic Conductivity (cm/sec) |
|---|---|
| MSE 1 Summary | 3.26E-05 |
| MSE 2 Summary | 3.21E-06 |
| MSE 3 Summary | 2.29E-06 |
| MSE 4 Summary | 9.71E-06 |
| MSE 5 Summary | 3.29E-05 |
| MSE 6 Summary | 3.20E-07 |
| MSE 7 Summary | 1.03E-04 |

The hydraulic conductivity value for each grouted column sample was determined according to *ASTM D5084--Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*. The tests were performed using *Method C of D5084 (Falling Head--Increasing Tailwater Pressure)*. A summary of the hydraulic conductivity results obtained from flexible wall permeameter testing is shown in Table 1. Tests were performed at low effective stresses to mimic a falling head test apparatus.

After the initial laboratory tests were completed, a CS variant selection matrix was compiled. MSE 6 (Nyacol NP6010 produced by Eka Chemicals) rated the highest and was selected to advance to the next phase of laboratory testing. Additional grout testing was performed using the Nyacol NP6010 CS to provide additional permeability data. The geometric mean of the hydraulic conductivity data set for MSE 6 was $2.9 \times 10^{-7}$ cm/sec.

After selecting the optimum CS variant, larger scale testing was conducted using specially constructed sand tanks. Three-dimensional sand tank testing was conducted to compare the grouting efficiency of two designs; the standard engineering design and a computer optimization-based design provided by

Lawrence Berkeley National Laboratory (LBNL). The standard design specifies a 0.76-meter diameter grout bulb, while the computer optimized design specifies a 1.22-meter diameter grout bulb. A 1.22-meter tall by 1.22-meter diameter round steel tank was used for the injection of the smaller diameter grout bulb, while a 1.5-meter tall by 1.5-meter diameter round steel tank was used for emplacement of the larger diameter grout bulb. The bottom and sides of the tanks were lined with drain material, designed to intercept and direct grout in contact with the tank wall to drainage ports, therefore preventing artificial boundary conditions in the sand tanks. The tanks were then filled with BNL sand conditioned and compacted to simulate subsurface conditions at the BLIP.

Once the tanks were filled with soil, an injection lance was driven into the sand so that the middle of the injection ports was located in the center of each tank. At this point, the tanks were placed into a specially designed load cell and pressure was applied to the load cell plate to simulate subsurface conditions. Approximately 68 liters and 341 liters of CS grout were injected into the 1.22-meter and 1.5-meter diameter tanks, respectively.

Five Guelph permeameter tests were conducted in the 1.22-meter tank while eleven tests were performed in the 1.5-meter tank to measure the saturated hydraulic conductivity of the grouted materials. Results for the 1.22-meter tank indicated that a core of well-grouted sand existed from the center of the tank, approximately 34 cm radially outward, with saturated hydraulic conductivity values ranging from $1.02 \times 10^{-6}$ to $4.70 \times 10^{-8}$ cm/sec. A grout halo existed from 34 to 54 cm, where the grout mixed with the in situ pore water to form a region that was not completely sealed with grout. Results for the 1.5-meter tank found a well-grouted core from the center to 30 cm radially outward, with saturated hydraulic conductivities ranging from $4.80 \times 10^{-7}$ to $8.20 \times 10^{-8}$ cm/sec. From 30 to 64 cm, there was an area with saturated hydraulic conductivities ranging from $1.74 \times 10^{-4}$ to $2.77 \times 10^{-6}$ cm/sec.

Samples of grouted and ungrouted sand were collected from the sand tanks and columns and sent to the Montana State University Soil Testing Laboratory where moisture retention curves were determined for each of the samples. The resulting moisture retention curves were later used in a modeling study to support the installation of the CS barrier at BNL.

Based on these results, both designs achieved a reduction in saturated hydraulic conductivity. The permeameter testing of the large sand tank showed this design created a core approximately 60 cm in diameter with saturated hydraulic conductivities in the desired range. Similarly, the permeameter testing of the small sand tank also demonstrated that the grout bulb had a core volume of reduced saturated hydraulic conductivity. Although the larger computer optimized based design had more pore volumes pass through the core area, it did not appear to significantly lower the saturated hydraulic conductivity of the core area compared to the standard engineering design.

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