BROOKHAVEN LINAC ISOTOPE PRODUCER (BLIP)

CLOSEOUT REPORT
REMOVAL ACTION
AREA OF CONCERN 16K

November 14, 2001

Prepared by:
Environmental Management Directorate and
Environmental Services Division

Environmental Management Directorate

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November 15, 2001

Ms. Gail Penny
EM Team Leader
Environmental Management Division
U. S. Department of Energy
Brookhaven Area Office
Upton, NY 11973

Dear Ms. Penny:

Subject: Final BLIP Closeout Report – Removal Action AOC 16K

Enclosed are 10 copies of the above-mentioned Closeout Report. This report includes a summary of the Removal Action project and its final status, the MSE, Inc. Viscous Liquid Barrier Deployment Completion Report, the September, 2001 Groundwater Status Report, and the October, 2001 Revised Modeling of the BLIP tritium Plume. This submission incorporates DOE comments on the draft report.

If you have any questions please feel free to call Jim Brower at extension 7513 or Drew Bennett at extension 5517.

Sincerely,

L. M. Hill, Director
Environmental Management

JEB:jr

Enclosures

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File: OU II/VII BLIP, AOC 16K

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1.0 Introduction

1.1 Purpose

The purpose of this closeout report is to document removal action activities performed to address radiologically contaminated soil surrounding the Brookhaven LINAC Isotope Producer (BLIP) target area. In accordance with the BLIP Engineering Evaluation/Cost Analysis (EE/CA) (CDM Federal Programs Corporation, 1999) and the BLIP Action Memorandum dated March 2000, the removal action activities consisted of the diversion of building roof runoff, capping the target area which extends beyond the footprint of the building, solidification of activated soils with a viscous liquid barrier and groundwater monitoring.

The scope of the viscous liquid barrier deployment is outlined in detail in the *Colloidal Silica Optimization Test Plan for the Viscous Liquid Barrier Hot Site Demonstration* (MSE, 1999a). The VLB technology was developed at Lawrence Berkeley National Laboratory with funding from the U.S. Department of Energy (EM-50). It uses low-pressure permeation grouting to deliver a colloidal-silica grout to the subsurface. The purpose of the grout injection was to reduce the permeability of the activated soil to minimize leachate generation and impacts to groundwater quality.

1.2 Regulatory Requirements

On December 21, 1989, the Brookhaven National Laboratory (BNL) site was included on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priority List (NPL). In May 1992, the Department of Energy (DOE) entered into an Interagency Agreement (IAG) with the United States Environmental Protection Agency (EPA) and the New York State Department of Environmental Conservation (NYSDEC) under CERCLA, Section 120. The IAG established the framework and schedule for characterizing, assessing and remediating the site in accordance with the requirements of CERCLA, and the Resource Conservation and Recovery Act (RCRA).

BNL originally identified numerous Areas of Concern (AOCs) (BNL Response Strategy Document, SAIC, 1992), of which the BLIP was identified as AOC 16K. The nature and extent of the AOC 16K radiologically contaminated soil have been addressed in the Final Operable Unit II/VII Remedial Investigation Report (IT Corp, February 1999), the BLIP EE/CA (CDM Federal Programs Corporation, 1999) and the Viscous Liquid Barrier Design for the BLIP (MSE, 2000). The BLIP was identified in the Operable Unit II Remedial Investigation Report (IT 1999) as requiring further action.

1.3 Site History

The BLIP is an active accelerator facility, which has been in operation since 1972. The facility is a national resource for producing the radioisotopes that are crucial in nuclear medicine for both research and clinical use. The BLIP also supports BNL research on diagnostic and therapeutic radiopharmaceuticals. The BLIP is located in the northwestern section of the BNL property, near the Linear Accelerator (LINAC) and the Alternating Gradient Synchrotron (AGS) ring (**Figure 1**).

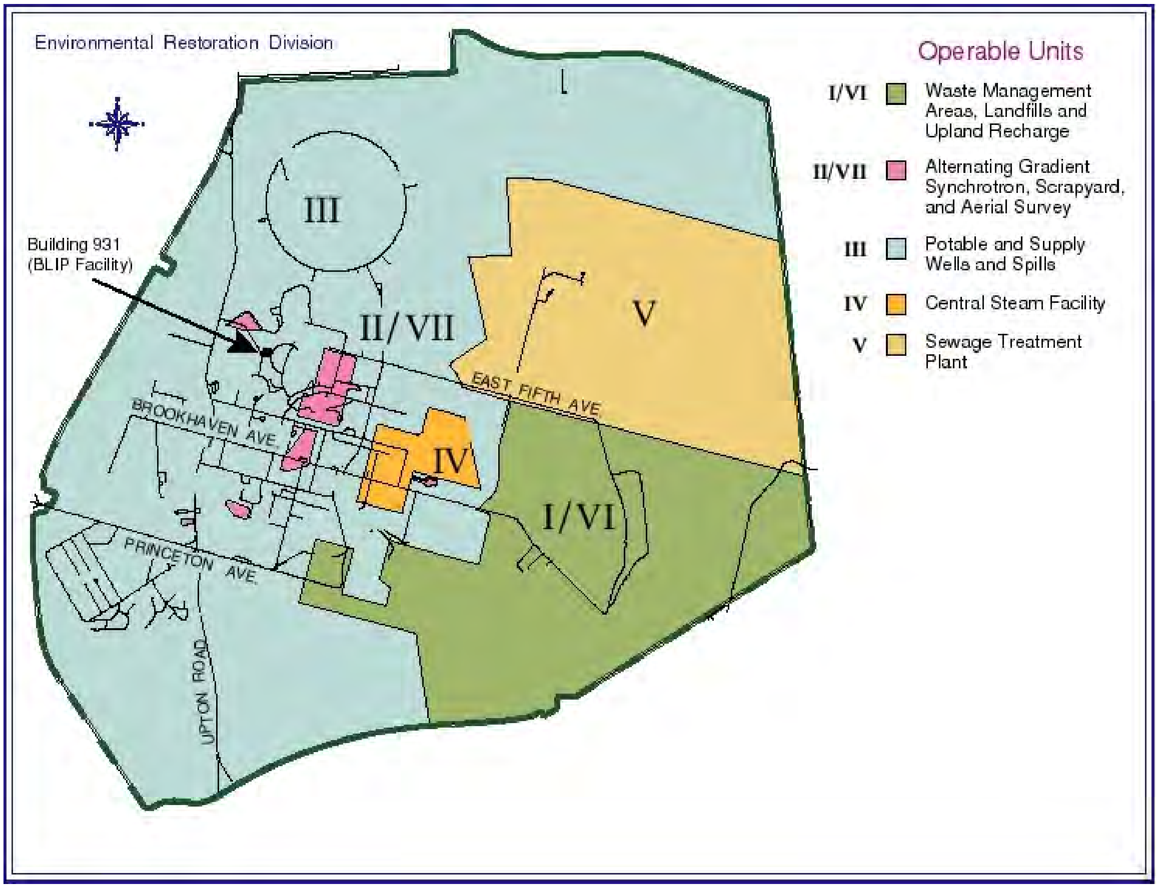


Figure 1. The BLIP facility location at the Brookhaven National Laboratory

The radiological equipment and target handling area for the BLIP are contained in Building 931B. The BLIP is built on an artificial hill that rises to just over 100 feet above mean sea level (MSL) (**Figure 2**). The hill is asymmetrical, with the surrounding land to the north, east and west at 85 to 90 feet and to the south at 70 feet above MSL.

Figure 2. The BLIP facility.

The BLIP targets are located at the bottom of a 30 foot underground tank (**Figure 3**). Within this tank, targets rest inside a water-filled 18-inch diameter shaft that runs the length of the tank. The targets are cooled by a 500 gallon closed loop primary cooling system. During irradiation, several radionuclides are produced in the cooling water (primarily tritium and beryllium-7), and radionuclides are produced in the soils immediately outside of the tank by their interaction with secondary particles produced at the target. Prior to 1985, the BLIP target was equipped with a secondary water system that acted as a beam stop, which absorbed most of these high-energy secondary particles. In 1985, this secondary was system was drained due to concerns of potential leakage of water into the LINAC tunnel in the event of a beam window failure. As a result of removing the water, most of the secondary particles produced in the target area now pass through the air gap between the primary system and the outer wall of the vessel, and are stopped in soils surrounding the BLIP vessel. As part of the 1985 redesign, leak detection devices were installed, and this open space is now used as a secondary containment system for the primary vessel. However, there is no method at present to prevent activation of the soil near the target as a result of contact with the high-energy secondary neutrons generated in the process.

The BLIP facility also includes an underground double-walled storage tank under Building 931C, used for storing wastewater generated by the BLIP while cooling the magnets and targets. This tank is designed in accordance with Suffolk County Sanitary Code Article 12. As part of the BLIP upgrades in 1996, the tank was relocated and reinstalled under the oversight of the Suffolk County Department of Health as tank number 423.

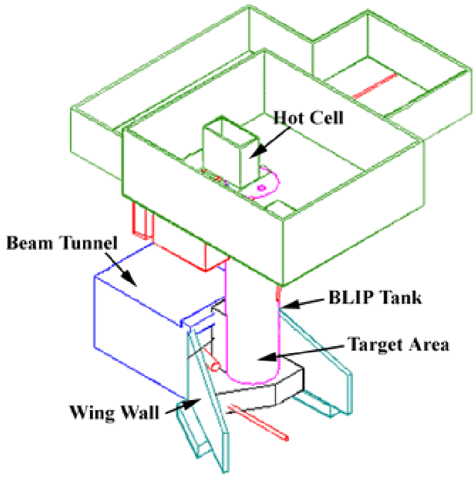


Figure 3. BLIP Beam Tunnel and Target Schematic

Whereas most of the radionuclides produced in the soils near the BLIP target vessel are very short-lived, tritium (half life 12.3 Yrs.) and sodium-22 (half life 2.6 Yrs.) are longer-lived, mobile, and represent a potential for contamination of the groundwater. In February 1988, perceptible losses of cooling water (about four gallons per day) were noted during BLIP operations, resulting in a total loss of 100 to 150 gallons of water. The cooling water had a tritium concentration of approximately 74 μCi/L. In May 1988, the leak was found to have originated at the primary recirculation pump, which is located within a concrete pit in Building 931B. The leak was repaired, the cracks in the concrete were patched and sealed, and the pit was lined with stainless steel. Although some of this water is believed to have subsequently entered the soil through cracks in the concrete, a soil sampling outside the BLIP indicated that concentrations were below the minimum detection limits for the isotopes of concern (principally, beryllium-7 and tritium). There were no monitoring wells downgradient from the BLIP at that time.

Monitoring well 064-02, south of the LINAC and the BLIP and west of the AGS, has been in use since 1993. In February 1998, samples from well 64-02 revealed a tritium concentration of 14,000 pCi/L and a sodium-22 concentration of 43.6 pCi/l, both levels below the drinking water standards (20,000 pCi/l for tritium and 400 pCi/l for sodium-22). Both values represented significant increases from previously measurements (up to 1,400 pCi/l for tritium and up to 27 pCi/l for sodium-22). To confirm the source and extent of the contamination, 13 temporary Geoprobe wells were installed in June 1998. The maximum tritium concentration detected in the Geoprobe wells was 53,000 pCi/L in a well located approximately 40 feet downgradient of the BLIP target. The maximum sodium-22 concentration was also detected in this well at 151 pCi/L. Furthermore, an inspection of the BLIP building revealed that the building's downspouts were not properly connected and that significant rainwater infiltration could occur along the building's foundation. When this water infiltrated the activated soil surrounding the target vessel, tritium and sodium-22 were leached from the soils and transported to the groundwater.

Once the source of the contamination was confirmed, BNL implemented a number of corrective actions to prevent rainwater from entering the soils surrounding the BLIP building. These actions included (1) re-connection and re-routing of the building's downspouts; (2) the sealing of existing pavement south of the building; (3) the placement of a gunnite cap on the western, northern, and eastern sides of the building; and (4) the installation of seven additional groundwater monitoring wells to allow BNL to verify that the storm water controls are effective.[1]

Groundwater monitoring results for 1999 and 2000 revealed a significant reduction in tritium and sodium-22, indicating that these actions were very effective in controlling surface water infiltration into the soils surrounding BLIP. In September 1999, an EE/CA was performed to assess whether other remedial actions were necessary. This analysis recommended that the activated soil zone near the BLIP target be stabilized with colloidal silica grout to provide an additional measure of safety should the capping and stormwater diversion controls fail. The purpose of the grout injection was to reduce the permeability of the activated soil and thereby minimize the potential for leachate generation. In addition, the grout would act to contain future soil activation from this operating scientific facility.

A Viscous Liquid Barrier (VLB) technology was selected and deployed through DOE's Subsurface Contaminants Focus Area (SCFA). The VLB technology was deployed for the first time at BLIP and helped SCFA achieve the first hot deployment of the technology whose development and demonstration the SCFA has supported since 1996. The viscous liquid barrier was installed at BLIP in May/June 2000 by MSE, Inc. Data on the verification of the barrier system were collected in June 2000 and August 2000.

1.4 EE/CA Objectives and Recommendations

The purpose and objectives of the *BLIP Engineering Evaluation/Cost Analysis* (CDM Federal, 1999) was to present a summary of the nature and extent of soil contamination; evaluate applicable technologies for removal of the identified contamination; develop and evaluate removal alternatives; and recommend a removal action alternative. The goal of the selected remedy for the activated soils was to prevent further groundwater contamination from rainwater coming in contact with the activated soils and leaching tritium and sodium-22 into the groundwater.

The alternatives evaluated in the Engineering Evaluation/Cost Analysis Report for the remediation of the activated zone of soil adjacent to the target area of the BLIP included the following:

- No Action with Institutional Controls
- Upgrade of Existing Cover
- Close Proximity Containment Using Cement Grout
- Close Proximity Containment Using Colloidal Silica Grout
- Excavation of Activated Soil Zone and Install Beam Stop

These alternatives were evaluated using appropriate criteria concerning public health and safety protection, effectiveness, feasibility, and cost.

The primary radioisotopes of concern in the soil at the BLIP are tritium and sodium-22. Of the remaining suite of isotopes detected in the soil, beryllium-7, the primary activation product of concern in the cooling water, has a half-life of 53 days. Other isotopes were detected, including

[1] The BLIP Facility, history, characterization and contamination issues were discussed in the *Operable Unit II Remedial Investigation Report* (IT 1999). The RI Report stated that the BLIP Facility remedial actions would be evaluated in an Engineering Evaluation/Cost Analysis (EE/CA).

iron-55 (half-life 2.7 years) and manganese-54 (half-life 312.5 days), but in smaller concentrations. The threat to public health and the environment is from the radioactive contamination in the soil shielding combined with the infiltration of rainwater through these soils, thus releasing radioactive contamination to underlying groundwater.

The recommended alternative was “close proximity containment of the activated soil using an injection of colloidal silica grout.” In addition, maintenance of the gunite cap and monitoring of the groundwater would continue. This action was undertaken as a non-time-critical removal action in accordance with the Interagency Agreement.

1.5 Cleanup Criteria

According to the EE/CA, the removal action objectives were based on the available contaminant data and activation and unsaturated zone modeling results. In general, the scope of the removal action was to reduce the threat of contaminant migration to the groundwater. Specific objectives include:

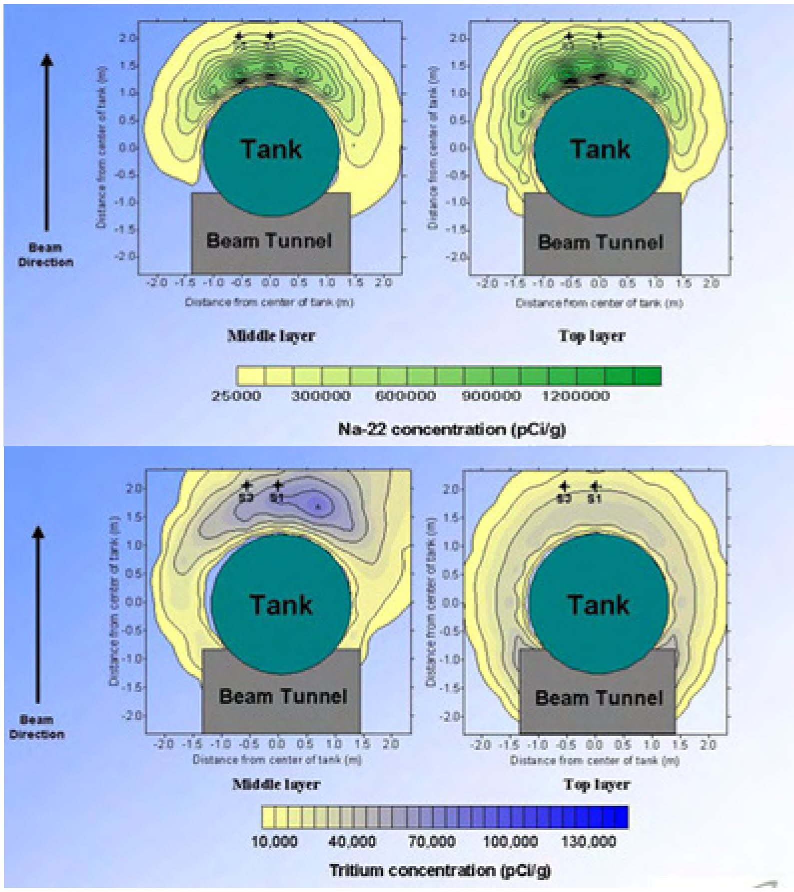
- Minimize threats to human health and the environment from contaminants;
- Minimize migration of contaminants to subsurface soils and groundwater;
- Minimize any future migration from future operations of the facility; and
- Dispose of wastes generated from the removal action (if necessary).

2.0 Remediation Activities

2.1 Field Testing and Modeling

During the EE/CA, BNL conducted numerical modeling of soil activation using Monte Carlo radiation transport codes, to gain a better understanding of the volume and magnitude of contamination resulting from activation of soil surrounding the BLIP target. Modeling efforts identified the major contributors to the activity as tritium, ^{7}Be, ^{22}Na, ^{54}Mn, and ^{55}Fe. These radionuclides account for more than 80% of the inventory.

Modeling also showed the highest concentrations of isotopes to be closest to the target and beam and the soil concentration to be much greater than might be expected from the sampling data taken. The resultant contamination "expected" near the tank is ~700,000 pCi/g. The other isotopes follow similar trends.



The volume of soil that needed to be treated is approximately 85 m^3. This assumes a cylinder two meters thick and three meters high surrounding the BLIP tank. The model projections indicate that this volume contains more than 99.9% of the activated soil inventory.

In order to optimize the grout injection design, it was necessary to characterize the physical properties of the soil at the BLIP site further. The contamination levels in the activation zone were measured during previous characterization efforts by BNL. Due to elevated levels of radioisotopes that pose risk to direct sampling of the activation zone, it was assumed the soil structure just outside the zone is similar; therefore, the samples for the site characterization were collected outside the activation zone. Samples collected during the BLIP site characterization determined parameters that affected the VLB design. The parameters included soil classification, contamination levels, porosity, moisture content, *in situ* permeability, and anisotropy ratios. These soil parameters were obtained by collecting soil samples from 19 geoprobe soil borings

Additional unsaturated zone modeling was conducted by MSE, Inc as part of the design. The modeling was conducted using the computer software PORFLOW to predict the behavior of the soil solidified with colloidal silica (CS). Results of the modeling efforts demonstrated that the silica-solidified sand would successfully perform as a barrier to limit infiltration of atmospheric precipitation. The model predicted the infiltration rate would be reduced to at least 0.0017 m/yr (note: natural groundwater recharge rates at BNL are approximately 0.6 m/yr), thus substantially exceeding the performance objective rate of 0.04 m/yr set by BNL. In addition, the modeling predicted flow paths within and around the solidified region and determined the dynamics of an initial "slug" of pore water that would occur if the gel did not solidify.

As part of the sand tank testing, MSE observed displacement of soil pore water from the injected CS gel. While MSE suspected that displacement might occur, they did not calculate the potential for release of contaminated pore water to the aquifer caused by this type of displacement. Although the potential for displacement of pore water was known by several project participants (e.g., the subcontractor MSE, Inc.), this possibility was not communicated to the DOE area office, BNL site management, or the regulatory agencies. This issue is discussed further in the Lessons Learned section of this report (Section 4.0).

2.2 Colloidal Silica Laboratory Testing

MSE selected nine different CS variants for laboratory testing, based on percent solids, particle size and particle size distribution. Several of the CS variants had a narrow particle size range, while others had a wider range of particle sizes. All of the CS variants were surface modified. Surface modification creates a more stable CS variant when exposed to natural salinity in soils. Column injection tests were conducted to select the CS variant, and sand tank testing was conducted to compare two injection designs with different sized grout bulbs.

A detailed accounting of these activities is presented in the *Final Completion Report: Viscous Liquid Barrier Deployment at Brookhaven National Laboratory* (MSE, 2001), which is found in Attachment A of this closeout report.

2.3 Viscous Liquid Barrier Deployment

The deployment of the barrier occurred in three phases including, barrier emplacement, grout field-testing, and technical system audit of barrier emplacement activities, and as-built documentation. A detailed accounting of these activities is presented in the *Final Completion Report: Viscous Liquid Barrier Deployment at Brookhaven National Laboratory* (MSE, 2001), which is found in Attachment A of this closeout report.

Equipment mobilization on the BNL site began on May 19, 2000. Installation of the barrier began on May 29, 2000 with the installation of GS-1. A total of 20 grout injection locations were utilized. Demobilization began on June 12, 2000.

During the injection process, “milky” water was unexpectedly observed in the LINAC tunnel sump. The fluid was characterized as incompletely gelled CS, which was displaced from soil into the sump area. Approximately 50 gallons of this material had to be collected and disposed of. This was probably an indication that some grout injections were displacing already injected grout prior to gelling. This material was analyzed and found to contain low levels of tritium and sodium-22.

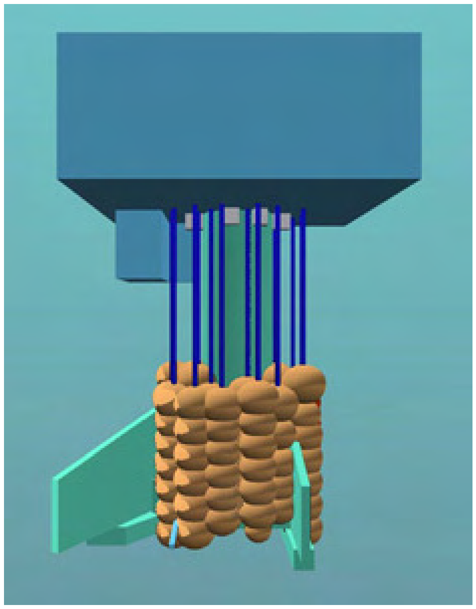


Figure 3. CS Barrier System stabilizing activated soil area.

3.0 Effectiveness Assessment

Several methods were used to assess the performance of the CS barrier system. A schematic diagram of the barrier system in place is shown in **Figure 3**. These include measurements to verify the integrity of the barrier, measurements on a test panel installed in an uncontaminated zone near the barrier and measurements of groundwater quality immediately downgradient of the BLIP facility.

3.1 Barrier Integrity Verification

Prior to the VLB emplacement, three boreholes were installed at an angle beneath the BLIP facility to aid in the barrier integrity verification. Borehole (geophysical) logging was performed prior to the emplacement as a baseline and after emplacement to monitor changes in soil moisture and isotope concentrations. This logging was performed using a suite of geophysical logging tools including electromagnetic (EM) conductivity, neutron-soil moisture, and spectral gamma (including total gamma). The results of this logging generally indicated that the grout had been distributed adequately but were somewhat inconclusive. After the CS injection period, indications of moisture increases, as compared to baseline, below the injection zone were observed in one of the boreholes. This information implies that moisture was moving towards the water table in that region. A porous cup lysimeter was also deployed, but no samples were collected because of suspected damage to the lysimeter during installation.

In situ permeameter testing was conducted on the VLB test panel in August and December 2000. Using geometric means of the field measured hydraulic conductivities; the total outflow/flux from the barrier was calculated as 0.0077m3/yr, 0.12m3/yr, and 0.15 m3/yr, respectively. These results indicate that the test panel, and thus, by inference, the colloidal silica barrier, meets the performance goal of less than 4cm/y flow rate or 0.22 m3/yr of water flux through the barrier.

A detailed accounting of these activities is presented in the *Final Completion Report: Viscous Liquid Barrier Deployment at Brookhaven National Laboratory* (MSE, 2001), which is found in Attachment A of this closeout report.

3.2 Groundwater Monitoring Demonstrating Performance

A groundwater monitoring system is in place downgradient of the BLIP to ensure that operational and engineered controls of the potential sources of groundwater contamination are effective. As noted previously, these controls include the diversion of downspouts for roof runoff, the gunite cap and sealed paved areas, and the stabilization of the activated soils with VLB. Five shallow groundwater monitoring wells are located immediately downgradient of the BLIP target (three wells are 40 feet downgradient separated by approximately 12 feet in the direction perpendicular to groundwater flow and two wells are 150 feet downgradient separated by 40 feet). These wells are sampled quarterly for tritium and sodium-22 as part of BNL Environmental Surveillance program. The groundwater monitoring system was enhanced in 1999 prior to the VLB deployment.

After surface water management controls were in place and prior to grout injection, tritium concentrations in groundwater downgradient of BLIP were less than 2,500 pCi/L. The VLB was installed at BLIP in May/June 2000 by MSE, Inc. In July 2000, the quarterly groundwater monitoring program at BLIP detected a slight increase in tritium concentrations (up to 5,700 pCi/L) but they did not exceed the 20,000 pCi/L drinking water standard. In the next sampling period, October 2000, one of three wells located 40 feet downgradient from the BLIP detected a tritium concentration of 56,000 pCi/L. The other two wells had tritium concentrations that were less than 5,000 pCi/L.

The significant increase in tritium concentrations observed in October 2000 triggered a number of actions at the BNL site, including implementation of BNL's Groundwater Protection Contingency Plan. The groundwater contingency plan is implemented to address off-normal groundwater monitoring data, and includes a series of near and long-term investigative actions. It is a serious step that reflects the BNL stakeholder concerns over protecting the environment. This plan also outlines the formal process of notifying BNL management, DOE, and regulatory and community stakeholders.

Several site inspections and technical meetings were held, including technical assistance from DOE's Subsurface Contaminants Focus Area. The review concluded that the use of the innovative VLB technology likely displaced some soil pore water contaminated with tritium into the groundwater. The magnitude of this displacement was not expected.

The tritium concentrations in the two key groundwater monitoring wells are summarized in **Figure 4**.

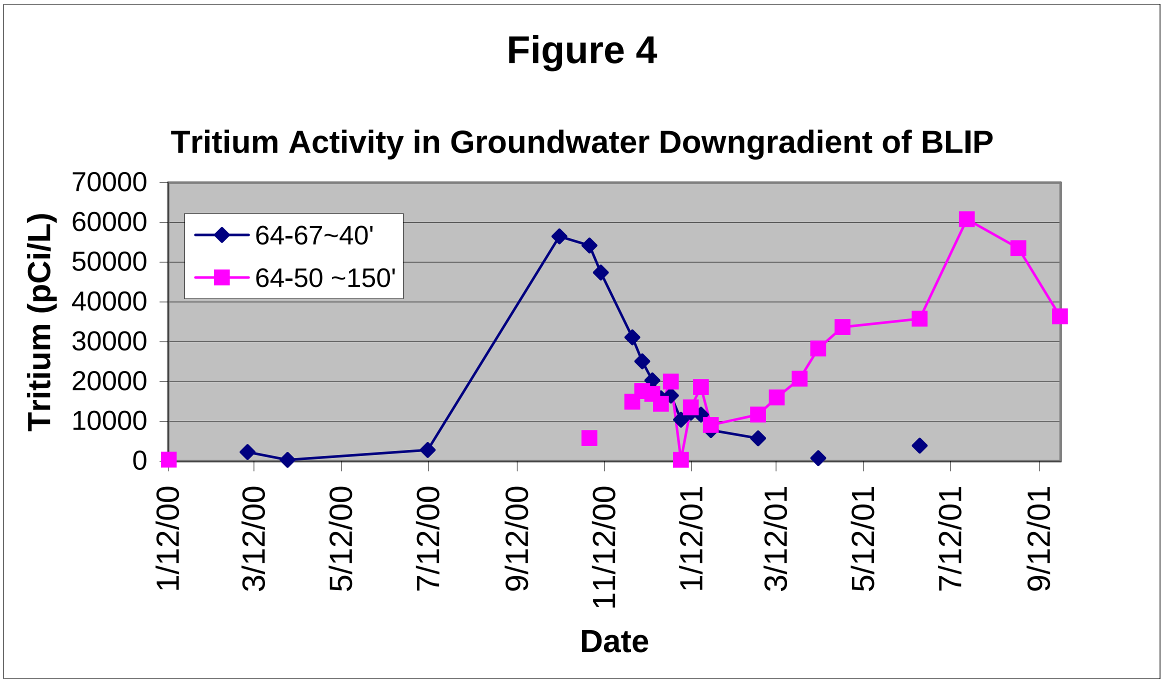


Figure 4: Tritium concentration trends in wells located downgradient of BLIP.

Note 1: Monitoring well 64-67 is located 40 feet downgradient of the BLIP target area. The timing of the October 2000 sampling of that well probably did not measure the peak activity in the plume at that time. The peak activity probably passed through well 64-67 in September 2000. That is the likely explanation for the peak tritium concentrations in monitoring well 64-50 in July 2001, located 150 feet downgradient of the BLIP target, being slightly higher than those measured in well 64-67.

Note 2: The drinking water standard for tritium is 20,000 pCi/L.

These data indicate that the tritium release from the grout injection is expected to be a one-time event and will dissipate relatively quickly in the aquifer. A complete discussion of the groundwater quality data is presented in Appendix B. Analytical groundwater quality model predictions, summarized in Appendix C, also support this conclusion.

In summary, the groundwater monitoring data indicate that stormwater diversions and capping are effective controls. A second control system that prevents water contact with the activated soils is provided with the VLB stabilization. Unfortunately, the VLB injection process did result in a groundwater impact that was promptly managed and is expected to dissipate quickly.

3.3 Displacement of Contaminated Soil Pore Water during CS Injection

As noted previously, the pore water displacement observed in the sand tank testing was an important issue that was not properly addressed in the design of the field deployment of the VLB. Due to the emplacement of an encapsulating barrier that encompassed the contaminated soils (as opposed to a containment barrier that would surround the contaminated soils), the pore water from the contaminated soils was displaced and subsequently migrated to the groundwater. The travel time to the groundwater, and the groundwater velocity were modeled, and the results were consistent with the actual arrival of the contaminants at the downgradient monitoring wells.

3.4 Meeting of Goals

The VLB met the technical remediation goals of significantly reducing the permeability of the activated soil and thus provided an additional control to prevent groundwater contamination in the future. The groundwater monitoring data now indicate that the activated soil area at the BLIP target is now being effectively controlled by the surface drainage improvements and the VLB and is no longer a significant source of groundwater contamination. Because the BLIP remains an active facility, the VLB will also serve to contain future activation products.

The performance of the VLB can be characterized as successful; however, its deployment was not. The displacement of contaminated soil pore water during the CS injection caused an impact to BNL's groundwater resource. This groundwater impact was promptly reported, is being managed, and is expected to dissipate.

Because of the groundwater impact caused by the CS injection, the goal of improving the control of the activated area "without harm to the environment" was not achieved. The objectives of minimizing threats to human health, migration of contaminants to the groundwater, and migration from operations of the facility in the future appear to have been met.

4.0 Lessons Learned

BNL has experienced varied levels of success among its technology deployment projects, including some that have been judged as highly effective and other judged as having been incomplete or having produced unexpected technical results, increased expenditures, and a loss of confidence on the part of the regulators. As a result, DOE's Brookhaven Area Office requested that a lessons learned analysis of these projects be performed. The BLIP VLB deployment was included. The complete findings of this evaluation are found in Attachment D. A summary of the key findings include

Identify a project owner- No central champion or project manager appears to have been identified for planning and executing the VLB deployment. It appears that there were multiple proponents with very different, if not competing, expectations for project success.

Unclear and ambiguous roles and responsibilities appeared to have impacted project direction and decision-making. There was no clearly identifiable owner of the demonstration. There was no clear decision making structure.

Improving a remedial action that is already effective risks the "no-harm" objective - A clear risk-benefit rationale to support the deployment of VLB at BLIP does not exist. The existing controls were already demonstrated to be effective, hence making it very difficult to achieve a "no-harm" objective.

Communication - The findings of the cold demonstration of the VLB installation do not appear to have been taken into account in planning the BLIP beam stop deployment. Apparently the risks of soil water displacement during grout injection were known by the vendor and were also identified by an independent review by the American Society of Mechanical Engineers (ASME). These risks were not communicated to BNL and as a result, were not identified in the EE/CA or Action Memorandum.

It was clear that the problem holders and the technology vendors did not have the same measures of success.

5.0 Stewardship Issues

The integrated remedial actions at the BLIP target area will require maintenance, recording keeping, and monitoring while the facility remains active scientifically and sometime thereafter until the activated soils decay in place to concentrations which can support unrestricted land use.

The stormwater diversions and cap inspection and repair have been included in BNL's Plant Engineering Preventative Maintenance Program. Groundwater monitoring will continue in the immediate vicinity on a quarterly basis in accordance with BNL's Environmental Monitoring Plan. These data will be reported to the facility operator on a routine basis and in the Site Environmental Report annually. The VLB requires no inspection or maintenance.

This removal action for this facility will be documented in the OU V Record of Decision and evaluated in accordance with the 5-Year Review guidance under CERCLA and reported to the IAG members.

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APPENDIX A

MSE Technology Applications

FINAL COMPLETION REPORT: VISCOUS LIQUID BARRIER DEPLOYMENT AT BROOKHAVEN NATIONAL LABORATORY

Western Environmental Technology Office

P.O. Box 4078 Butte, Montana 59702 (406) 494-7100

FINAL COMPLETION REPORT: VISCOUS LIQUID BARRIER DEPLOYMENT AT BROOKHAVEN NATIONAL LABORATORY

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Prepared for:

U.S. Department of Energy
National Energy Technology Laboratory
Pittsburgh, Pennsylvania 15236
Contract No. DE-AC22-96EW96405

May 2001

REVIEWS AND APPROVALS:

Prepared by: ______________________________
Project Engineer

Reviewed by: ______________________________
Project Manager

Approved by: ______________________________
Program Manager

EXECUTIVE SUMMARY

Within the U.S. Department of Energy (DOE) facilities, many waste contaminated areas exist that require interim or long-term containment. The waste requiring containment is mainly mixed waste containing hazardous and radioactive constituents or highly radioactive waste. In some cases, containment allows time for technologies to be developed that can treat the isolated waste or allows the waste to degrade to a level at which the risk to human health and the environment is minimal. Until recently, containment systems used for environmental purposes have been under great scrutiny. However, the need for containment of untreatable or extremely high level radioactive contaminants along with the high cost of treatment alternatives for the waste have outweighed reservations regarding the development and demonstration of containment systems.

The viscous liquid barrier (VLB) technology has the ability to provide containment of waste in the subsurface. Since the emplacement of this containment system uses a low-energy (permeation) implementation method, few contaminants are brought to the surface during grouting, and destruction to fragile infrastructure does not occur. Technology advantages include reduced worker exposure to contaminants at hazardous/radioactive sites, isolation of waste, reduced costs, limited site subsurface disruption, and increased ability to isolate contamination that is in an infrastructural setting.

The VLB technology was selected to be used at the Brookhaven Linear Accelerator (LINAC) Isotope Producer (BLIP) site located at Brookhaven National Laboratory (BNL) on Long Island, New York, to provide in situ containment. This containment would prevent contaminant migration to the groundwater while allowing continued operation of the facility and limiting impacts to the environment. The BLIP facility, considered an accelerator facility, is a national resource for producing radioisotopes, which are crucial to nuclear medicine for both research and clinical use. During operation, a LINAC-generated proton beam impinges a target to produce the required isotopes. High-energy secondary neutrons created in the process pass through the target cooling water and into the surrounding soils. This bombardment of high-energy neutrons on the soil has resulted in the activation of soil and produced several radionuclides including tritium (^{3}H) and sodium-22 (^{22}Na). Elevated levels of both contaminants have been detected in groundwater samples collected from monitoring wells downgradient of the BLIP facility. Although both radioisotopes were found at levels below the drinking water standards, the significant increase in ^{3}H warranted further investigation (Ref. 1). The groundwater contamination is a result of contaminant transport from the activated soil zone via infiltrating water.

Storm water management actions were implemented to decrease the infiltration of water through the activated soil zone; however, the barrier provides supplemental coverage to prevent future contamination of the groundwater. The objective of the BLIP remediation is to remove or stabilize activated soil such that additional contaminants do not reach the aquifer at levels in excess of the drinking water standards (Ref. 1). The overall goal of the project was to construct and verify the performance of a subsurface hydraulic barrier emplaced using a viscous liquid chemical grout material [i.e., colloidal silica (CS)] and downstage permeation grouting methods at the BNL BLIP site.

This project consisted of site characterization, laboratory column and sand tank testing, modeling, the barrier deployment/emplacement, and integrity verification of the emplaced barrier.

The site characterization for the BLIP was conducted first. This determined the areal extent of the contamination along with the soil parameters that were needed for the barrier design. Soil samples were collected and tested and in situ permeability measurements were made. Further details of the site characterization are included in Section 2 of this report.

Column and sand tank testing were performed at the MSE laboratory and are further discussed in Section 3. Using native BNL soils, column tests were conducted to determine which of the CS variants would best reduce the saturated hydraulic conductivity of the soils. Once the initial laboratory tests were completed, a selection matrix was compiled to compare the variants. The CS that scored highest was selected to advance to the next phase of testing. In this second phase of testing, two sand tanks filled with BNL soils were injected with the CS grout under simulated subsurface conditions, permeameter testing was performed on the grouted soils, samples were collected, and the tanks were excavated to determine the extent of the grouted areas. The information obtained during this testing was used to aid in the development of the barrier design. Samples from the columns and the tanks were sent to an independent laboratory to determine the moisture retention curves to be used in subsequent computer modeling.

Section 4 of this report discusses the computer modeling that was performed to predict the behavior of the soil solidified with CS. The simulation was conducted using the moisture retention curves developed from the previous column and sand tank samples. Results of the unsaturated flow simulation demonstrate that the CS barrier would successfully limit the infiltration of precipitation and thus mitigate the contaminant migration to the groundwater. In addition, modeling was performed to simulate the "slug" of pore water that would be displaced from the contaminated soil by the injected CS grout. It was predicted that the displaced, contaminated pore water would reach the water table within 10 to 25 days.

The barrier emplacement in the spring of 2000 is detailed in Section 5, along with information on the construction quality control/quality assurance and the as-builting of the completed VLB. A VLB test panel was emplaced prior to and in close proximity to the actual VLB in order to test and refine equipment and procedures and to provide a barrier that could be tested without compromising the integrity of the actual barrier. For ease of testing, the test panel was emplaced using the same design (i.e., grout bulb size and injection interval) but at a shallower depth than the VLB. Grout quality was monitored throughout the emplacement, and deviation surveys were conducted for each grout string to ensure complete grouting of the barrier. Computer as-built representations were developed at the completion of each grout string so the design could be altered if necessary by modifying the size or location of the ensuing grout bulb strings.

Several methods of verification were used to test the integrity of the VLB test panel; these methods are discussed in Section 6 of this report. Two boreholes that were installed alongside and terminated beneath the BLIP tank were used to collect geophysical logging data including soil moisture and isotope concentrations. The measurements collected post emplacement were compared to the baseline measurements. Changes were detected in the formation that correspond to the zone in which the VLB was installed, and an increase in moisture was measured that was likely due to the pore water (with some amount of gamma-emitting isotopes) being displaced out toward the geophysical boreholes. In addition, in situ permeameter testing was conducted on the test panel to measure the saturated hydraulic conductivity, which could then be used in the modeling determination of the resulting flux through the barrier. Permeameter testing of the test panel resulted in a mean saturated hydraulic conductivity value of $\sim 7.5\times10^{-5}$ centimeters per second (cm/sec). The saturated hydraulic conductivity values, along with the soil moisture retention curves previously discussed, were used to simulate the flux through the barrier. The results from the modeling indicate that although the saturated hydraulic conductivity may only have been decreased by two orders of magnitude, the goal set by BNL to reduce the flux through the barrier from 30 centimeters per year (cm/yr) to 4 cm/yr would be met.

While the objective of reducing the flux through the contaminated soils at the BLIP is being met, there was an exception. Contaminated pore water migrated to the groundwater and was detected at downgradient monitoring wells at levels in excess of the drinking water standards (DWS); however, the levels have since fallen below the DWS. This event is a one-time occurrence that was anticipated and predicted by the modeling of the pore water displaced during the VLB emplacement (as previously discussed). The two actions, VLB containment and gunnite cap, are working together to prevent the leaching of ^{3}H and ^{22}Na from the activated soils surrounding the BLIP target area into the groundwater while allowing continued operation of the BLIP facility.

The Comprehensive Environmental Response, Compensation, and Liability Act removal action goal of keeping the groundwater contamination levels below the drinking water standards is being met. The VLB and cap remedial actions are consistent with the future use of BNL and are steps toward the overall remediation goals of the site.

ACKNOWLEDGEMENTS

The Viscous Liquid Barrier Deployment was funded by the DOE Office of Science and Technology. BNL was the host for the deployment of this innovative containment technology. DOE's Brookhaven Area office successfully obtained regulator approval for the remediation project, as well as funded the site management activities. BNL's Environmental and Waste Technology Center coordinated the site logistical support, completed all permitting, and managed the radiological testing. As the VLB technology developer, Lawrence Berkeley National Laboratory provided a review of the final barrier design and evaluation of the field emplacement activities and procedures.

MSE Technology Applications, Inc., thanks each of the team members for their valuable contributions. Without these contributions, this project could not have been completed.

A special thanks to John Heiser of BNL who made a substantial effort throughout the VLB deployment project.

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TABLES

ACRONYM LIST

2-D	two-dimensional
3-D	three-dimensional
^{3}H	tritium
^{22}Na	sodium-22
^{55}Fe	iron-55
AGS	Alternating Gradient Synchrotron
ASTM	American Society for Testing and Materials
AOC	Area or Concern
^{7}Be	beryllium-7
bfl	below floor level
bgs	below ground surface
BLIP	Brookhaven Linear Accelerator Isotope Producer
BNL	Brookhaven National Laboratory
$CaCl_2$	calcium chloride
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COBD	Computer Optimization-Based Design
cm	centimeter
cP	centipoise
CS	colloidal silica
CT	computer tomography
DOE	U.S. Department of Energy
dpm	per minute disintegrations
EE/CA	Engineering Evaluation/Cost Analysis
EM	electromagnetic
EPA	U.S. Environmental Protection Agency
ERT	electrical resistivity tomography
ftbgs	feet below ground surface
gpm	gallon(s) per minute
HASP	Health and Safety Plan
ID	inside diameter
L	liter
LAS	large area smears
LBNL	Lawrence Berkeley National Laboratory
LINAC	linear accelerator
m	meters
M	molar
MSE	MSE Technology Applications, Inc.
MSU	Montana State University
NTSDWS	New York Safe Drinking Water Standards
OD	outside diameter
pcf	pounds per cubic foot
P	matric potential
pCi	picoCuries
psi	pounds per square inch
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control

ACRONYM LIST (CONT'D)

RCA	radiological controlled area or a rad zone
RCT	Radiological Control Technician
RWP	Radiological Work Permit
RWT	Radiological Work Technician
SED	Standard Engineering Design
SP-SM	sand with silt or gravel
SW-SM	well-graded sand with silt or gravel
VLB	viscous liquid barrier
yr	year

1. INTRODUCTION

1.1 PROJECT BACKGROUND

Within the U.S. Department of Energy (DOE) facilities, many radiological contaminated areas exist that require some type of interim or long-term containment. Generally, the contamination requiring containment is mixed waste containing hazardous and radioactive constituents or highly radioactive waste. In some cases, containment allows time for technologies to be developed that can treat the isolated waste or allows the waste to degrade to a level to which the risk to human health and the environment is minimized.

Until recently, containment systems used for environmental purposes have been under great scrutiny. However, the need for containment of untreatable or extremely high level radioactive contaminants along with the high cost of treatment alternatives for the waste have outweighed reservations regarding the development and demonstration of containment systems.

The Brookhaven Linear Accelerator (LINAC) Isotope Producer (BLIP) site, located at Brookhaven National Laboratory (BNL) on Long Island, New York, is where the application of an in situ containment can alleviate the contaminant migration while limiting the impact to the facility and the environment. The BLIP is located in the northwestern section of the BNL property, near the LINAC and the Alternating Gradient Synchrotron (AGS) ring. This facility, considered an accelerator facility, is a national resource for producing radioisotopes, which are crucial to nuclear medicine for both research and clinical use. During operation, a LINAC-generated proton beam impinges a target (typically salts encapsulated in stainless steel) to produce the required isotopes. High-energy secondary neutrons created in the process pass through the target cooling water and into the surrounding soils. This bombardment of high-energy neutrons on the soil has resulted in the activation of soil and produced several radionuclides including tritium (^{3}H) and sodium-22 (^{22}Na). Both contaminants have been detected in groundwater samples collected from monitoring wells downgradient of the BLIP facility. Since 1993, a monitoring well south of the LINAC and BLIP indicated concentrations of ^{3}H up to 1,450 picoCuries/liter (pCi/L), and ^{22}Na up to 27 pCi/L. On February 9, 1998, elevated levels of ^{3}H (14,000 pCi/L) and ^{22}Na (43.6 pCi/L) were found. Although both radioisotopes were found at levels below the drinking water standards of 20,000 pCi/L for ^{3}H and 400 pCi/L for ^{22}Na, the significant increase in ^{3}H warranted further investigation (Ref. 1). The groundwater contamination is a result of contaminant transport from the activated soil zone via infiltrating water. Storm water management actions have been taken to decrease the infiltration of water through the activated soil zone; however, the barrier provides supplemental coverage to prevent future contamination of the groundwater.

The BLIP is a division of Area of Concern (AOC) 16: Aerial Radioactive Monitoring System Results, and has been designated as subAOC 16K in the BNL Response Strategy Document (Ref. 1). The BLIP has been identified in the Operable Unit II/VII Remedial Investigation Report as requiring further action. Per the March 10, 2000, Action Memorandum, the removal action is part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process for environmental restoration. The nontime-critical removal action involves the installation of colloidal silica grout barrier, the maintenance of the existing cap, and continued groundwater monitoring. The action will be accomplished in accordance with the Interagency Agreement between DOE, the U.S. Environmental Protection Agency (EPA), and the New York State Department of Environmental Conservation.

The objective of the remediation of the BLIP is to remove or stabilize activated soil such that contaminants do not reach the aquifer at levels in excess of the drinking water standards (Ref. 1).

Several options were presented in the BLIP Engineering Evaluation/Cost Analysis (EE/CA) ranging from removal of the activated soils to in situ encapsulation of the activated soils to prevent activation products from migrating to the groundwater. Removal of activated soils would require partial demolition and loss of service to the BLIP facility. Conversely, in situ containment will prevent the leaching of ^{3}H and ^{22}Na from the activated soils surrounding the BLIP target area into the groundwater while allowing continued operation of the BLIP facility. In situ containment provides additional benefits. The technology will allow time for development of new technologies that can treat the isolated activated soils and will allow time for radioactive material to degrade to an acceptable level of risk (during the removal of contaminated soil) to human health and the environment.

Construction of a viscous liquid barrier (VLB) to encapsulate the activated soils at the BLIP facility was selected as the preferred alternative, as outlined in the BLIP EE/CA (Ref. 1). The overall goal of the VLB project was to construct and verify the performance of a subsurface hydraulic barrier emplaced using a viscous liquid chemical grout material [i.e. colloidal silica (CS)] and downstage permeation grouting methods at the BNL BLIP site.

1.2 TECHNOLOGY DESCRIPTION

The VLB technology has the ability to provide either long-term or interim containment of waste in the unsaturated soil zones. Since the emplacement of the VLB uses a low-energy delivery system, few contaminants are brought to the surface during grouting, and destruction to fragile infrastructure does not occur. The CS grout is chemically and biologically benign and permeates the soil matrix, displaces the pore water, and seals the pore voids. The barrier fluid containment performance is controlled by the grout gel time, CS colloid particle size, CS solids content, and VLB injection spacing.

Benefits of the VLB technology include those listed below.

- Reduced worker exposure at hazardous/radioactive sites.

- Interim or long-term isolation of waste.

- The ability to contain waste material in situ, decreasing the mobility of waste through the unsaturated soils and preventing the waste from entering the groundwater.

- Cost-effective technology.

- The viscous liquid is compatible with multiple wasteforms (i.e., radioactive waste, organics, and inorganics) and is not degraded biologically or chemically, resulting in a long-term containment system.

- The viscous liquid containment system can be emplaced around areas of a sensitive nature (i.e., around piping, under storage tanks and infrastructure) for source control purposes because the low-energy emplacement method allows nondestructive emplacement, limiting surface disruption.

1.3 VISCOUS LIQUID BARRIER DEPLOYMENT OBJECTIVE

The overall objective of the VLB technology deployment is to emplace the VLB to reduce the contaminant flux originating at the activated zone below the BLIP to the groundwater. The primary driving mechanism for the contaminant flux is water moving through the soils, carrying the isotopes downward to the water table. The objective of the VLB emplacement is to cause a reduction in the rate at which water moves through the soils, thereby reducing the amount of contaminants transported to the water table.

This report contains the following sections:

- Site Characterization;
- Laboratory Testing;
- Modeling;
- Field Preparations and Emplacement;
- Barrier Integrity Verification; and
- Results and Conclusions.

The major threat to the environment is the contamination of groundwater because:

- the groundwater beneath BNL is designated as a sole source aquifer under the Safe Drinking Water Act;
- it is classified as a source of potable drinking water; and
- it is the primary source of drinking water in the area.

The goal of keeping the groundwater contamination levels below the drinking water standards should be met. The remedial actions, maintenance of the gunnite cap, and emplacement of the VLB, are consistent with the future use of BNL and are steps toward the overall remediation goals of the site. The VLB alternative objective of reducing the flux through the contaminated zone should:

- reduce the contaminant migration to the groundwater;
- protect human health and the environment; and
- be technically feasible and cost effective.

2. BROOKHAVEN LINAC ISOTOPE PRODUCER SITE CHARACTERIZATION

To optimize the grout injection, it was necessary to characterize the soil at the BLIP site. Samples collected during the BLIP site characterization determined parameters that affected the VLB design. The contamination levels in the activation zone were measured during previous characterization efforts by BNL.

Soil parameters obtained during the BLIP site characterization were used for the VLB design.

Due to elevated levels of radioisotopes that pose risk to direct sampling of the activation zone, it was assumed the soil properties just outside of the zone are similar; therefore, the samples for the site characterization were collected outside the activation zone. The parameters included soil classification, contamination levels, porosity, moisture content, in situ permeability, and anisotropy ratios. These soil parameters were obtained by collecting and testing samples from a series of boreholes located both inside and outside of the BLIP facility (Figure 2-1).

2.1 SOIL PROPERTIES

Generally the soil under the BLIP facility is classified (Unified Soil Classification System) as poorly graded sand with silt or gravel (SP-SM) or well-graded sand with silt or gravel (SW-SM). The BLIP soil consists of fine-to medium-grained angular sand with approximately 90% to 95% quartz; several percent feldspar; and trace amounts of biotite, hornblende, and garnet. A Standard Proctor test indicates the soil's maximum dry density is 121.0 pounds per cubic foot (pcf).

2.2 BROOKHAVEN LINEAR ISOTOPE PLANT CONTAMINATION LEVELS

To identify the contamination under the BLIP, soil samples were collected by BNL in September 1998 from boreholes S1, S2, S3, and S4. Analytical data (Table 2-1) from these boreholes indicate that S1 and S3 are located within the activation zone and S2 is located near the perimeter of the activation zone. Sample S4 is outside the activation zone. In April 1999, boreholes S5 and S6 were sampled to better define the activation zone perimeter and validate BNL subsurface activation models. Data from S5 and S6 indicate they were located near the edge of the activation zone, which validates BNL modeling results.

Five radionuclides (beryllium-7 (^{7}Be), carbon-14, ^{22}Na, iron-55 (^{55}Fe), and ^{3}H) found within the activated soil represent 80% of the inventory and span the range of half-lives of all detected radionuclides. The half-lives are 53 days for ^{7}Be, 5,730 years for carbon 14, 2.6 years for ^{22}Na, 2.7 years for ^{55}Fe, and 12.3 years for ^{3}H. The greatest concentration of the radionuclides occurs from 26 to 30 feet below the floor surface, near the BLIP tank.

2.3 POROSITY AND MOISTURE CONTENT

Porosity and moisture content of the BLIP soil were determined by testing samples collected from boreholes SC1, SC2, and SC3. Soil samples (Figure 2-2) were collected in 4-foot intervals from 15 to 35 feet below ground surface (bgs) using a Geoprobe® tooled with a Macro-Core soil sampler. Figure 2-3 shows the collection of a sample using the Geoprobe.

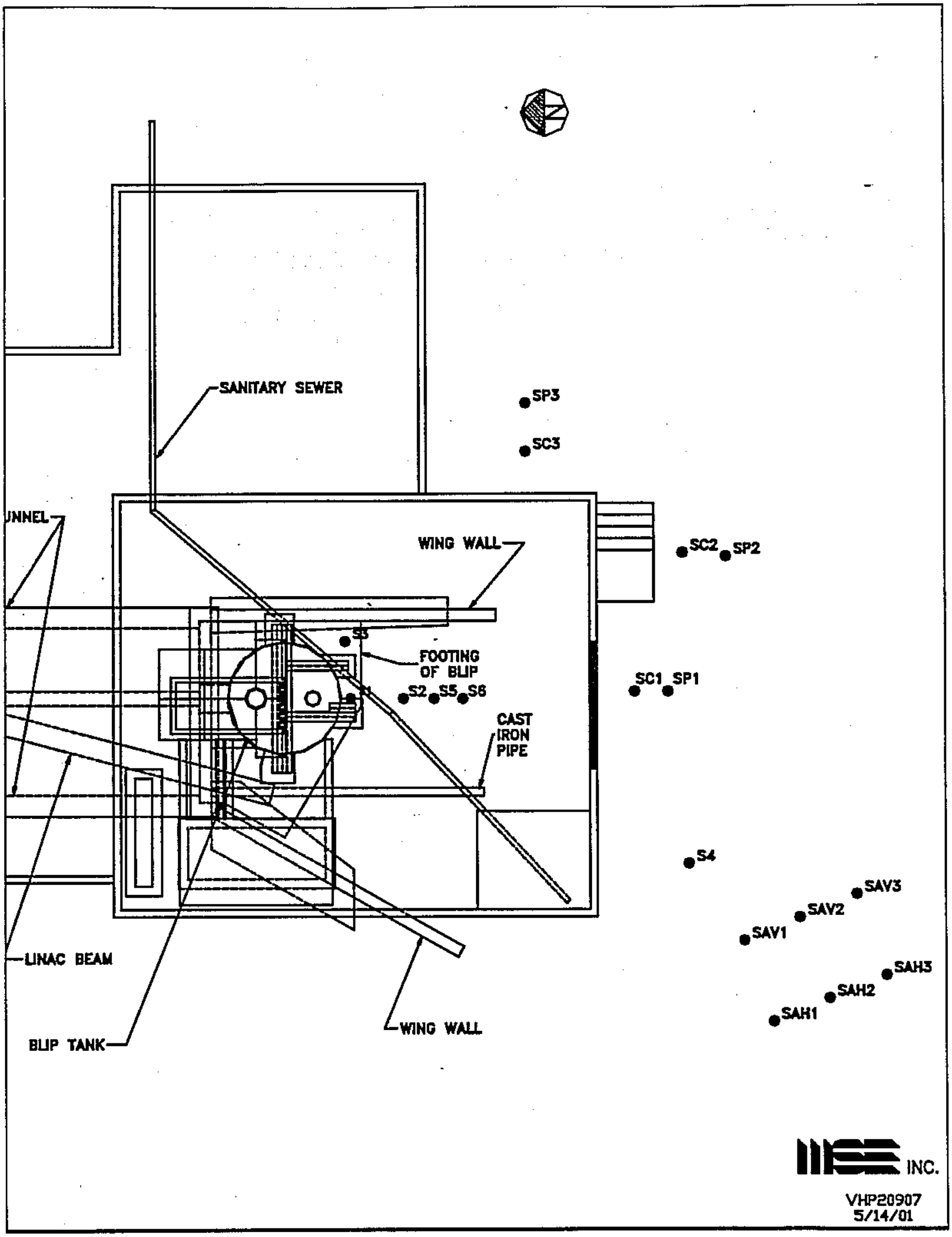

Figure 2-1. BLIP site characterization borehole locations.

Table 2-1. BLIP contaminants.

Sample Number	Contaminant	Sample Concentration (pCi/gram) at Specific Depth in Feet				
		4-8 ft	18-20 ft	24-26 ft	26-28 ft	28-30 ft
S1	^{7}Be	NA	NA	506	19,600	73,200
	^{22}NA	NA	NA	U	11,100	42,600
	^{55}Fe	NA	NA	U	4060	5900
	^{3}H	NA	NA	46	1550	4020
	Carbon-14	NA	NA	U	2.87	4.53
S2	^{7}Be	NA	21.1	884	1600	1920
	^{22}Na	NA	13.4	612	335	U
	^{55}Fe	NA	U	U	U	U
	^{3}H	NA	2.96	61.0	116	214
	Carbon-14	NA	U	0.34	0.55	U
S3	^{7}Be	NA	NA	5070	27,200	31,000
	^{22}Na	NA	NA	3280	18,100	19,700
	^{55}Fe	NA	NA	1440	3830	8040
	^{3}H	NA	NA	409	1620	3830
	Carbon-14	NA	NA	0.72	2.53	5.64
S4	^{7}Be	U	NA	NA	U	NA
	^{22}Na	U	NA	NA	U	NA
	^{55}Fe	U	NA	NA	U	NA
	^{3}H	U	NA	NA	U	NA
	Carbon-14	0.37	NA	NA	U	NA
Sample Number	**Contaminant**	**Sample Concentration (pCi/gram) at Depth in Feet**				
		22 -24	24-26	26 –28	28 –30	30 -32
S5	^{7}Be	25.51	46.66	87.72	87.27	55.17
	^{22}Na	82.76	159.4	285.9	286.3	195.2
	^{55}Fe	NA	NA	NA	NA	NA
	^{3}H	5.33	15.58	22.88	64.90	52.00
	Carbon-14	NA	NA	NA	NA	NA
Sample Number	**Contaminant**	**Sample Concentration (pCi/gram) at Depth in Feet**				
		22 -24	24-26	26 –28	28 –30	33 - 35
S6	^{7}Be	-0.04	7.72	19.73	10.92	5.48
	^{22}Na	0.08	25.58	66.02	34.76	17.44
	^{55}Fe	NA	NA	NA	NA	NA
	^{3}H	3.42	6.39	4.39	17.36	20.61
	Carbon-14	NA	NA	NA	NA	NA

Soil porosity, expressed as a percentage, was calculated by comparing the dry bulk density to the particle density of the soil. The following equation was used:

$$\eta = 100[(D_p - D_b)/D_p]$$

where, η = %porosity, D_p = particle density, and D_b = dry bulk density.

The porosity of the samples varied from 28.6% to 33.0% and averaged 30.8%. The moisture content ranged from 3.5% to 11% and averaged 5.7% by weight (Table 2-2).

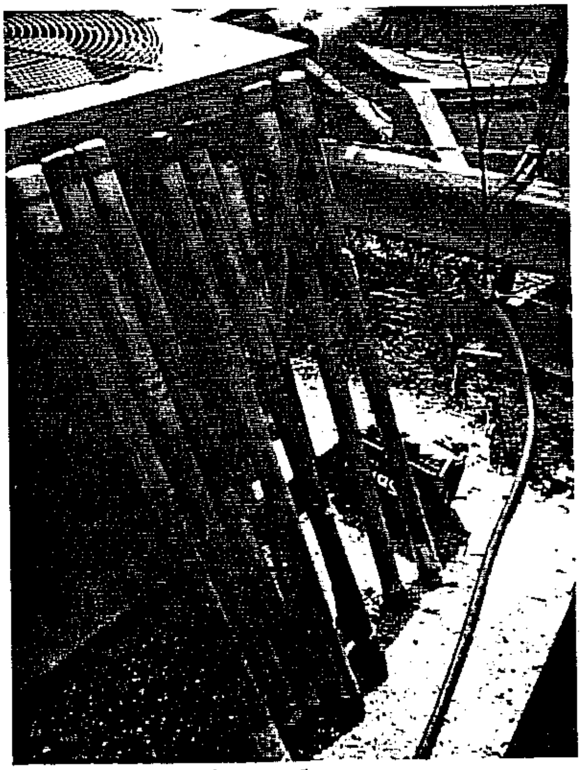

Figure 2-2. Soil samples.

Figure 2-3. Sample collection with Geoprobe.

Table 2-2. BLIP soil properties.

Sample Location & Interval	Soil Properties					
ft-bgl	% Moisture	Wet Unit Weight, pcf	Dry Unit Weight, pcf	Specific Gravity	Particle Density, pcf	% Porosity
SC1						
15 – 19	5.8	121.6	114.9	2.66	166.1	30.8
19 – 23	3.5	118.7	114.7	2.66	166.1	30.9
23 – 27	5.0	117.9	112.3	2.67	166.7	32.6
27 – 31	5.4	119.5	113.4	2.66	166.1	31.7
31 – 35	5.4	119.5	113.3	2.63	164.2	31.0
SC2						
15 – 19	5.5	124.6	118.1	2.66	166.1	28.9
19 – 23	5.6	123.9	117.3	2.66	166.1	29.4
23 – 27*	5.2	113.7	108.0	2.66	166.1	35.0
27 – 31	11	131.2	118.2	2.65	165.4	28.6
31 – 35	5.4	117.2	111.3	2.66	166.1	33.0
SC3						
15 – 19	5.0	122.9	117.0	2.64	164.8	29.0
19 – 23*	5.8	114.5	108.2	2.67	166.7	35.1
23 – 27*	6.2	113.9	107.2	2.65	165.4	35.2
27 – 31	4.6	117.9	112.7	2.66	166.1	32.1
31 – 35	5.7	120.1	113.6	2.65	165.4	31.3
Average	5.7	121.3	114.7	2.66	165.8	30.8

* Full sample not collected. These numbers are not used in the average calculation.

2.4 IN SITU PERMEABILITY

The in situ permeability of the subsurface was determined using Guelph permeameters. The tests were conducted in boreholes SP1, SP2, and SP3. Figure 2-4 shows a permeameter test in progress. The boreholes were drilled to 15 feet bgs, the in situ permeability was measured at that depth, and then the holes were drilled to 25 feet bgs, and the tests were repeated. Table 2-3 summarizes the in situ permeability measurements.

Measurements at 25 feet bgs in boreholes SP2 and SP3 were inconclusive due to the hole sloughing in and erratic water flows. Using only the four conclusive test results, the geometric mean of the BLIP in situ permeability is 1.8×10^{-3} centimeters per second (cm/sec). This value is consistent with the permeability of silty sand.

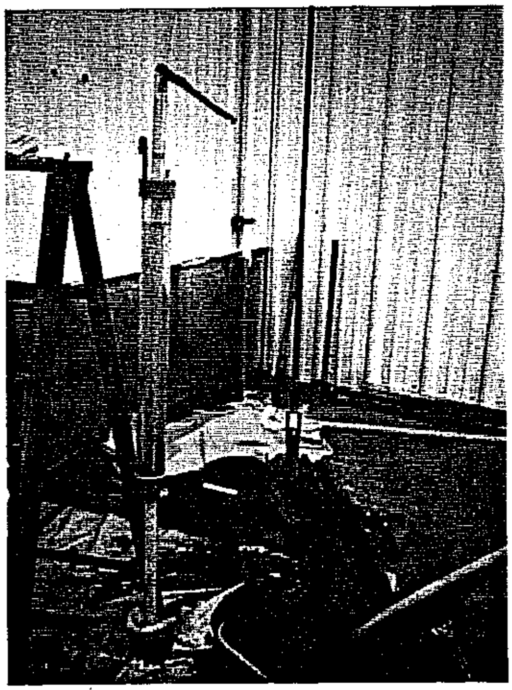

Figure 2-4. Guelph permeameter.

Table 2-3. Guelph permeameter measurements.

Depth	SP 1	SP 2	SP 3
15 feet bgs	5.2×10^{-3} cm/sec	2.4×10^{-3} cm/sec	8.5×10^{-4} cm/sec
25 feet bgs	1.0×10^{-3} cm/sec	Inconclusive - hole sloughed in	inconclusive - erratic water flows

2.5 ANISOTROPY

Anisotropy of the BLIP soil was determined by driving 2-foot Shelby tubes both vertically and horizontally (Figure 2-5) to collect vertical (SAV1, SAV2, and SAV3) and horizontal (SAH1, SAH2, and SAH3) samples.

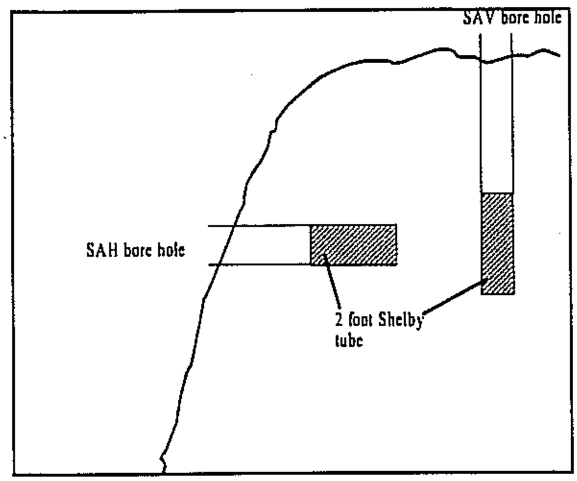

Figure 2-5. Anisotropy sample arrangement.

The permeability of the vertical and horizontal samples was measured via a constant head permeability test, and the anisotropic ratios were calculated using the permeability values as shown in Table 2-4. The calculated anisotropic ratio for the BLIP soil is 0.59 (vertical vs. horizontal). The Army Corp of Engineers Soil Mechanics Information Analysis Center indicated that an anisotropic ratio of 0.5 to 1.0 can be expected in construction fill material made of clayey sand to sandy gravel, which is consistent with the results from the BLIP site characterization.

Table 2-4. Anisotropic ratio permeabilities.

Location	Permeability	Average Permeability
SAH 1	2.20×10^{-2} cm/sec	Average Horizontal Permeability = 2.99×10^{-2} cm/sec
SAH 2	2.47×10^{-2} cm/sec	
SAH 3	4.94×10^{-2} cm/sec	
SAV 1	4.99×10^{-2} cm/sec	Average Vertical Permeability = 1.76×10^{-2} cm/sec
SAV 2	4.35×10^{-3} cm/sec	
SAV 3	2.50×10^{-2} cm/sec	
Ratio of vertical vs. horizontal permeability = 0.59		

2.6 SUMMARY OF SITE CHARACTERIZATION

The BLIP site ch2aracterization was successful in determining soil parameters that were crucial for the VLB design. The soil parameters were determined with samples obtained from the uncontaminated zone. The maximum dry density was approximately 121.0 pcf, while porosity averaged 30.8%, and the average moisture content was 5.7% by weight. The geometric mean of the in situ permeability of the samples was 1.8×10^{-3} cm/sec. Contaminated samples collected from the activation zone validated results from the BNL model, which was used to determine the areal extent and the levels of the contamination.

The primary contaminants of concern are ^{22}Na and ^{3}H because the other radionuclides are either short lived or do not migrate to the groundwater.

3. COLLOIDAL SILICA LABORATORY TESTING

This section focuses on the testing performed to support the selection of the CS variant that best reduced the saturated hydraulic conductivity of the native BNL sands in the laboratory. Column injection tests were conducted to select the CS variant, and sand tank testing was conducted to compare two injection designs with different sized grout bulbs.

Nyacol NP6060 was selected from a field of nine CS variants.

3.1 COLLOIDAL SILICA VARIANT TESTING

MSE selected nine different CS variants for laboratory testing, based on percent solids, particle size, and particle size distribution. Several of the CS variants had a narrow particle size range, while others had a wider range of particle sizes. All of the CS variants were surface modified. Surface modification creates a more stable CS variant when exposed to natural salinity in soils.

To provide unbiased results during the initial testing phase, the CS variants were labeled MSE 1 through MSE 9. The CS variant testing involved a series of consecutive tests. The goal of this testing was to identify the CS grout that achieved the highest reduction of hydraulic conductivity in the BNL soils. The following laboratory tests provided a systematic method for determining the best CS variant to use in the unconsolidated BLIP sands. The selected variant was then used for further laboratory testing. The CS variant tests included:

- CS variant drain-in tests;
- CS grout gel time determination;
- CS grout column injection;
- CS grout cure time observations; and
- CS grout hydraulic conductivity testing.

3.1.1 Colloidal Silica Variant Drain-In Tests

The drain-in tests were used to identify CS variants that gel prematurely in the presence of native BNL soil. In this test, BNL BLIP soil was packed into vertical columns, each of the CS variants (without electrolyte solution) was poured on the top of the sand columns, and the volume that flowed through the sand column was collected and measured. If it did not prematurely gel, the majority of the volume would flow through the sand column. Results from the tests performed on the nine CS variants are shown in Figure 3-1. For all the samples tested, most of the CS variant flowed through the sand columns; therefore, all of the variants passed the drain-in test.

3.1.2 Colloidal Silica Grout Gel Time Determination

The CS variants were made to gel by adding one part by volume electrolyte solution to five parts of each of the CS variants. A 90-minute State 2 gel time (± 20%) was determined by viscometer and jar tests for each of the CS variants. State 2 gel time viscometer readings correspond to a viscosity between 10 and 12 cP. State 2 gel time is defined as a highly flowing gel that appears to be only slightly more viscous than the initial polymer solution. This gives the lab team 90 minutes to inject the

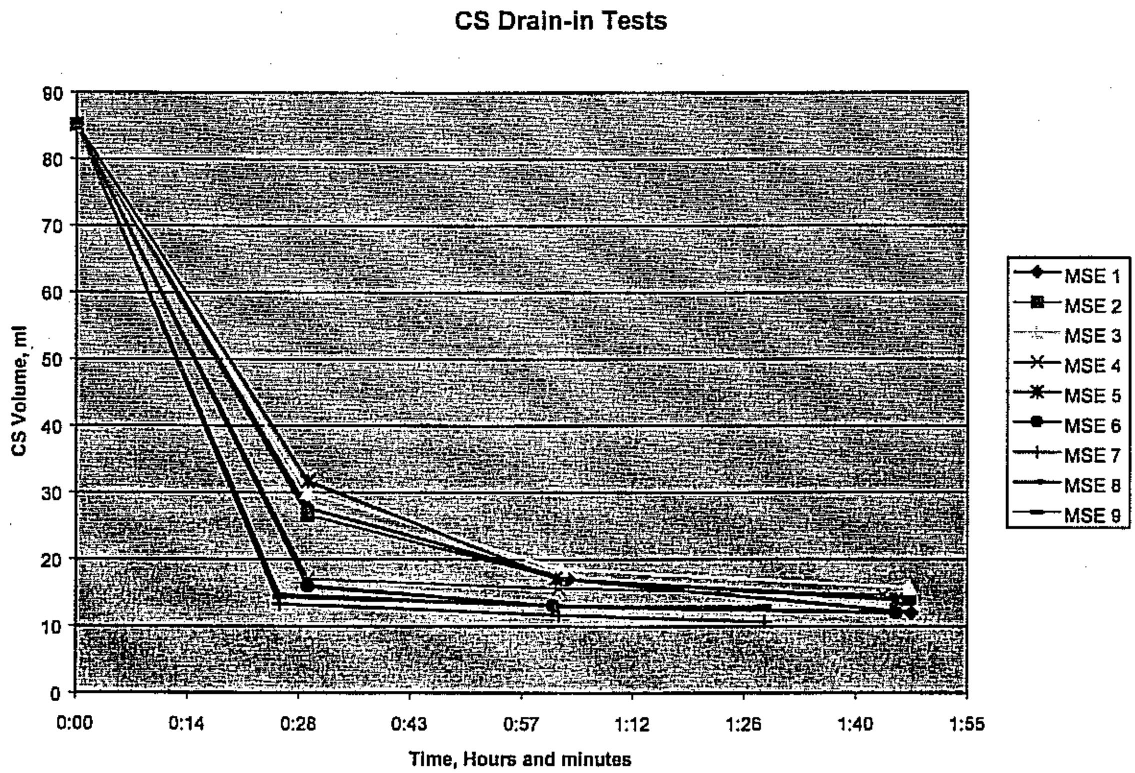

Figure 3-1. CS variant drain-in tests.

CS grout before the liquid starts to become viscous. The grout will obtain a State 9 gel after an additional 90 minutes when it becomes a rigid gel with no gel-surface deformation upon inversion of the sample jar. The process of gelation for the jar tests was recorded by assigning gel states according to gel time states modified by Lawrence Berkeley National Laboratory (LBNL) (Ref. 2).

Calcium chloride ($CaCl_2$) was used as the initial electrolyte solution for all nine variants. Two CS variants did not gel with the addition of the $CaCl_2$ electrolyte solution at any molarity used, so other electrolyte solutions with varying molarities were tried, without success. Therefore, these variants were eliminated from further laboratory testing because they did not gel.

Since the gel time of the CS grout with soil is an important issue, gel time jar tests were repeated with BNL soil added to neat grout (grout without any additives) for the remaining CS variants. All of the remaining CS grouts gelled to State 2 within 90 minutes (± 20%). Although this test does not represent how the CS will react when injected into the subsurface at BNL, it is an indicator that reveals how the CS grouts will react to the native BNL soil.

3.1.3 Colloidal Silica Grout Column Injection

For each of the remaining seven CS variants, a series of four sand columns were injected with the CS to measure the reduction in hydraulic conductivity resulting from the grouting process. The columns were packed with native BNL sand that was dried and re-wetted to simulate the original BLIP soil moisture content of 5% by weight. The sand in each of the columns was packed volumetrically to 90% of the Standard Proctor Test for BNL BLIP soil. The column injection apparatus assembly is shown in

Figure 3-2. Grout was injected into each column until 2.5 pore volumes of grout were collected in each of the overflow containers. The columns were allowed to cure for 28 days before hydraulic conductivity tests were initiated.

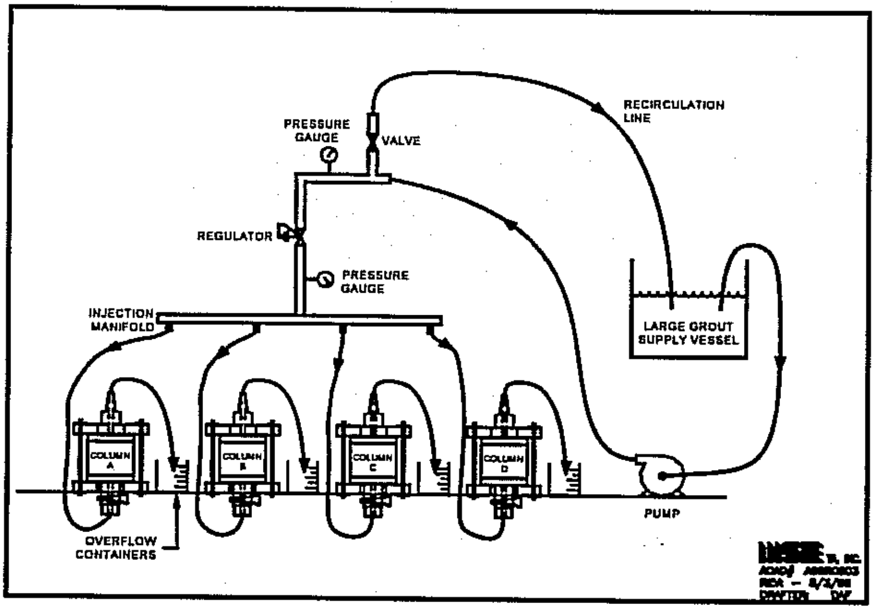

Figure 3-2. Schematic of the column injection apparatus.

3.1.4 Colloidal Silica Grout Cure Time Observations

The grouted CS sand columns were visually inspected periodically to determine if the CS grout had cured. It was noted that the columns grouted with CS variants with larger colloid particle size did not appear to cure as fast as the sand columns grouted with CS variants having a smaller colloid particle size. This supports the theory that larger colloid particle size variants produce a more stable silica sol and therefore take longer to cure (Ref. 2).

3.1.5 Hydraulic Conductivity Testing

3.1.5.1 Falling Head Permeameter Testing

Initially, a falling head permeameter test apparatus was used to determine the hydraulic conductivity of the grouted samples, and the testing was conducted according to the *Methods of Soil Analysis (MSA) 13-3.3 Falling Head Method*. After the samples cured, they were loaded into the falling head test apparatus. Table 3-1 shows the hydraulic conductivity values obtained during the falling head tests.

While the falling head tests produced data that indicated good hydraulic conductivity reduction by some of the CS grouts tested, the tests did not provide enough information to equally compare the grouted sample sets due to problems with the seals between the sample and the acrylic columns. Therefore, for further comparison of all the samples, saturated hydraulic conductivity testing was performed in the flexible wall permeameter.

Table 3-1. Hydraulic conductivity values from falling head tests.

Sample Set	Hydraulic Conductivity Values, cm/sec		
	Sample 1	Sample 2	Sample 3
MSE 1	6.32 E -07	1.17 E-07	3.23 E-05
MSE 2	1.96 E-04	1.407 E-07	4.78 E-06
MSE 3	3.07 E-05	**	**
MSE 4	3.01 E-08	6.80 E-08	3.84 E-08
MSE 5	**	**	**
MSE 6	1.88 E-04	1.19 E-05	**
MSE 7	2.65 E-06	2.51 E-05	**

*** Samples with poor seals between the sand and the acrylic tubing.*

3.1.5.2 Flexible Wall Permeameter Testing

The majority of hydraulic conductivity testing described in the *Colloidal Silica Optimization Test Plan for the Viscous Liquid Barrier Hot Site Demonstration* (Ref. 3) was to be performed in a falling head apparatus. However, because the falling head apparatus was giving some erratic results due to poor seals between the grouted sand samples and the acrylic columns, resulting in unexpectedly high hydraulic conductivity values (denoted with ** in Table 3-1), flexible wall permeameter testing was also performed. Samples were removed from the falling head apparatus and trimmed to fit into the flexible wall permeameter. The hydraulic conductivity value for each sample was determined according to American Society for Testing and Materials (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 saturated hydraulic conductivity results obtained from flexible wall permeameter testing is shown in Table 3-2. Tests were performed at low effective stresses to mimic the falling head apparatus. During several of the tests, grout flowed out of the samples with the permeameter water.

Before the data were analyzed, each data set was tested for outliers using the Extreme Value Test and DataQuest software. No outliers were identified. The mean and geometric mean of each data set were calculated. During previous studies, the distributions of data from grouted sand samples have followed a log-normal distribution. While there was not enough data to definitively determine whether the data in Table 3-2 were log-normally distributed, this assumption was made for comparing the data sets to determine the grout of choice. Therefore, the geometric mean defined the central tendency of the data for comparison purposes. The grout designated as MSE 6 had the lowest geometric mean value for hydraulic conductivity.

3.1.6 Colloidal Silica Variant Selection Matrix

After initial laboratory tests were completed, a CS variant selection matrix was compiled. Each CS variant was awarded points based on the following data during this initial testing phase: saturated hydraulic conductivity points, CS variant sensitivity/reasonable range of electrolyte molarity, availability, relative cost, performance consistency, initial viscosity, and grout bleeding in permeameter tests.

Table 3-2. Flexible wall permeameter hydraulic conductivity results.

	Grout Sample	Hydraulic Conductivity (cm/sec)
MSE 1 Summary	Mean	8.28E-05
	Geometric Mean	3.26E-05
MSE 2 Summary	Mean	5.31E-05
	Geometric Mean	3.21E-06
MSE 3 Summary	Mean	4.46E-06
	Geometric Mean	2.29E-06
MSE 4 Summary	Mean	9.41E-05
	Geometric Mean	9.71E-06
MSE 5 Summary	Mean	1.18E-04
	Geometric Mean	3.29E-05
MSE 6 Summary	Mean	1.7E-06
	Geometric Mean	3.2E-07
MSE 7 Summary	Mean	2.05E-04
	Geometric Mean	1.03E-04

MSE 6 was selected to advance to the next phase of laboratory testing because it had the highest point value of the variants. MSE 6, Nyacol NP 6010, is a CS produced by Eka Chemicals Inc. – Paper Division. Additional quantities of CS and electrolyte solution were shipped to the MSE Testing Facility in Butte, Montana, to complete the larger scale CS grout optimization testing.

3.1.7 Additional Hydraulic Conductivity Testing

Further testing was performed on samples grouted with NP 6010 to replicate the results. For the replicate tests, samples were prepared in smaller diameter columns; consequently, they did not require trimming following the curing period. The cured samples were removed from the columns and the ends of the samples were trimmed flat, placed in a membrane, and loaded into the flexible wall permeameter.

Because more data points were available for grouted MSE 6 samples, a more complete analysis of the data was performed. A histogram of the hydraulic conductivity results is shown in Figure 3-3. The data appears to be log-normally distributed. The assumption of log-normal distribution was verified using the DataQuest software. The data set was then log transformed, and all subsequent data analysis was performed on the transformed data.

Figure 3-4 is a histogram of the data following transformation. The high and low data points were analyzed using the Extreme Value Test. Neither the high nor the low values were statistical outliers. Table 3-3 is a summary of all flexible wall permeameter data for NP 6010.

As shown in Table 3-3, the geometric mean of the entire data set is 2.9×10^{-7} cm/sec. The data set includes data from samples that were pushed out of columns and trimmed and those that were pushed out of columns and placed in the permeameter. Because sample handling concerns exist, the data were also analyzed as distinct sets.

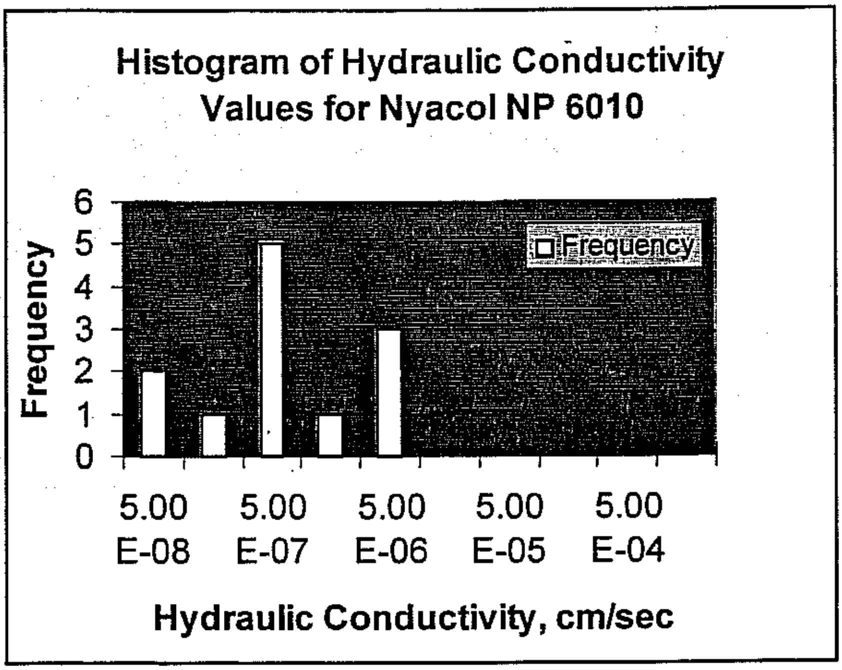

Figure 3-3. Histogram of hydraulic conductivity values for NP 6010.

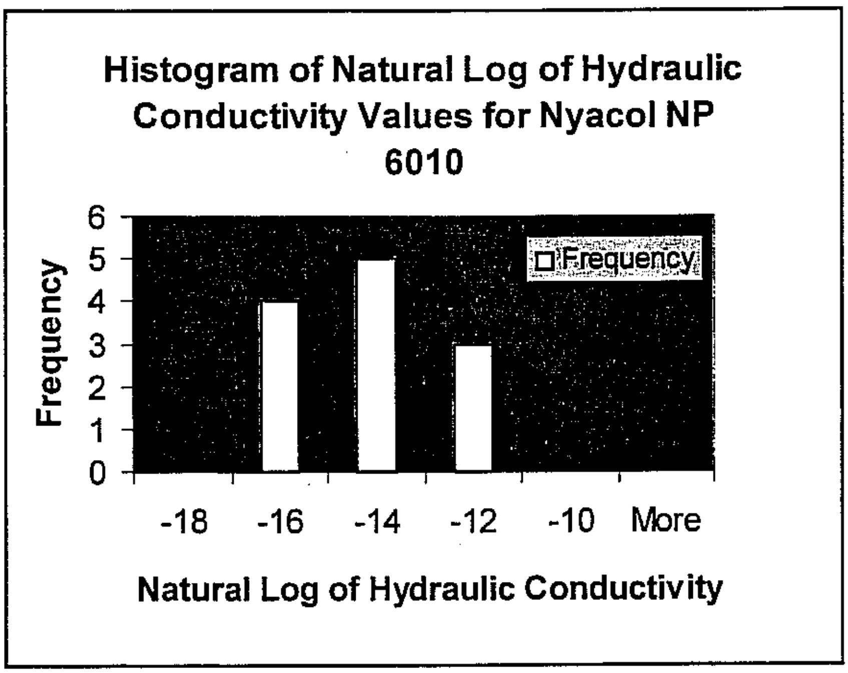

Figure 3-4. Histogram of natural log values of hydraulic conductivity.

Table 3-3. Summary of hydraulic conductivity sample results for NP 6010.

MSE 6/NP 6010 Summary	Hydraulic conductivity (cm/sec)
Mean of Trimmed Samples	1.3E-06
Geometric Mean of Trimmed Samples	2.5E-07
Mean of Pushed Samples	9.9E-07
Geometric Mean of Pushed Samples	3.2E-07
Overall Mean	1.1E-06
Overall Geometric Mean	2.9E-07

Trimmed samples had a geometric mean of 2.5×10^{-7} cm/sec, and samples not requiring trimming had a geometric mean of 3.2×10^{-7} cm/sec. These results indicate that hydraulic conductivity values were not significantly impacted by the trimming techniques used.

3.1.8 Dye Testing

Three dyes were tested for compatibility with the selected CS and for their ability to color BNL soil samples. The dyes tested were Palatin Voilet R, Lissamine Green G, and Nylomine Blue AG. Dyed CS samples with concentrations ranging from 0.035% to 0.33% by weight were mixed and added to BNL soil. The sand showed good color change with both the blue and green dye at concentrations ranging from 0.1% to 0.33%. The violet dye did not effectively change the soil color at any concentration attempted; therefore, the blue and green dyes were tested for State 2 gel times at varying dye concentrations. Gel tests were conducted on CS mixtures with a 0.33% dye concentration for blue and green dyes. At this concentration, both dyes accelerated the gel time of the CS grout. Concentrations were determined for both dyes that did not significantly affect the CS grout gel time. These dye concentrations were used during the sand tank testing to make it easier to identify grouted sand during sand tank excavation.

3.2 SAND TANK TESTING

After selecting the optimum CS variant and dyes that could be used to help identify grouted zones, larger scale testing was conducted using two-dimensional (2-D) and three-dimensional (3-D) sand tanks to determine the best injection design. Two injection designs were considered: one based on computer optimization, and one based on standard engineering practices.

Sand tank testing was performed to determine the best injection design.

3.2.1 Two-Dimensional Sand Tank Testing

The objective of the 2-D sand tank testing was to determine the reduction in hydraulic conductivity within the grout bulb overlap zone; LBNL suggests this area is a zone of weakness in the grouting process, based on computer modeling. This may be explained by considering the case where the first grout bulb emplaced creates a gelled grout core, significantly reducing the saturated hydraulic conductivity, while a surrounding grout halo reduces the hydraulic conductivity, but not to the extent of that in the core. This halo zone of decreased hydraulic conductivity therefore could be problematic when a second grout bulb is emplaced adjacent to the first. As the grout from the second injection approaches the gelled grout halo, it meets more resistance to flow due to the reduced hydraulic conductivity. The degree to which the flowing grout enters this grout halo remains to be proven. The more grout that enters this halo zone, the further the hydraulic conductivity of the zone is reduced and the less concern regarding a zone of weakness. This testing was designed to evaluate the overlap zone between two grout bulbs.

A 2-D sand tank was constructed to visually verify grout bulb overlap during injection and for hydraulic conductivity testing in the overlap area. Electrical resistivity tomography (ERT) measurements were also obtained before and after grout injection of each grout bulb to determine if this geophysical method could be used as an emplacement verification tool. Two sides of the rectangular tank were constructed of plexiglass to observe grout injection. Guelph permeameter hydraulic conductivity tests were not successfully conducted in the 2-D tank because there was "communication" between test locations due to a fracture that occurred during the injection of the second grout bulb.

3.2.1.1 Test Tank Preparation

The 2-D tank was constructed of plywood and plexiglass with injection manifolds on each side. The bottom was lined with a sheet drain material to simulate gravity drainage by directing excess grout to the grout drainage ports located in the bottom area of the test tank. The injection spacing for this test tank was designed to match the injection spacing determined by the computer optimization-based design (COBD) for 4-foot grout bulbs. Three injection ports, having the same configuration as the lance injection rod used during the VLB Cold Demonstration at BNL, were added to the sides of the tank for grout injection. The BLIP soil added to the tank was conditioned to simulate the 5% moisture content of the site and volumetrically compacted to 90% of the Standard Proctor for the soil.

3.2.1.2 Grout Injection

The CS grout mixtures used for this test were colored with two different dyes to differentiate between the two grout bulbs in the test tank. To simulate field conditions, injection of the first grout bulb was followed by the injection of the second grout bulb approximately 30 hours later. Injection rates from each side were varied throughout the injection process to simulate a spherical injection; beginning at approximately 1.0 gallon(s) per minute (gpm) and reduced proportionally as a function of time to simulate the advance rate of a spherical plume of CS grout injected at a constant rate from a point source. A State 2 grout gel time of 90 minutes was selected for both grout bulbs during this test to allow ample time to complete the injections before the CS grout began to gel. Two batches of grout were mixed for this test, one with the addition of blue dye for the first grout bulb and one with the addition of green dye for the second grout bulb. Grout quality testing (verification of gel time) was performed on each batch.

During the emplacement of the first grout bulb, flow rates, pressures, and grout volumes were recorded. During injection, the blue dye separated from the CS grout in the sand near the injection ports. However, the wetting front of the grout advanced across the face of the tank to the other set of injection ports. At this point, injection was halted before the design volume of 16 gallons was injected. Figure 3-5 shows the 2-D tank after the injection of the first grout bulb.

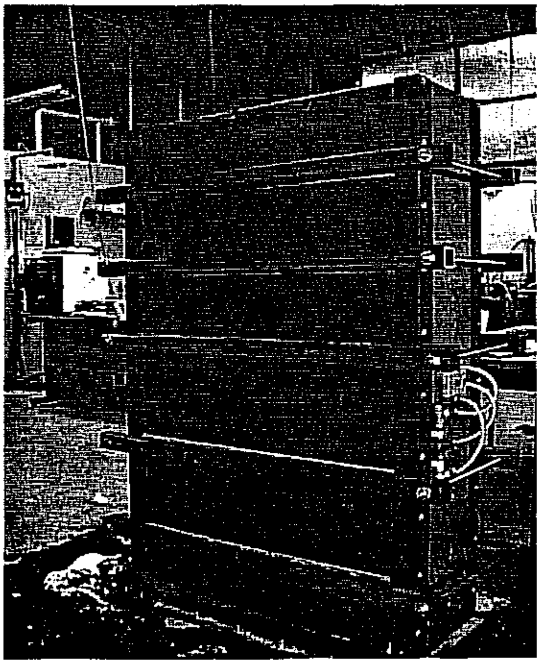

Figure 3-5. 2-D tank after the injection of the first grout bulb.

During the injection of the second grout bulb, the flow rates and pressures were also recorded. After 5 gallons of green-dyed grout were injected, the top of the sand tank developed a fracture while injecting at only 10 pounds per square inch (psi) and 0.38 gpm. The test was stopped at this time before the design volume of 16 gallons was injected.

3.2.1.3 Grout Bulb Testing

3.2.1.3.1 Electrical Resistivity Tomography Testing

Electrical resistivity tomography (ERT) data were acquired to determine the applicability of ERT imaging of the in situ grout injection process for future large-scale projects. The objective of the ERT monitoring was to delineate the extent of the grout in the tank after two grout bulb injections to determine grout bulb overlap.

The electrical resistivity of soil is primarily a function of the amount of interconnected (void) space in the soil, the amount of fluid in the void space, the salinity of the fluid, and to some degree the mineral composition of the soils. Clean, sandy soils saturated with fresh water generally have higher electrical resistivities than soils composed of sandy clays or sands saturated with salt water. To form a VLB, CS is activated with electrolyte solution (salt water). Therefore, the injection of grout should cause an observable decrease in the electrical resistivity of the soil, which is the basis for using ERT to monitor the grout injections.

Three ERT data sets were obtained over the course of grout injection into the tank. An initial data set was obtained prior to grouting to provide the baseline electrical resistivity values for the soil in the tank. A second set of ERT data was obtained after the first grout injection, and a third data set was collected after the second grout injection. The data were inverted, and estimates of the resistivity distribution across the sand tank were obtained for each of the three data sets.

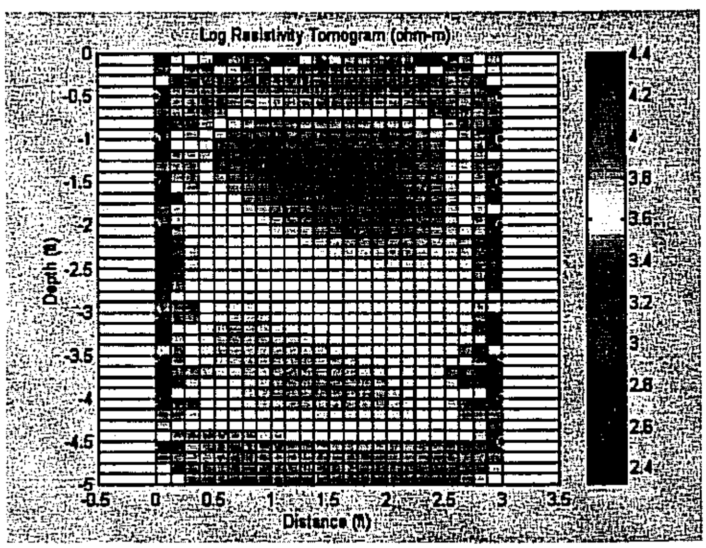

Figure 3-6. Pre-injection electrical resistivity distribution.

The pre-injection results are shown in Figure 3-6, while Figures 3-7 and 3-8 show the results after the first and second injections, respectively. Resistivities are plotted on a log scale. The pre-injection results (Figure 3-6) indicate the average resistivity of the ungrouted sand ranges from 5,000 ohm-meter (m) to 25,000 ohm-m (yellow to red).

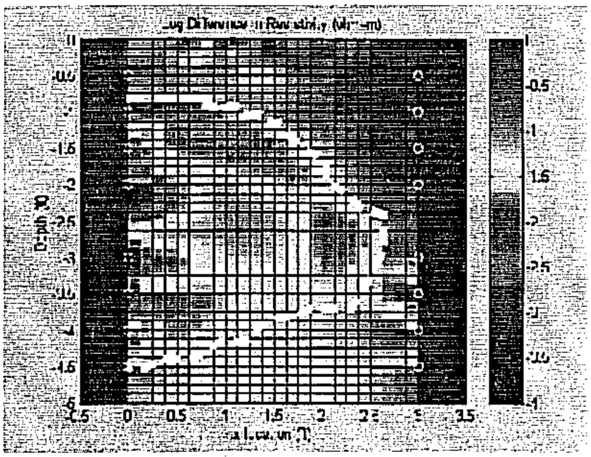

Figure 3-7. First grout injection and baseline electrical resistivity difference plot.

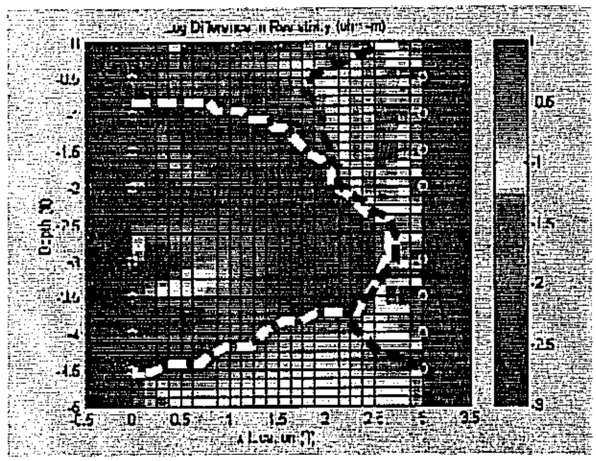

Figure 3-8. Second grout injection and first grout injection electrical resistivity difference plot.

Figure 3-7 shows the change in resistivity between the baseline data and the data acquired after the first grout injection (from the left side of tank). A distinct decrease in electrical resistivity, indicated by the yellow and green, can be seen. This signature corresponds to the region where the grout was observed during injection. The estimated grout bulb extents are outlined in white. Areas that did not experience a change in resistivity are indicated by the redder colors.

The final resistivity plot (Figure 3-8) shows the difference between data acquired after the second grout injection (from the right side of tank) and the data acquired after the first grout injection (from the left side of tank). The plot indicates that resistivities in the upper right side of the tank decreased, most likely a result of the presence of grout. The redder colors indicate little to no change in resistivity. The prominent red area present in the plot is believed to be partly due to the fact that grout was injected into much of the void space in the center of the tank. When the extents of the first grout bulb are considered (shown in white), the estimated extents of the second injection (outlined in black) show the sand tank to be well grouted.

The results suggest the ERT technique could be used to monitor CS grout injections to verify that successive grout injections intersect. Additional work may be required to implement this technique of monitoring the injection process in the field.

3.2.2 Three-Dimensional Sand Tank Testing

Three-dimensional sand tank testing was conducted to compare the hydraulic conductivity of the Standard Engineering Design (SED) (Ref. 4) used during the VLB Cold Demonstration and a COBD provided by LBNL after the completion of the VLB Cold Demonstration. The SED specifies a 2.5-foot-diameter grout bulb, while the COBD specifies a 4-foot-diameter grout bulb. A 4-foot-tall by 4-foot-diameter steel tank was used for the injection of the 2.5-foot-diameter grout bulb, while a 5-foot-tall by 5-foot-diameter steel tank was used for emplacement of the 4-foot-diameter grout bulb. Shelby tube samples were collected from the 4-foot grout bulb but not from the 2.5-foot grout bulb. Guelph permeameter tests were conducted on both of the injected grout bulbs to determine the in situ saturated hydraulic conductivity of the grouted sand. Adjacent samples were collected from the 4-foot grout bulb to try to establish a saturated hydraulic conductivity profile for the COBD.

3.2.2.1 Standard Engineering Design Sand Tank Test

The SED test was conducted in a 4-foot-tall by 4-foot-diameter steel tank where a 2.5-foot-diameter grout bulb was emplaced for hydraulic conductivity testing. The principle objective of this test was to determine the hydraulic conductivity of the selected CS grout using the same design as was used at the VLB Cold Site Demonstration completed at BNL during the summer of 1997.

3.2.2.1.1 Test Tank Preparation

The bottom and sides of the 4-foot tank were lined with a drain material, designed to intercept and direct grout in contact with the tank to the drainage ports, therefore preventing artificial boundary conditions in the sand tank. The tank was filled with BNL sand conditioned to 5% soil moisture by weight and compacted to within 90% of the Standard Proctor Test for the soil to simulate BNL subsurface conditions. Figure 3-9 shows soil being loaded into the 4-foot tank during tank preparation.

Figure 3-9. Soil being loaded into the 4-foot tank.

Once the tank was 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 the tank. To ensure leakage around the injection rod was not a problem, a thin layer of bentonite clay was placed around the upper part of the injection rod. At this point, the 4-foot tank was placed into a specially designed load cell and pressure was applied to the load cell plate to simulate pressures experienced at 30 feet bgs. Figure 3-10 shows the 4-foot tank during placement of the load cell plate.

3.2.2.1.2 Grout Bulb Injection

Approximately 18 gallons of blue-dyed grout was injected into the 4-foot tank via a hose attached to the injection rod. Grout quality assurance (QA) tests were performed on samples of the grout to verify the grout met the gel time target; gel times were within the design envelope.

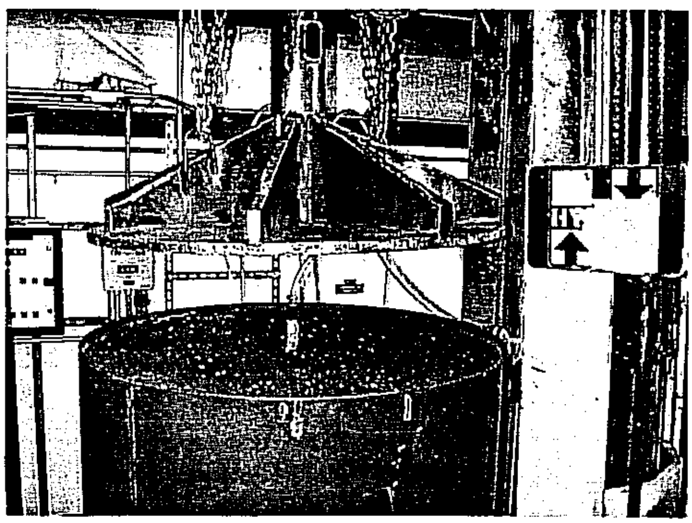

Figure 3-10. 4-foot tank during placement of the load cell plate.

After injection, two standard laboratory samples were prepared using the dyed grout; one was composed of neat grout and the other made by pouring sand into neat grout. Both samples were prepared and allowed to cure in a flexible wall permeameter membrane held in place by a sample mold. These samples were allowed to gel and form a mixture of what should represent the lowest limit of hydraulic conductivity for the NP 6010 CS grout. The standard laboratory samples were tested on the flexible wall permeameter according to *ASTM D5084, Method C.*

As expected, the hydraulic conductivity measured for the neat grout sample was lower than the hydraulic conductivity measured for the sample with sand poured into the neat grout, 2.94×10^{-8} cm/sec and 5.33×10^{-8} cm/sec, respectively.

3.2.2.1.3 Grout Bulb Testing

Shelby Tube Testing

After injecting the 2.5-foot grout bulb into the 4-foot tank, the load cell and the injection rod were removed from the tank. Shelby tube sampling was attempted but refusal was encountered between 8 and 10 inches below the surface at the first sample location. Refusal was also encountered at the other sample locations. It was decided not to collect these samples from the 4-foot tank in order to minimize grout bulb disturbance/fracturing within the tank.

Guelph Permeameter Testing

Several weeks after injecting the 2.5-foot grout bulb in the 4-foot tank, attempts were made to run Guelph permeameter tests in the ungrouted areas of the 4-foot tank to determine the initial hydraulic conductivity of the ungrouted compacted sand. Grout was discovered at all of the testing locations; therefore, the work plan was modified to obtain the hydraulic conductivity of the ungrouted BLIP sands. Three 55-gallon drums were filled with BNL soil conditioned to 5% soil moisture and compacted to 90% of the Standard Proctor for the soil. One Guelph permeameter test was conducted in each of the barrels. The results of the three hydraulic conductivity tests conducted for ungrouted BNL soil were 3.09×10^{-4} cm/sec, 3.89×10^{-3} cm/sec, and 2.38×10^{-3} cm/sec with a geometric mean of 1.42×10^{-3} cm/sec.

Five Guelph permeameter tests were conducted on the 4-foot tank to measure the saturated hydraulic conductivity of the grouted material; the results are presented in Table 3-4. As stated previously, a 2.5-foot-diameter, or 30-inch-radius, grout bulb was injected into the small sand tank. As shown in Table 3-4, from the center of the tank, approximately 13 inches radially outward, there appears to be a core of well-grouted sand with a saturated hydraulic conductivity ranging from 1.02×10^{-6} to 4.70×10^{-8} cm/sec. From 15 to 21 inches, there appears to be a grout halo where the grout mixes with the in situ pore water to form an area that is not completely grouted.

Table 3-4. Hydraulic conductivity results for the 4-foot test tank.

Test #	Vertical Location, inches below the sand surface	Horizontal Location, inches outward from the injection rod	Radial Distance, inches from injection point	Hydraulic Conductivity, cm/sec
1	23	15 North	15.03	2.30E-04
2	15	6 East	10.82	1.02E-06
3	24	10 North East	10.00	4.70E-08
4	22	21 West	21.10	6.92E-04
5	27	13 East	13.34	3.73E-07
Geometric Mean				4.91E-06

Excavation

The 4-foot tank was excavated in 6-inch lifts to determine the shape and size of the injected grout bulb. At 90-degree intervals, measurements were taken every 6 inches radially outward from the center of the tank with an electrical resistivity meter. Figure 3-11 depicts the grout bulb as determined by these measurements.

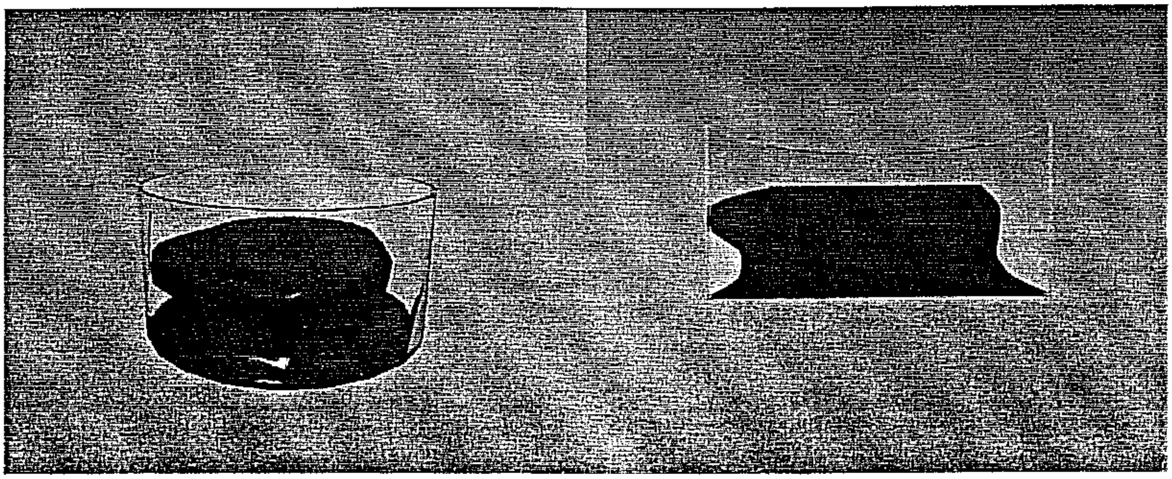

Figure 3-11. Isometric and lateral views of the grout bulb in the 4-foot tank.

3.2.2.2 Computer Optimization-Based Design Sand Tank Test

The objective of this test was to determine the effectiveness of the CS grout to reduce the hydraulic conductivity of the BLIP site sand using the optimization-based design from the LBNL computer model of the VLB Cold Demonstration. Approximately three and one-half times the volume of grout injected during the SED tank test was injected into the 5-foot tank. Based on the computer modeling conducted by LBNL, the additional grout injected into the sand should help dissolve the air remaining in the formation, allowing the grout to completely fill the pore space. The LBNL model showed this would reportedly create a core area within the grout bulb that would achieve a saturated hydraulic conductivity of $1x10^{-7}$ cm/sec or less.

3.2.2.2.1 Test Tank Preparation

To accommodate this test, the 5-foot tank was lined with a drain material and small drain holes were drilled into the tank bottom, allowing grout to drain and prevent boundary conditions within the tank. The tank was placed into the load cell, and soil was conditioned and placed in the tank as previously described in Section 3.2.2.1.1.

Once the tank was filled, the lance injection rod was driven into the sand in the 5-foot tank so that the center of the injection ports was located in the center of the tank. Consistent with the 4-foot sand tank test, the injection rod was sealed with bentonite and pressure was applied to the soil in the tank from the load cell to simulate pressures experienced at 30 feet bgs.

3.2.2.2.2 Grout Bulb Injection

A hose was attached to the top of the injection rod and CS grout was injected into the 5-foot tank. The State 2 gel time for this tank test was adjusted to 120 minutes to allow enough time for injection. A total of 90 gallons of grout was injected into the test tank. Grout was collected for jar and viscometer tests to verify the CS grout met the State 2 gel time target; gel times were within the design envelope for both batches of grout. Upon completion of the grout injection, the tank was removed from the load cell and allowed to cure for several weeks.

3.2.2.2.3 Grout Performance Testing

Computer Tomography Scans

Four Shelby tube samples were collected from different locations and depths within the tank. The Shelby tubes were pushed into the grouted sand immediately after the load cell was removed from the tank. The Shelby tubes were left in place while the grout was allowed to cure and were then collected during the excavation of the 5-foot tank. The Shelby tubes were carefully transported to the Montana State University-Bozeman (MSU) Soil Physics lab for computer tomography (CT) scans. Figure 3-12 shows two of the CT scans for a sample taken 18 inches north of the injection point. The top of the Shelby tube sample was 2.2 feet below the sand surface in the 5-foot tank. Scan A was taken at 0.23 feet from the top of the sample, and Scan B was taken 0.33 feet from the top of the sample.

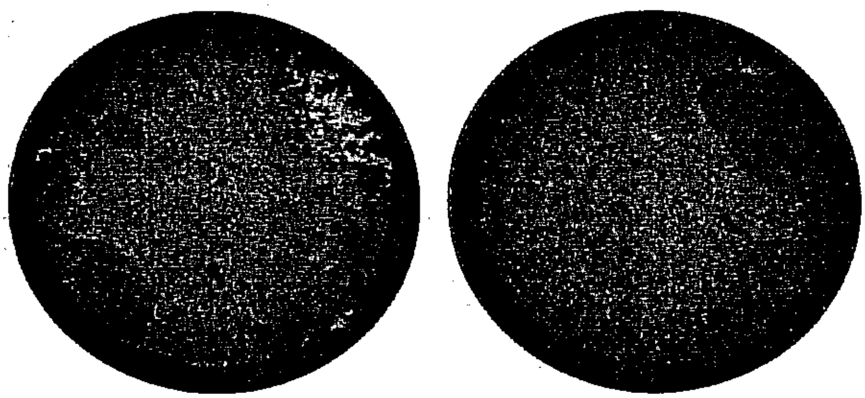

Figure 3-12. CT scans for sample taken 18 inches north of the injection

While the CT scans are qualitative and not quantitative in nature, certain aspects of the grouted samples and the sampling procedures can be observed in the scans. The darkest areas in the scans are stones within the sand mixture, and the lightest areas in the scans are void spaces or areas disturbed during sampling. The dark gray areas of the sample indicate areas of porosity reduction. In the area of approximately 2 o'clock in Scan B, there is a rock with an area of disturbance located above the rock possibly due to sampling. In Scan A, a larger area of disturbance is shown in the same area just above the rock pictured in Scan B. There is also some sample disturbance shown at approximately 4, 7, and 9 o'clock around the smaller stones in contact with the Shelby tube, pictured in Scan A. The lighter areas around the rocks in contact with the Shelby tube indicate how easily the grout samples are fractured during the sampling process.

Guelph Permeameter Testing

Two of the holes created by the Shelby tubes were used for in situ Guelph permeameter testing. Hydraulic conductivity measurements were also made at nine additional locations within the tank using Guelph permeameters. Figure 3-13 shows the 5-foot tank during Guelph permeameter testing and Table 3-5 summarizes the in situ saturated hydraulic conductivity values obtained from testing.

Table 3-5. Hydraulic conductivity results for the 5-foot tank.

Test #	Vertical Location, inches below the sand surface	Horizontal Location, inches outward from the injection rod	Radial Distance, inches from injection point	Saturated Hydraulic Conductivity, cm/sec
1	30.6	20.8 West	21.08	3.28E-05
2	40	6 North	8.48	3.70E-07
3	36	12 South	12.16	4.80E-07
4	41.5	16 East	17.67	1.74E-04
5	28	22 Northwest	15.62	1.04E-05
6	44	22 Southeast	19.31	2.77E-06
7	41	18 North	22.80	3.18E-05
8	24	14 Southwest	17.20	3.29E-06
9	41	24 South	25.00	2.99E-06
10	24	6.5 Northwest	11.93	8.20E-08
11	47	Center	13.00	1.44E-02
Geometric Mean				6.25E-06

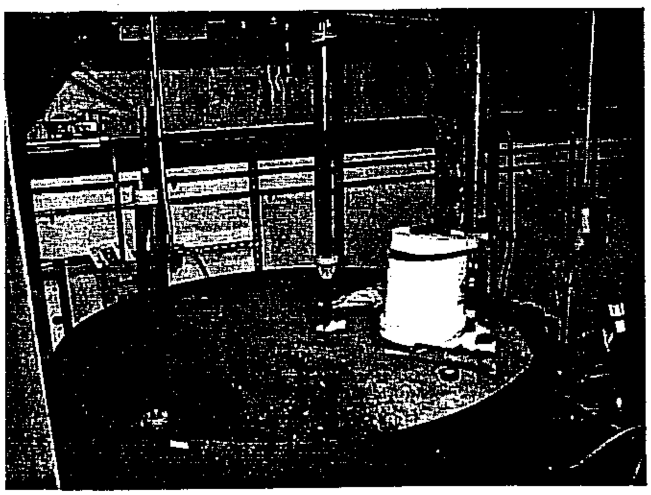

Figure 3-13. The 5-foot tank during Guelph permeameter testing.

As shown in Table 3-3, from the center of the 5-foot tank to approximately 12 inches radially outward, there appears to be a core of well-grouted sand with saturated hydraulic conductivities ranging from 4.80×10^{-7} to 8.20×10^{-8} cm/sec. From approximately 13 to 25 inches, there is an area with saturated hydraulic conductivities ranging from 1.74×10^{-4} to 2.77×10^{-6} cm/sec, not including results from Test #11. Results from Test #11, located 13 inches directly below the injection tip, suggest that during downstage permeation grouting the bottom of the grout bulbs does not get grouted until the rod string advances to the next injection interval. This is implied by the saturated hydraulic conductivity value obtained during the test since the saturated hydraulic conductivity of the ungrouted BNL soils ranges from 1×10^{-2} to 1×10^{-3} cm/sec. Because grouted sand was not encountered while testing location #11, the test was not included in the geometric mean in Table 3-5.

Excavation

The 5-foot tank was excavated in 6-inch lifts to determine the shape and size of the injected grout bulb. At 90-degree intervals, measurements were taken every 6 inches radially outward from the center of the tank with an electrical resistivity meter. Figure 3-14 depicts the grout bulb as determined by these measurements. The anomaly shown near the surface of the tank was due to a leaky hose, which allowed grout to flow between the load cell plate and the soil surface.

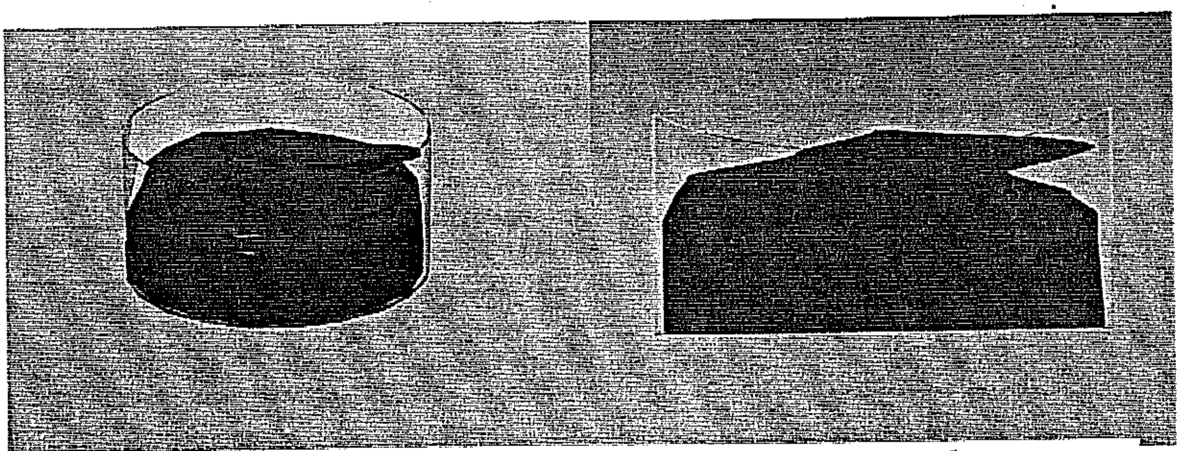

Figure 3-14. Isometric and lateral views of the grout bulb in the 5-foot tank.

3.3 CONCLUSIONS

3.3.1 Test Columns

The CS, NP 6010, selected after laboratory testing reduces the saturated hydraulic conductivity of the native BLIP soils. The saturated hydraulic conductivity for the sand columns grouted with NP 6010 was reduced three to four orders of magnitude. In addition to reducing the saturated hydraulic conductivity of the BNL soils, NP 6010 proved to be a very stable silica that produced repeatable results in all phases of the laboratory testing. The consistency of the NP 6010 performance demonstrated during the laboratory testing is considered an important feature for field emplacement.

3.3.2 Sand Tanks

The 3-D sand tank testing was conducted to compare the saturated hydraulic conductivities of sand grouted according to the SED with sand grouted per the COBD. The larger grout bulbs specified by the COBD were simulated by LBNL to create a grout bulb with a core having a saturated hydraulic conductivity of 1×10^{-7} cm/sec.

The Guelph permeameter tests conducted on the larger sand tank showed that this design created a core approximately 60 cm in diameter with saturated hydraulic conductivities in the desired range. This 60-cm diameter corresponds to half of the diameter of the grout bulb size specified in the COBD. The Guelph permeameter tests conducted on the smaller sand tank also showed that the grout bulb created had a core area of reduced saturated hydraulic conductivity. The smaller grout bulb, with a design diameter of 76 cm, produced a core area within the bulb of approximately 68 cm in diameter. The geometric mean of saturated hydraulic conductivity for the 1.5-meter tank was 3.87×10^{-6} cm/sec, and the geometric mean of the saturated hydraulic conductivity for the smaller tank was 4.91×10^{-6} cm/sec.

Based on these results, it appears that either design achieves a reduction in saturated hydraulic conductivities. Both designs also created similar core areas. Although the COBD 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 SED.

4. MODELING OF UNSATURATED FLOW IN SOIL SOLIDIFIED WITH COLLOIDAL SILICA

4.1 MODELING SUMMARY

Modeling was conducted using the computer software PORFLOW™ to predict behavior of the soil solidified with CS. This simulation was conducted using water retention curves for the silica-solidified soil as determined through soil-laboratory measurements. Results of the modeling efforts demonstrated that the silica-solidified sand would successfully perform as a barrier to limit infiltration of atmospheric precipitation. The model indicates the infiltration rate would be reduced from the actual rate of 0.3048 meter/year (m/yr) to at least 0.0017 m/yr, thus exceeding 23 times the performance objective rate of 0.04 m/yr set by BNL. In addition, the modeling predicted flow paths within and around the solidified region and determined the dynamics of an initial "slug" of pore water that will be pushed out from the soil by the CS injection.

4.2 DATA USED

4.2.1 Data Source

The soil parameters used for modeling are based on measurements taken by the MSU Soils Physics lab, where moisture retention curves were determined for samples of both native sand and solidified soils.

The solidified soil was extruded from a test column of BNL soil injected with CS. The CS injection was completed in the MSE laboratory. Colloidal silica was injected into a series of columns at the pore volume ratios of 0.5, 1, 1.5, 2, and 2.5, as measured at the intake port located at the bottom of the column. To provide a conservative prediction of flow conditions in the solidified sand, the water retention curve determined for the material injected with the lowest pore volume ratio of 0.5 was used for the modeling efforts.

4.2.2 Moisture Retention Curves

Water retention measurements were collected via two different methods to construct the retention curves (Ref. 5). The hanging water column method was used for the low matric potential, i.e., for the range of 0.02 m to 0.8 m, and a pressure plate apparatus was used for matric potential in the range 0.8 m to 27 m.

Other laboratory-determined data necessary to construct the moisture retention curves, such as volumetric moisture content, bulk density, saturated hydraulic conductivity, and total porosity, were obtained using the appropriate ASTM laboratory procedures or methods of calculations.

The moisture retention curves were fitted to the laboratory data using van Genuchten formulas (Ref. 6). The soil retention curves were fitted to the laboratory data using a nonlinear optimization by least squares minimization with the Levenberg-Marquardt algorithm (Ref. 7). A summary of the fitting parameters used for modeling efforts is given in Table 4-1.

Table 4-1. Soil parameters used for modeling.

Soil		Native BLIP sand	Solidified sand (0.5 pore volume)
θ (Total porosity - volumetric)		0.341	0.323
Van Genuchten Fitting parameters	N	2.306	1.409
	α[1/m]	3.257	3.215
	S_r (Relative residual saturation)	0.117	0.316
θ (Residual moisture content - volumetric)		0.04	0.102
K_s (Saturated hydraulic conductivity) [cm/s]		2.3×10^{-2}	1.35×10^{-6}

4.3 MODELING EFFORTS

4.3.1 Software Used

The simulation of unsaturated flow within and around the CS-solidified block of soil was performed using PORFLOW™. PORFLOW™ is a general purpose software developed by Analytic & Computational Research, Inc. for simulation of transient or steady-state multiphase fluid flow, heat, salinity, and mass transport in multiphase, variably saturated, porous or fractured media with dynamic phase change (Ref. 8).

4.3.2 Boundary Conditions

The simulation of unsaturated flow within the unsaturated soil beneath the BLIP was conducted using a simplified 3-D approach, i.e., cylindrical coordinates. The cylinder was set vertically with the upper circular surface simulating the land surface and the lower circular surface simulating an interface of unsaturated and saturated flow, i.e., the water table. The saturated flow beneath the BLIP has not been simulated. The cylindrical domain is 17.98 m high and has a radius of 13.41 m. The model simulated the flow conditions within a 1-radian portion of the cylindrical domain. Each element is 0.3048 m high and 0.3048 m wide and has a length equal to the length of a 1-radian arc at the given radius. For example, the last element of each layer is 13.41 m long if measured along its outer side. Side views of such a cylindrical domain are presented in Figures 4-1, 4-2, 4-3, and 4-4. Because the software refers to modeling results with respect to directions X-, X+, Y-, and Y+, the same terminology is used in this report.

The surfaces and their corresponding notations for the solidified cylinder are listed below and marked in Figure 4-5:

- X- the upper surface (pie shape) for the solidified cylinder;
- X+ the lower surface (pie shape) for the solidified cylinder;
- Y- the axis of the cylinder; and
- Y+ a 1-radian portion of the side of the cylinder.

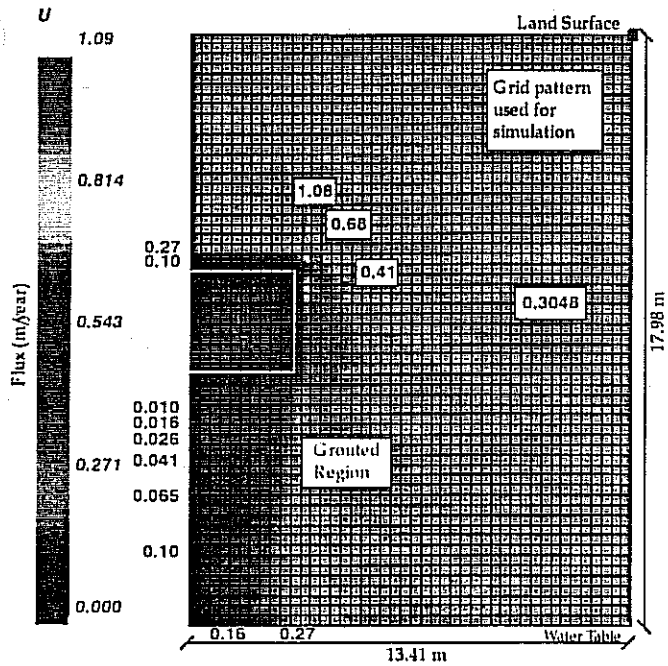

Figure 4-1. Distribution of the vertical component of 1-radian portion of the cylindrical modeled domain.

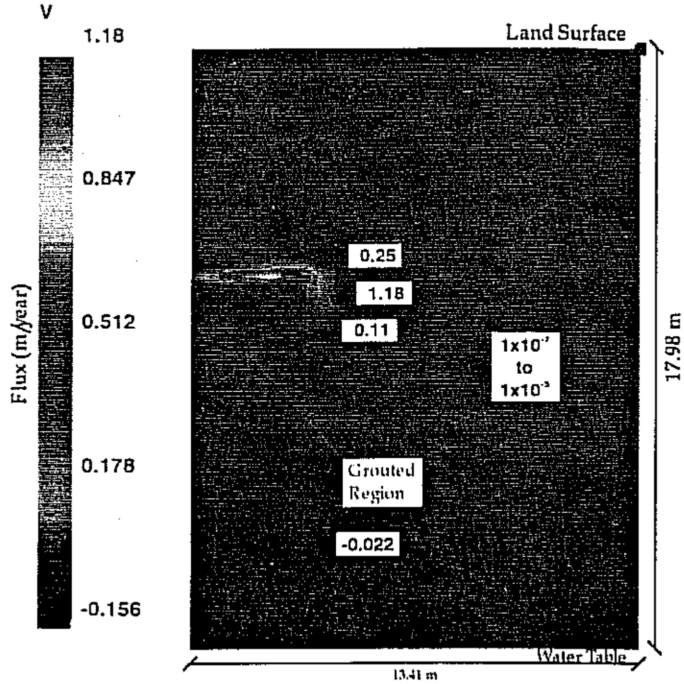

Figure 4-2. Distribution of the horizontal component of flux in a 1-radian portion of the cylindrical modeled domain.

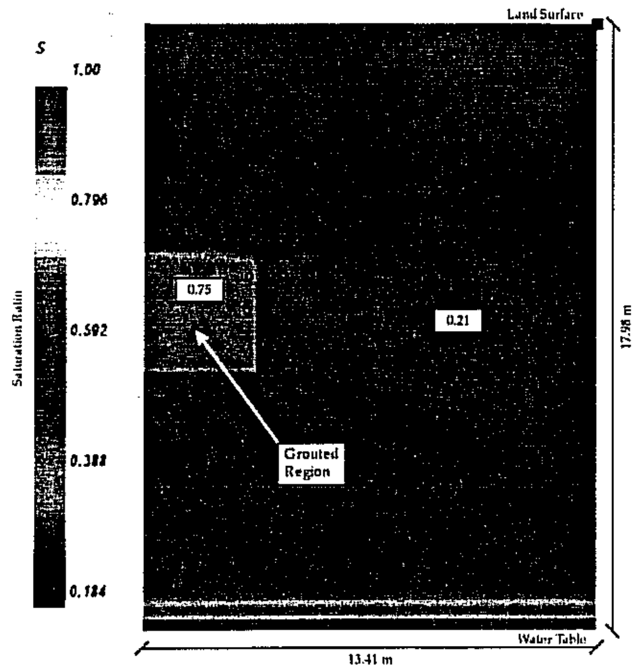

Figure 4-3. Water saturation (S) distribution in a 1-radian portion of the cylindrical modeled domain.

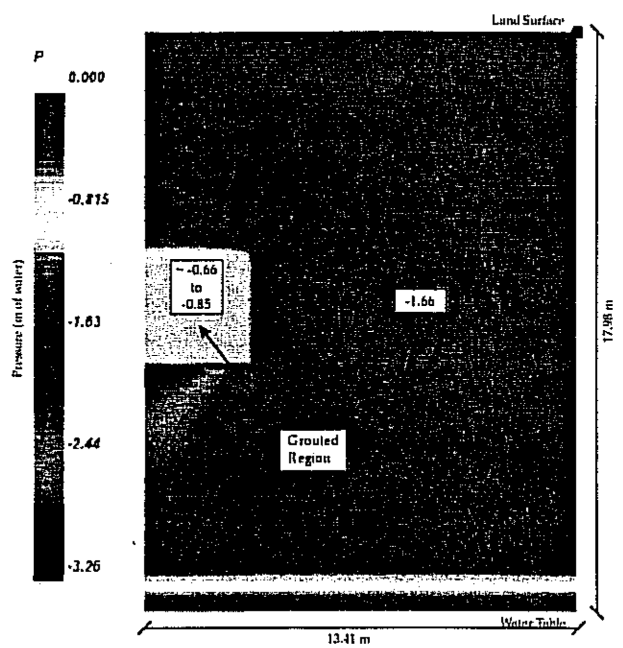

Figure 4-4. Water pressure (P) distribution in a 1-radian portion of the cylindrical modeled domain.

The boundary conditions listed below for the simulated domain were used for the simulation of both a pre-injection flow regime and post-injection flow conditions:

- constant flux boundary with 0.3048 m/yr flux at the land surface;
- X+ constant pressure (hydraulic head) boundary of 0 value at the water table;
- constant flux boundary with 0-m/yr flux along the cylinder axis; and
- Y+ constant flux boundary with 0-m/yr flux at 17.98 m from the axis.

To simulate the impact of the solidified material on the post-injection flow conditions, a smaller cylindrical domain (Region2) with the material properties of the CS-solidified sand was introduced in the modeled domain. Region2 is denoted in Figures 4-1 through 4-5 as the "Grouted Region." This cylindrical object is 3.35 m high and has a radius of 3.35 m.

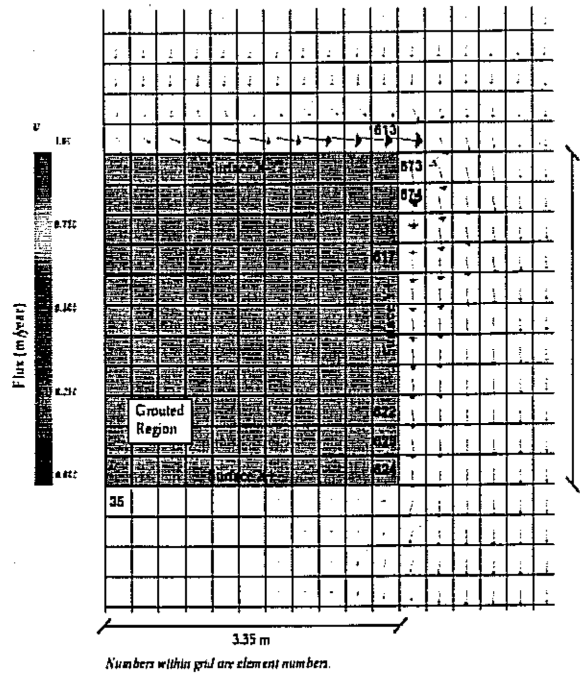

Figure 4-5. Total flow vectors in a 1-radian portion of the cylindrical modeled domain.

4.3.3 Modeling Approach

In the unsaturated zone, pore water is under a negative pressure (lower than the atmospheric pressure), which is caused by surface tension. This negative pressure, which is called matric potential (P), is a function of the saturation. This relationship, called the water retention curve or the soil moisture characteristic curve, is one of the entry parameters used for the simulation of unsaturated flow. The same function, as defined by van Genuchten, was used for native and solidified sands but with a different set of constants (Table 4-1).

The modeling efforts for the BLIP site consisted of four steps.

1) The water retention curve for the unconsolidated sand was used to simulate flow and to "establish" moisture conditions in the entire modeled domain for the boundary conditions. This step modeled the flow regime without a solidified region, hereafter referred to as the pre-injection model.

2) The output file of the pre-injection model was then used as the input for the steady-state simulation to predict the post-injection flow regime at equilibrium.

3) The output file of the pre-injection model was also used as the input for the transient simulation to model changes of the post-injection flow regime over time.

4) Flow of the slug of water that was pushed out from the solidified soil by the injection of CS was simulated to predict its time of arrival at the water table.

4.4 MODELING RESULTS

All simulations were performed using consistent units, i.e., time in years, and spatial measurements and coordinates in meters. All final simulations achieved an acceptable water balance for the modeled domain (Ref. 9).

The results of flow simulation were analyzed with respect to the performance goal set for the barrier. This goal was set based on calculations of radioactive contaminant transport provided by BNL. The goal is to reduce the flux released from the solidified material from 0.3048 m/yr to 0.04 m/yr. Considering that the cross-sectional area of a 1-radian portion of the solidified region is 5.61 m^2, the flux of 0.04 m/yr corresponds to an outflow of 0.22 m^3/yr from the entire block.

4.4.1 Steady-State Flow Conditions

Results of the steady-state flow simulation (Figures 4-1 through 4-5 and Table 4-2) include values of:

- flux [m/yr];
- vertical and horizontal components of flow vectors (flux) [m/yr];
- water saturation ratio, i.e. the ratio of volumetric moisture content to total porosity;
- matric potential [m of water]; and
- flow [m^3/yr or m^3/time of simulation].

The vertical components, U, of the flow vectors, i.e., fluxes (Figure 4-1) are always positive, signifying that the flow in the domain is downward. They range from nearly zero (0.0004 m/yr) in elements 617 to 623 (Figure 4-5) to 1.08 m/yr in elements 673 and 674. In element 35, located adjacent to the bottom-center of the solidified soil, the vertical component of flow is 0.002 m/yr. For most of the modeled domain, to the right of the solidified Region2, the U value equals the rate of recharge, 0.3048 m/yr.

The horizontal component, V, of the flow vectors is positive within most of the modeled domain (Figure 4-2), i.e., this flow component is from left to right. The maximum V value, 1.18 m/yr, appears in element 613 (Figure 4-5). To the right of the solidified region, where fluxes equal the recharge rate, horizontal components of the flow vectors approach zero (1.0 E-7 m/yr). Under the solidified region, however, the horizontal components of flow change their directions (negative values of V) with water moving very slowly toward the cylinder's axis. In element 35, the V value is -0.0008 m/yr.

The fluxes beneath the solidified soil (Figure 4-5), if integrated over the bottom area, add up to a total outflow of 0.00386 m^3/yr. The fluxes leaving the solidified area through the cylindrical side (Y+) add up to 0.00576 m^3/yr. Together 0.0962 m^3/yr of water flows through and leaves the solidified block of sand. This value corresponds to the average flux of 0.0017 m/yr.

Disregarding the high values of water saturation, S, adjacent to the water table, the highest S value (0.75) occurs within the solidified region (Figure 4-3). This saturation value corresponds to volumetric moisture content of 0.24. The lowest water saturation developed directly beneath the solidified region, with the absolute lowest value, 0.156, in element 35. Within the majority of the modeled domain, water saturation is 0.21. This value corresponds to volumetric moisture content of 0.071.

Matric potential, P, (Figure 4-4) ranges from -3.35 m in element 35, where the saturation ratio is also the lowest, to zero at the water table. For the majority of the solidified region, values of P range from -0.66 m to -0.85 m.

Although information regarding the horizontal and vertical component of fluxes, saturation ratios, and matric potential within and adjacent to the solidified region are very indicative that the performance goals will be surpassed, the most convincing data come from the simulation of the total outflow of the solidified region. Modeling of the steady-state conditions shows that the outflow will occur through surfaces Y+ and X+ of the solidified material, while inflow comes through surface X-. These data are presented in Table 4-2.

4.4.2 Transient Flow Conditions

The results of the transient flow simulation in semilogarithmic scale (Figure 4-6 and Table 4-2) indicate that the steady-state conditions are yet to be achieved after 30 years of flow simulation. Nevertheless, the outflow from the solidified region is always much lower than the performance goal, set at 0.22 m^3/yr. By the end of the 30-year period, the difference between the performance goal and the modeled outflow is 23 fold. The maximum outflow from the solidified region occurs after one-half a year of transient flow simulations when the sum of the flows through face X+ and face Y+ is approximately 0.052 m^3/yr.

Table 4-2. Flow balance of the solidified region.

Face	Steady-state flow		Flow after 30-year transient simulation	
	Inflow rate [m^3/yr]	Outflow rate [m^3/yr]	Inflow rate [m^3/yr]	Outflow rate [m^3/yr]
X-	0.00962		0.00962	
X+		-0.00576*		-0.00447
Y+		-0.00386		-0.00360
Y-	0.00000	0.00000	0.00000	0.00000
Total	0.00962	-0.00962	0.00962	-0.00807
Difference	0		0.00155	

* Negative sign denotes flow leaving the region. ′ Boundary conditions of flux = 0

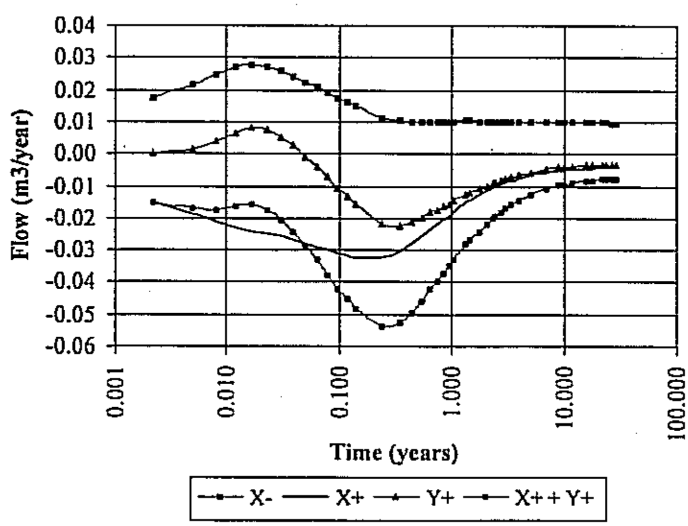

Figure 4-6. Transient flow.

4.4.3 Water Slug Modeling

Because CS was injected into sand with an average volumetric moisture content of 0.05, the CS will replace this moisture by pushing it out of the solidified region. This water, approximately 2.4 m^3, will eventually reach the water table. To evaluate the time of arrival of this contaminated water, an additional transient-state flow simulation was conducted. For this simulation, it was assumed the release of the total 2.4 m^3 of water to the unconsolidated sand took 2.2 days (rate of 398 m^3/yr). This release was evenly distributed throughout the bottom (X+) and the cylindrical side (Y+) of the solidified material. Results of the modeling indicated that the bulk of the released water would reach the water table within 10 to 25 days. Figure 4-7 depicts the water saturation at 16.2 days.

4.5 MODELING CONCLUSIONS

- The results of the unsaturated flow simulation demonstrate that the performance goal of the barrier constructed using CS grout will be met. The total outflow from the solidified region at steady-state conditions of flow 0.00962 m^3/yr is a factor of 23 lower than the maximum allowable flow set at 0.22 m^3/yr.

- According to simulations of transient flow conditions, the minimal difference between the allowable flow rate and the outflow from the solidified region occurs after half a year. At that time, the allowable flow (0.22 m^3/yr) is only four times greater than the outflow (0.052 m^3/yr) from the solidified region.

- The modeling indicates that the majority of contaminated soil moisture that will be pushed out from the solidified sand by CS will reach groundwater within 10 to 25 days.

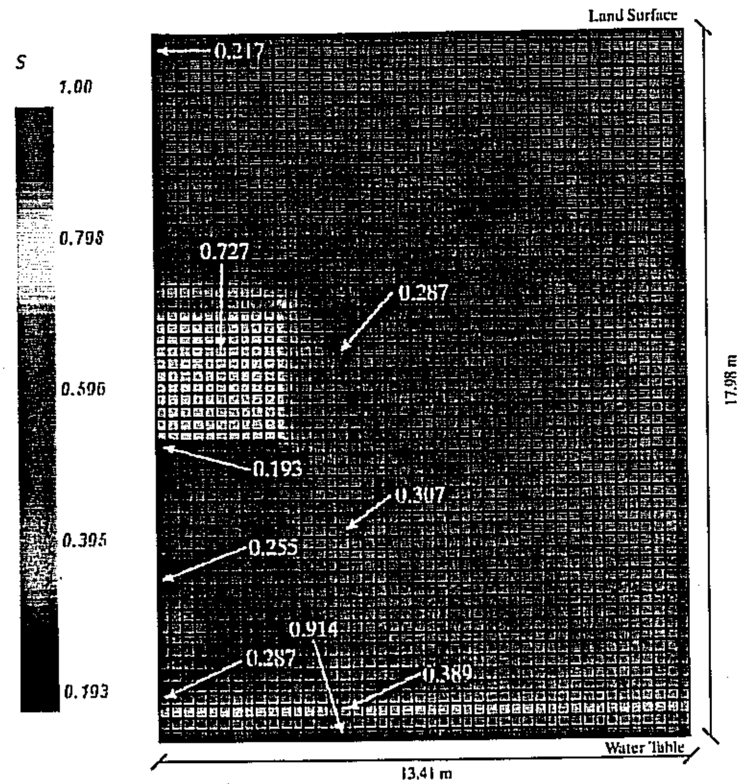

Figure 4-7. Water saturation (S) at 16.2 days after injecting 2.4 m^3 of water.

5. VISCOUS LIQUID BARRIER DEPLOYMENT

5.1 VISCOUS LIQUID BARRIER EMPLACEMENT

5.1.1 Grouting Equipment

The equipment required for the emplacement of the VLB at the BLIP facility was selected or designed specifically for the project to provide a robust, efficient grout delivery and grout quality testing system. The major components of the grout delivery/testing systems are presented below with a brief description for each.

- Direct-Push Rig - A Geoprobe Advance 66DT diesel-powered, track-mounted soil-probing rig that uses a hydraulic hammer system to drive grout injection rods into the subsurface.
- Direct-Push Injection Rod - Geoprobe 2.125-inch outside diameter (OD) by 1.5-inch inside diameter (ID) probe rods with special injection tips and a grout-injection drive cap.
- Grout Mixing/Delivery System - Gasoline engine-powered, hydraulically driven, positive-displacement, two-component variable-ratio grout pump with an in-line mixer.
- Grout Flow Control Stations - Two grout flow control stations equipped with pressure regulators, shutoff valves, flow control valves, flowmeter/totalizers, pressure gauges, and grout hoses.
- Hole Deviation Tool - A 1-inch-diameter Slope Indicator inclinometer with a referenced torque-rod system and data logger.
- Field Computer - Laptop computer with AutoCAD software for as-builting in the field.
- Grout Laboratory Equipment - Viscometer with temperature bath, specific conductivity meter, and pH meter for measuring grout quality.

5.1.2 Mobilization/Field Preparation

The grouting equipment was mobilized on May 11, 2000, from Butte, Montana, to BNL. MSE personnel met the semitractor trailer at BNL on May 19, 2000, to off-load the equipment and begin project setup. In addition, 33 tote bins containing CS and electrolyte were received at the project site and arranged in preparation for grouting operations (Figure 5-1).

Figure 5-1. Preparing the CS tote bins for injection.

5.1.3 Field Testing and Test Panel Installation

After the initial equipment setup was completed, injection tests were conducted to optimize the grout injection equipment before installation of the test panel. The testing was performed in the designated test area located outside the BLIP building on the east edge of the driveway leading to the BLIP. Initial testing was conducted to select the injection tip to be used with the 2.125-inch Geoprobe rods. Four different injection tip designs were evaluated in the Brookhaven sandy soils to identify the most efficient tip for the injection of the CS grout. The injection testing also included Geoprobe rod seal optimization. A good seal would ensure the rod connections did not leak, which could potentially allow grout to wash out the seal created by the drive rod and the soil and form a grout conduit to the surface. The test injections also allowed final adjustments to be made on the grout injection pump for a proper mix ratio.

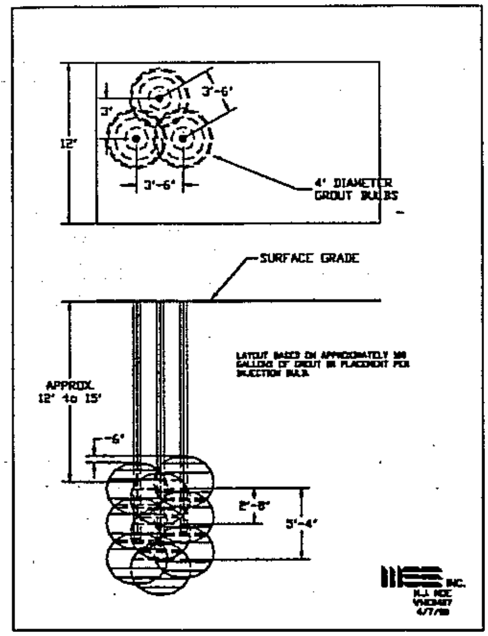

Figure 5-2. Test panel layout.

After completing the field testing and optimization, the test panel was laid out (Figure 5-2) in preparation for emplacement. A modification was made to the test panel design, based on the success of the earlier injection tests to inject into shallower depths (7 to 10 ft bgs) while maintaining rod/soil seals. Injection depths were decreased, creating a shallower test panel for ease of future permeameter testing. Injection horizons were raised to approximately 2 feet to 10 feet bgs. Injection depths for each injection hole are presented in Table 5-1 showing original design depths and the new field modified depths. The test panel maintained the 30% vertical and horizontal bulb overlap to mimic the VLB design for the BLIP.

Table 5-1. Test panel injection depths.

Injection Hole	Original Injection Depths With Design Injection Volume	Field Modified Injection Depths With Actual Injection Volume
TP-1	1st Injection - 12.00 ft – 90 gal 2nd Injection - 14.25 ft – 90 gal 3rd Injection - 16.50 ft – 90 gal	1st Injection - 10.0 ft – 90 gal 2nd Injection - 12.5 ft – 90 gal 3rd Injection - 15.0 ft – 90 gal
TP-2	1st Injection - 12.00 ft 2nd Injection - 14.25 ft 3rd Injection - 16.50 ft	1st Injection - 10.0 ft – 90 gal 2nd Injection - 12.5 ft – 90 gal 3rd Injection - 15.0 ft – 90 gal
TP-3	1st Injection - 12.00 ft 2nd Injection - 14.25 ft 3rd Injection - 16.50 ft	1st Injection - 11.25 ft – 90 gal 2nd Injection - 13.75 ft – 150 gal 3rd Injection - 16.25 ft – 120 gal

5.1.3.1 Test Panel Injections

Grout injection began at TP-1 where a pilot hole was pushed to 5 feet into the ground using the Geoprobe rig. Figure 5-3 shows grout injection of the test panel. The pilot rod, with an oversize drive point, created a slightly oversized hole in which the injection rod could be placed. The purpose of the pilot hole was to create a near-perfect vertical starter hole for the injection rod, allowing grout flow to be established without flowing to the surface. The verticality of the pilot rod was measured using a bubble level and a calibrated 24-inch digital level. The rod was driven down to 5 feet bgs while checking plumbness periodically and making adjustments to the Geoprobe drive head as necessary. The pilot rod was then pulled from the ground and the injection rod placed down the hole.

Figure 5-3. Test panel injection.

Once the injection rod was down the pilot hole, the injection drive head was placed on top of the rod and the grout injection hose attached. Flow to the rod was established and allowed to stabilize for a few seconds before advancing the rod with the Geoprobe. The rod was driven down to the first injection horizon while flow to the injection rod continued. Once at the first injection horizon, flow was increased to approximately 2.0 gpm. Flow rates were monitored and recorded at the flow control rack, along with grout specific conductivity measurements for quality control (QC). Once the design volume of grout was injected into the first horizon (90 gallons), the injection rod string was driven down to the next horizon (while injecting grout to maintain flow), and the process was repeated.

After completing the injection of grout into the second horizon, the process was repeated at the third horizon. Once the design volume of grout was injected into the third horizon, the injection rod string was pulled from the hole. The injection hole was then backfilled to within 2 to 3 feet of the surface with 10- to 20-mesh silica sand and activated CS. After setting, the remainder of the hole was backfilled with neat cement grout (Figure 5-4). The procedure was repeated for the second and third injection locations of the test panel.

Figure 5-4. Test panel injection holes.

5.1.4 Viscous Liquid Barrier Emplacement in the Brookhaven LINAC Isotope Producer Facility

5.1.4.1 Radiological Work Preparation

Preparations for emplacement of the VLB in the BLIP began early in the field schedule. Equipment and supplies stored in the BLIP target handling room were moved out or moved to the side so as not to interfere with grout injection operations. Once most of the equipment and supplies were out of the way, plastic sheeting (Herculite) was laid out to cover the concrete floor. All seams were joined together and sealed with duct tape to prevent radiological contamination from getting under the protective cover.

Upon completion of the test panel, final preparations were made to the equipment before bringing it inside the BLIP building. As seen in Figure 5-5, the Geoprobe rig was painted with a special strip-coat material that allowed the coating to be removed along with any radiological contamination once the project was completed. Plastic sheeting and duct tape were used to cover movable parts such as hydraulic lines and control levers.

A rod decontamination rack was built for the storage and decontamination of injection rods and tips. In addition, a pipe-vise tripod was also covered with Herculite and duct tape, protecting it from contamination.

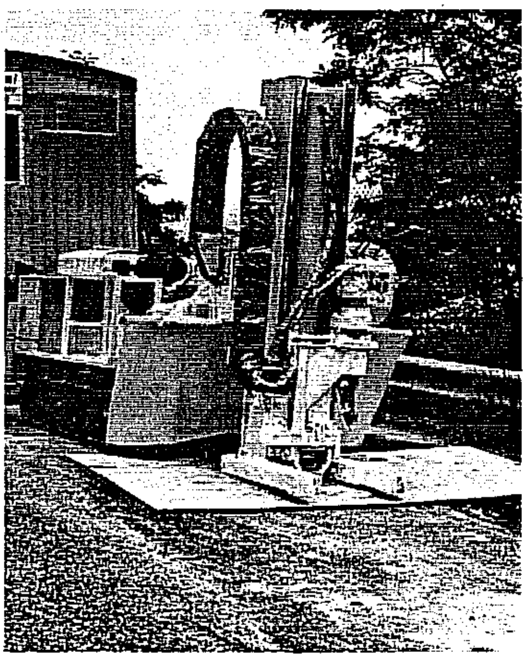

Figure 5-5. Geoprobe rig with strip coating.

Once all the equipment was ready, project personnel began moving it into the BLIP building. Only tools, equipment, and supplies that were needed were placed inside the building to reduce the potential for contamination. The Geoprobe rig was loaded into the building with a forklift (Figure 5-6). Once the equipment was inside the BLIP building, radiological control zones were set up to control access and potential contamination. A radiological buffer zone was located inside the large garage door to provide a space for grout hoses and Geoprobe exhaust hose, allowing the building to be secured at night.

In order to operate the Geoprobe rig inside the building, a flexible metal hose was attached to the exhaust of the Geoprobe rig and routed outside the building. To prevent potential airborne contamination in the air cleaner and engine, a flexible cloth air duct was brought from outside the building and attached to the air-cleaner intake manifold. Hoses are shown in Figure 5-7. In addition, sheets of aluminum were placed on the floor to prevent the Geoprobe rig from ripping up the Herculite as it was moved around inside the building.

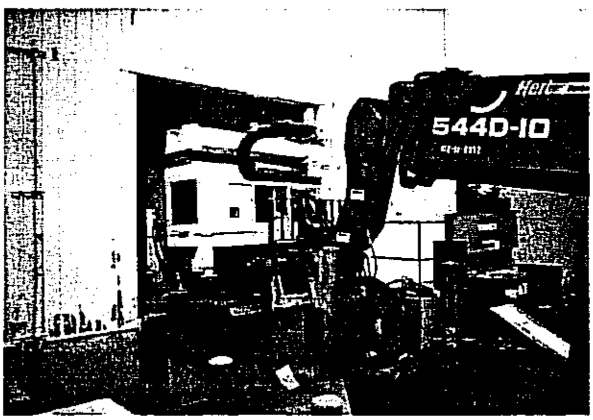

Figure 5-6. Loading Geoprobe into the BLIP.

Figure 5-7. Air intake and exhaust hoses.

After equipment was set up in preparation for the grouting operations, the injection hole locations were measured and marked on the Herculite floor cover before radiological controls were put in place. Outside the building, preparations were made: additional supplies of electrolyte solution were prepared, tote bins of CS were moved to the grout pump area, flow control racks were hooked up and prepared, and grout hoses from the control racks were laid out and taped down.

Once the preparations were completed, the area was designated as a radiological controlled area (RCA) or rad zone and access was limited to necessary personnel. Personnel were permitted entry after review, signature, and adherence to the personal protective equipment requirements stated in the BNL Radiological Work Permit (RWP). The designated safety level was a modified Level D, based on respiratory protection that could be upgraded by the Radiological Control Technician (RCT) if conditions existed to change the posted area to "Airborne Radioactivity Area."

5.1.4.2 Barrier Installation

Installation of the barrier began May 29, 2000, with the injection of the first grout string, location GS-1. Procedures established for working in the rad zone were used throughout the emplacement process. Therefore, the same general procedure described for GS-1 was used on GS-2 through GS-20, the only differences being the number and depths of injections. A 3-inch-diameter hole was cored through the concrete, using the approved standard operating procedure for coring concrete in a radiological contamination zone (Figure 5-8). The procedure used water to mitigate dust during coring operations; a shop wet/dry vacuum provided water removal.

Once the concrete was cored, the Geoprobe rig was moved over the hole in preparation for grouting. A pilot hole was pushed down to 15 feet below floor level (bfl) using the pilot rod with the slightly oversized tip. As with the outside test panel, the pilot hole was checked for verticality periodically until the rod was driven down to 15 feet bfl (Figure 5-9).

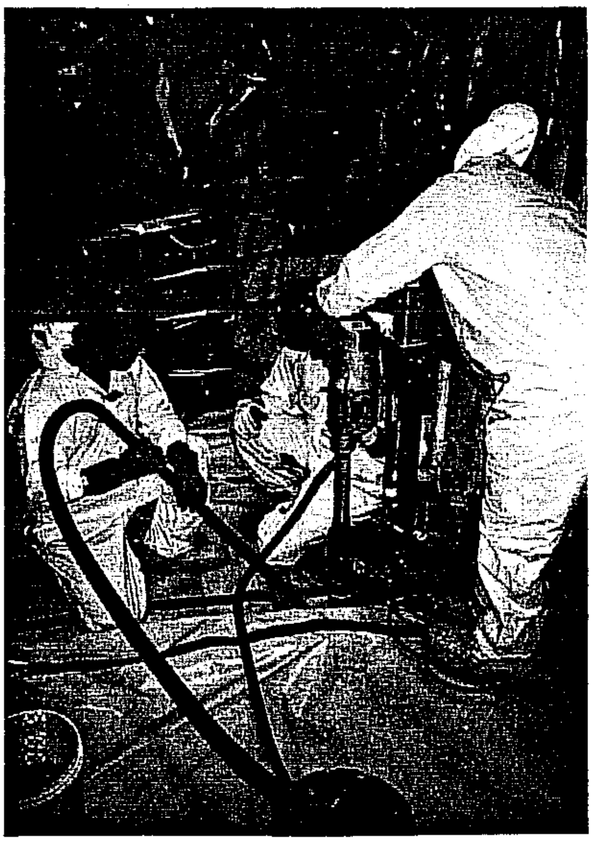

Figure 5-8. Coring the BLIP floor.

Figure 5-9. Checking verticality of the rod string.

Once the pilot hole was created, the pilot rod was pulled from the hole and the injection rod assembly was placed down the hole. A grout supply hose from the flow control rack was attached to the injection cap on the injection rod assembly. The injection rod was then checked for verticality before grout flow was established. When the rod verticality was verified, the Geoprobe operator signaled to personnel on the flow control rack outside the building to start grout flow. Figure 5-10 shows the flow control rack during injection. Once flow was established to the injection rod, the rod was driven down to the first injection horizon, stopping to add additional drive rods as necessary. Injection horizons and grout injection volumes for each injection location are further discussed in Section 5.4 of this report.

Figure 5-10. Flow control rack.

When the total injection depth was reached, a deviation survey was conducted to measure the verticality of the injection string. The survey was completed using personnel inside and outside the BLIP building: the Geoprobe crew lowered the probe down the rod while one person ran the data logger/recorder outside the rad zone. To conduct a survey, a special top plate was attached to the top of the injection rod and aligned. The deviation tool was then attached to a torque rod and placed into the injection rod down to the 0.5-meter mark on the electrical cable. The opposite end of the electrical cable, stored in the buffer area, was plugged into the data logger. The reference lines on the torque rod and top plate were aligned, and a deviation reading was recorded. Figure 5-11 shows the deviation survey in progress. The rod was then lowered down to the next cable reference mark for the next reading. The survey was completed by repeating the measurement procedure at 0.5-meter increments until reaching the bottom of the injection rod.

After completing the survey, the torque rods were retracted from the hole, one section at a time, so radiological swipes could be made by the RCT. Swipes were taken on all sections of the torque rod and deviation tool to ensure that radiological contamination was not brought up with the tool.

Figure 5-11. Deviation survey in progress.

The injection rods were pulled immediately after completion of the deviation survey. In order to clean the rods of grout and potential contamination, a thick, rubber rod wiper was placed over the rod to clean it as it was pulled from the hole, allowing most of the accumulated grout and soil to fall back into the injection hole. The rods were pulled from the hole in 5-foot lengths and swiped to monitor for contamination, as seen in Figure 5-12. When it was determined the rods were not contaminated, they were placed on the Herculite-covered rack for cleaning. Any rods or injection tips that were contaminated were placed in plastic sleeves and sealed until they could be decontaminated.

At the end of each grouting session, grout lines to the injection drive caps were disconnected, and in-line check valves were removed from the lines. The grout lines were drained to the outside flow control rack until they were empty. A fresh water supply was connected to the grout pump to wash out any activated grout from the in-line mixing system and supply hoses. Excess grout and wash water are directed to a tote bin set aside to receive waste grout and rinse water. Once the inside grout lines were empty, the in-line check valve was reinstalled, and the grout lines were flushed with water. Water flowing through the inside grout lines was directed to a sink inside the BLIP building that drained to a sanitary sewer. Approximately 5 to 10 gallons of wash water were allowed to flow through each line.

Figure 5-12. BNL RCT swiping injection rods.

The injection holes were backfilled with a mixture of 10- to 20-mesh silica sand and CS grout to within 15 feet of the surface. After the grout gelled, neat cement grout was poured down the hole to seal the remaining portion of the injection hole to within 6 inches of the surface (Figures 5-13 and 5-14). BNL Engineering was responsible for patching the concrete floor once the grouting operations were completed.

5.1.4.3 Injection Rod and Tip Decontamination

The RCT took swipes, or large area smears (LAS), of the injection rods and tips as they were removed from the hole; the swipes were then analyzed for radiological contamination. Contamination was primarily limited to the 3-foot-long injection tips; results from the swipes ranged from less than 1,000 disintegrations per minute (dpm) up to 8,000 dpm. The majority of the 5-foot injection rods did not have detectable contamination ($>$1,000 dpm), requiring less decontamination time between holes; however, several rods did measure from 1,000 to 2,000 dpm. The injection tips were decontaminated by disassembling the solid drive point from the injection tip tube. Any material accumulated in the tube was removed by pushing a long cleaning brush through the injection tip tube into a plastic catch bag to contain the contaminated material (Figure 5-15). The injection tube was then placed in a bucket of water and scrubbed clean. The solid point was also scrubbed clean with wash water and a brush. The injection tip components were swiped after being cleaned to check for remaining contamination. Once the swipes were clean, the injection tips were reassembled and placed with the others for service.

5.1.4.4 Injection Sequence

The injection sequence (Figures 5-16 and 5-17) was designed to optimize the grout injection process in terms of pore water management in the subsurface. By starting in back of the activated zone area on one side and working toward the front, pore water in the soils would effectively be pushed out rather than trapped within the grouted area. However, for radiological contamination control purposes, the sequence of injection was modified in order to work on the area furthest to the back so that if contamination was encountered, it would be confined to areas previously grouted and would not be spread due to further work in the area. To achieve the two objectives, the injection pattern was changed to allow work to progress outward to keep contamination in check while taking pore water management into consideration. A more thorough discussion of the injection sequences and grout volumes injected is presented in Section 5.4 of this report. The injections next to the BLIP tank were completed first, followed by the outer injections, keeping at least one inner injection ahead of the outside injections.

Figure 5-13. Backfilling with sand and CS.

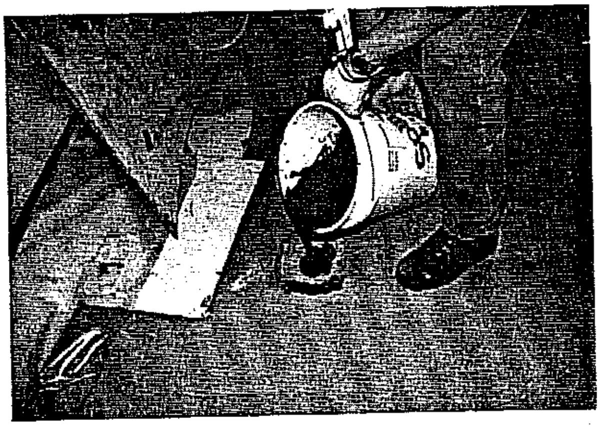

Figure 5-14. Pouring grout in the hole.

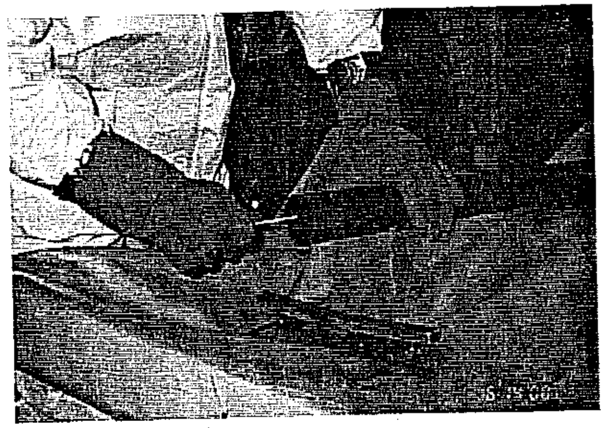

Figure 5-15. Decontamination of the rods.

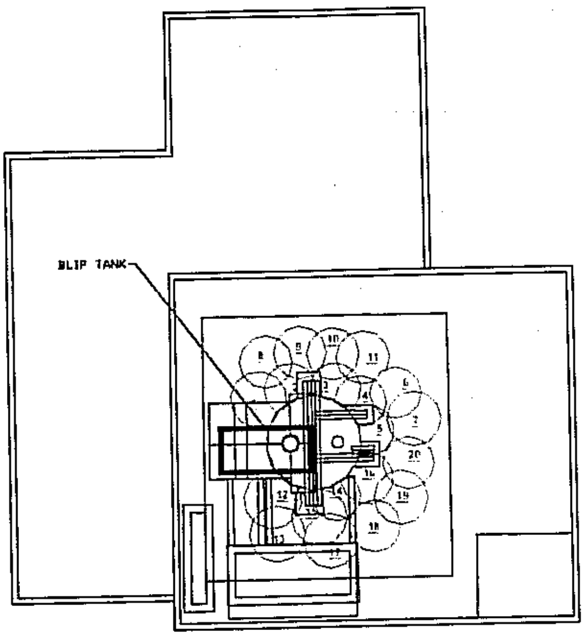

Figure 5-16. Designed locations and order of injections.

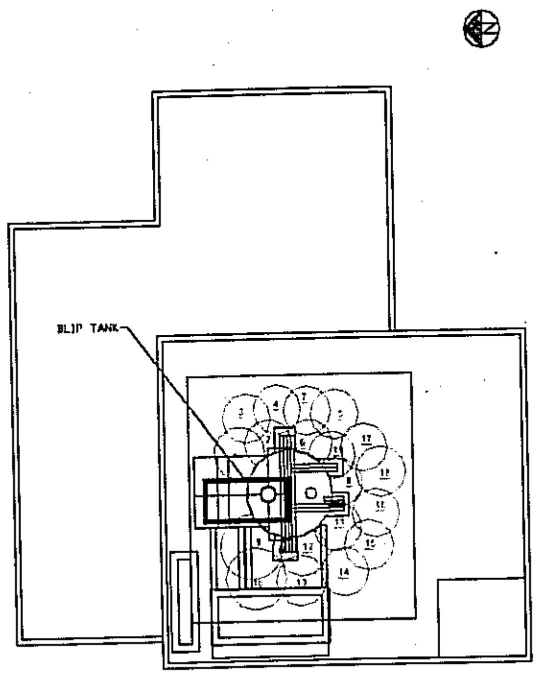

Figure 5-17. Actual locations and order of injections.

Several injection locations were modified due to the facility equipment interfering with maneuvering the rig and to optimize the grout placement in the subsurface. One injection location was omitted from the injection pattern due to other injection location and grout bulb volume changes.

Where possible, two grout injections were completed simultaneously to maximize productivity. The injection pairs included GS-11 and GS-3, GS-16 and GS-14, GS-17 and GS-18, GS-19 and GS-20, and GS-6 and GS-7. When grouting two locations at once, one would typically be started first to get two or three injection horizons ahead of the second injection location to avoid cross-hole interference.

5.1.5 End of Project Equipment Decontamination and Radiological Surveys

Once all grout injections were complete, clean up and removal of equipment and tools from the RCA was initiated. The injection rods were cleaned, and the outer surfaces were surveyed for radiological contamination. Although the rods surveyed clean on the outer surfaces, they could not be released due to the inability to survey the inner surfaces. The rods and injection tips were stored in a rad zone for eventual disposal as rad waste.

Tools and equipment were surveyed out of the RCA. Once the smaller items were surveyed out of the area, project personnel began removing the protective covering from the Geoprobe rig. After the strippable paint and plastic covers were removed, the RCT surveyed the Geoprobe. Because the results of the Geoprobe frisk were less than 100 corrected counts per minute (< 100 counts per minute above the background level), the RCT released it from the RCA; it was loaded onto the forklift and removed from the building. The remaining equipment was surveyed out of the area, leaving only the radiological waste to be bagged, labeled, and stored for eventual monitoring and disposal. The Herculite flooring was the last to be removed, bagged, and stored for later monitoring to determine if rad waste disposal was necessary. The RCT then removed the RCA control, allowing easier access in and out of the BLIP Building.

5.1.6 Demobilization

Demobilization activities began on June 12, 2000, including packing equipment and unused supplies into crates, organizing the return of unused CS, arranging the pickup of empty tote bins, and coordinating the return of rental equipment. The grouting equipment was demobilized from BNL to Butte, Montana.

5.2 GROUT FIELD TESTING

5.2.1 Quality Assurance/Quality Control Testing

A field laboratory for CS grout testing was assembled during site preparation at the BLIP. The purpose of the field lab was to allow on-going testing of the grout quality so the emplacement team could be alerted to any irregularities in the grout mixture. The laboratory team performed material acceptance testing, electrolyte molarity testing, gel time, and viscometer testing. Figure 5-18 shows the field laboratory during viscometer and jar testing. Field equipment used during this testing included viscometer; water bath; pH meter; specific conductivity meter; thermometer; pipette; hydrometers; and various laboratory sample jars, cylinders, and beakers.

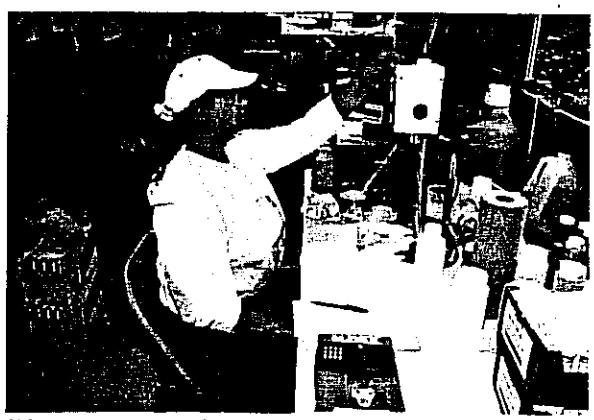

Figure 5-18. Viscometer testing in the field laboratory.

Prior to beginning grout injection activities each day, the viscometer and the specific conductivity meter were calibrated, and the water bath temperature was confirmed. The pH meter was calibrated prior to acceptance testing.

5.2.2 Acceptance Testing

Grout materials, consisting of Nyacol NP 6010 CS and one molar (M) $CaCl_2$ were delivered to the site on May 19, 2000. The specific gravity of the NP 6010 and $CaCl_2$ were measured; both were within the specified parameters. The CS viscosity and pH were also measured and were within the acceptable range. State 2 and State 9 gel times were determined using a $CaCl_2$ electrolyte solution of 0.24 M mixed with the CS for the acceptance testing. The grout gelled to State 2 and State 9, with the State 9 gel time approximately twice as long as the State 2 gel time. At State 2, the grout appears only slightly more viscous than the initial polymer solution, and viscosity readings range between 10 and 11 cP. At State 9, there is no gel surface deformation upon inversion of the sample jar, and the viscosity is approximately 70,000 cP. All grout materials were accepted following testing.

5.2.3 Electrolyte Solution Molarity Testing

The proper electrolyte solution molarity must be determined to produce a State 2 gel time of 90 minutes for the CS grout. Initial on-site laboratory testing indicated that a $CaCl_2$ electrolyte solution of 0.196 M would produce a CS grout with a State 2 gel time of 90 minutes when mixed 1 to 5 by volume with CS. Large batches of the electrolyte solution were then mixed for the deployment. Baseline viscometer and jar tests were conducted using samples from the larger batches of electrolyte solution to confirm State 2 gel times. The $CaCl_2$ concentration of 0.196 M was used throughout the emplacement of the VLB at BNL.

5.2.4 Grout Gelation Testing

A State 2 gel time of 90 minutes ± 20 minutes was the desired gel time for the VLB hot deployment.

Grout samples were collected from the flow control racks during the emplacement of the test panel and the barrier at BNL. Figure 5-10 shows the flow control racks where samples were collected throughout the VLB emplacement. A sample was collected and tested for each of the emplaced grout bulbs. Nine grout bulbs were injected to form the test panel, and 99 grout bulbs were injected to form the BLIP VLB. Out of a total of 108 grout bulbs emplaced during the VLB deployment, only 3 grout bulbs did not have State 2 gel times within the desired gel time range. These three samples were collected when the pump seals were leaking due to excessive wear. Once the seals were replaced, the desired gel time was again achieved. However, all neat grout samples collected gelled to State 9 and then cured, forming a rigid material.

5.3 TECHNICAL SYSTEMS AUDIT OF VISCOUS LIQUID BARRIER EMPLACEMENT ACTIVITIES

To ensure the QA and QC procedures outlined in the project-specific quality assurance project plan (QAPP) were being followed, a technical systems audit was performed during the emplacement of the VLB. The audit was conducted on May 31, 2000, and June 1, 2000, at BNL. The audit was conducted by observing daily activities and conducting interviews with field personnel. MSE's Project QA Officer performed the audit.

The QA/QC audit resulted in no significant findings.

The scope of the assessment included:

- documentation;
- data acquisition;
- equipment;
- emplacement; and
- safety.

5.3.1 Documentation

A logbook was maintained at the site to record the highlights of daily activities on a timeline basis. This was a bound logbook with notes being written in permanent ink. Activity worksheets were used to document data, based on the task being performed. The worksheets were used to record grout installation parameters such as pressure, flow, and injection horizons per grout bulb injected. Upon completion, worksheets were maintained in a central file at the work site.

Observation: Logbook notes were not reviewed for accuracy.

Recommendation: Implement a daily review of major completed items at the completion of the workday to recap major events and ensure documentation accuracy. Get concurrence of the Project Manager or Field Team Leader at the end of the last entry in the logbook each day. Logbook entries should be consistently kept throughout the progression of daily activities. Logbook activities should be delegated to others when key personnel are out of the construction zone.

Corrective Action: Field logbook maintenance procedures were reviewed. Proper review and formatting requirements were discussed and accepted by the Project Manager and Field Team Leader.

5.3.2 Data Acquisition

Bulb string placement documentation was gathered using a down-hole deviation tool to measure the verticality of the borehole. Data were gathered via a datalogger. The logged data were then transferred to DigiPro software via a serial data transfer link. The data could then be transferred through Excel to Mechanical Desktop modeling software for as-built emplacement drawings. The grout injection volumes were manually entered onto the preprinted data sheets. This information was manually entered into computer spreadsheets.

Observation: The bulb placement data were not transferred manually, and as a result, there was little risk of error. Injected grout volume data were manually imported to the modeling software; therefore, a slight risk of error exists with this task.

Recommendation: Verify the accuracy of the injected grout volume data after each data import.

5.3.3 Equipment

The equipment being used for grout emplacement was found to be in good working condition and used specifically for this project. Pump ratios were verified by manually measuring the desired ratios of fluids, mixing them adequately, and measuring the specific conductivity of the activated grout (mixed solution). This specific conductivity was then compared to the specific conductivity of the solution being pumped. Initial problems encountered with the pump were diagnosed to be associated with the packings in the pump. The Teflon packings were replaced with neoprene, and the pump performed very well during the remainder of the audit. A magnetic-flux flowmeter was used to meter the amount of activated grout pumped per grout bulb.

Observation: Calibration reports for this meter were not available at the site.

Recommendation: This is an issue of concern because this type of flowmeter is sensitive to the fluid being metered (i.e., it must be calibrated to the operating conditions in which it is placed). The calibration reports should be maintained at the field site to ensure the flowmeter is indicating the correct amount of grout pumped to each bulb.

Resolution: Project personnel indicated that the accuracy of the flowmeter was roughly checked by observing the volume of grout in the tote bins before and after each bulb injection. There was good agreement between these rough checks and the flowmeter readout; therefore, the flowmeter readout was used as the amount of grout pumped to each bulb for the purpose of developing an as-built representation of the VLB.

5.3.4 Emplacement and Testing

Real-time testing of grout was achieved using "jar tests," a viscometer, and specific conductivity readings as described previously. Rod verticality was checked every 6 inches for the initial rod, every 2.5 feet for the second rod, and once for each subsequent rod. This portion of the injection rod installation determined the overall direction the injection rods would take. Final borehole position was verified using the deviation tool as previously described. Overall placement of the bulb string seems to be very controlled. Multiple checks were in place to ensure proper emplacement of the barrier. The overall attitude of the field team was quality driven and focused on completing the project in the "best" available way.

Observation: A timely and effective means of communication between the Flow Control Engineer and Gel Test Engineer needed to be established. This was required to ensure that consistent testing is maintained for the grout bulb being injected.

Corrective Action: Corrective action implemented on site consisted of improved communication between the Gel Test Engineer from the Flow Control Engineer: the Flow Control Engineer would notify the Gel Test Engineer when a new injection horizon began or when injection problems occurred, and the Gel Test Engineer would notify the Flow Control Engineer of any changes in grout quality.

5.3.5 Safety

Personnel working in the radiological zone had received specialized training on the hazards associated with their work and environment. Only trained personnel were allowed in the "Hot Zone." Other members of the field team had received skill training through experience with their associated tasks. A Health and Safety Plan (HASP) was prepared for this project and work site to specifically address the associated hazards. It was a project requirement for all members of the field team to be familiar with the HASP. "Tool box" safety meetings were conducted daily before the beginning of work activities. Topics varied from day to day and included the plan of the day and related safety items.

The field crew was exposed to many hazards throughout the progression of this project. They were working extended hours (12 to 14 hours per day) 6 days a week for several weeks, in difficult conditions (80+ temperatures at 80%+ humidity). Extreme care was taken to ensure that crew members did not become complacent through repetitive duties.

Observation: Timely review of the HASP was not always maintained.

Recommendation: The HASP should be reviewed immediately by all personnel at the field site, and the HASP signature page should be signed to indicate that a worker has reviewed the HASP. Review and acceptance of the site HASP must be made from all workers entering the VLB work site. Timely review and acceptance of the HASP must be made before personnel are allowed to begin work on site.

Resolution: All personnel, other than visitors, are required to review and sign the HASP before beginning work at the site.

5.3.6 Conclusions

The audit yielded favorable comments regarding the overall activities of the field crew. There is no reason to believe that overall project quality was being sacrificed or neglected. Multiple checks of grout quality and placement were maintained throughout the emplacement process. No significant findings were identified during the assessment. The minimal finding were addressed, and corrective actions were implemented immediately.

5.4 VISCOUS LIQUID BARRIER AS-BUILTING

Near real-time as-built drawings were constructed in the field during the emplacement using injection data and grout string locations, as well as the deviation data to determine the actual grout bulb placement in the subsurface. The construction of the as-builts provided a QC check of the constructed barrier. The drawings helped determine when modifications were necessary, including redesign of grout string locations and addition of grout to fill any void spaces to compensate for injection rod deviation that had occurred.

The as-built drawings provided a QC method during VLB emplacement.

As per the design package, grout string locations were measured from the steel plates in the floor surrounding the BLIP tank. These plates were the only visible surface objects in the BNL drawings supplied to MSE that showed relationship to underground structures. Grout string locations (denoted as GS#) were not injected in a sequential fashion as shown in the design package, rather the following order was used: GS-1, GS-2, GS-8, GS-9, GS-11, GS-3, GS-10, GS-5, GS-12, GS-13, GS-16, GS-14, GS-17, GS-18, GS-19, GS-20, GS-6, GS-7, and GS-4. This injection order was followed to alleviate the potential spread of contamination and to optimize the grout injection process, as previously discussed in Section 5.1. GS-15 was not injected due to surface obstructions, but the surrounding injections were modified to compensate for this situation.

Table 5-2 lists the injection locations, differences between the designed and actual injection locations and grout volumes, and other information gathered during emplacement.

Table 5-2. Injection locations and as-built information.

Injection Location	Order of Injection	Designed # of Grout Bulbs	Actual # of Grout Bulbs	Injection Location Changes	Comments
GS-1	1	1	1	None	--
GS-2	2	6	5	None	Footing ~31' bgl
GS-3	6	7	7	18" N & 15" E	Footing ~34.75' bgl Bulb G – only 25 gal
GS-4	19	5	5	None	--
GS-5	8	5	5	None	--
GS-6	17	7	6	None	Footing ~33.00' bgl Bulb F – only 35 gal
GS-7	18	7	7	None	--
GS-8	3	6	6	None	Bulb A – only 35 gal
GS-9	4	6	6	None	--
GS-10	7	7	7	None	Footing ~34.94' bgl Bulb G – only 25 gal
GS-11	5	7	7	None	Footing ~34.75' bgl Bulb G – only 25 gal
GS-12	9	5	5	26" S & 4" W	Footing ~30.69' bgl
GS-13	10	6	6	5.5" S	--
GS-14	12	6	5	None	Footing ~30.8' bgl
GS-15	Not injected	NA	NA	NA	NA
GS-16	11	6	6	None	Footing ~31.00' bgl Bulb F – only 25 gal
GS-17	13	6	5	6" S & 12" E	Footing ~33.66' bgl Bulb F – only 10 gal
GS-18	14	7	7	None	--
GS-19	15	8	7	None	Footing ~34.50' bgl Bulb G – only 10 gal
GS-20	16	8	6	None	Footing ~34.50' bgl Bulb F – only 50 gal

The final as-built representation of the VLB shown in Figure 5-19 represents the barrier as emplaced. The drawing was constructed using the grout string locations, including those that deviated from the design, and the actual injected volumes of grout for each of the bulbs.

Included in Appendix A are seven drawings of the BLIP building (Building 931B) and its subsurface structures. These drawings were constructed from drawings provided by BNL and have been modified to represent any variations encountered during the VLB emplacement field work.

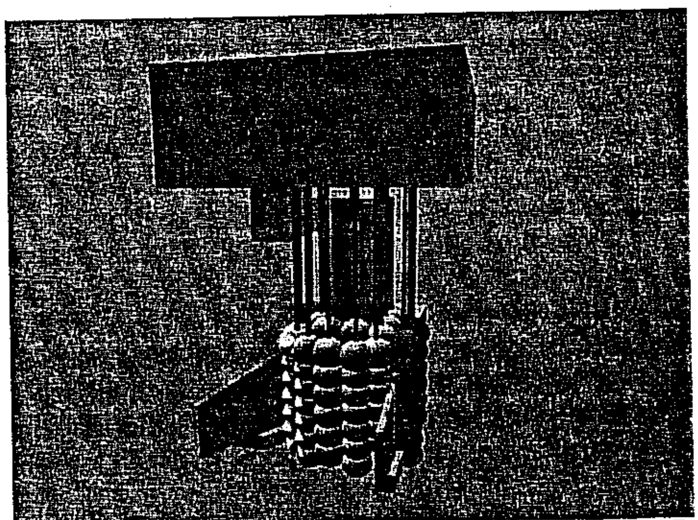

Figure 5-19. Final as-built representation of the VLB.

6. BARRIER INTEGRITY VERIFICATION

Prior to the VLB emplacement, three boreholes were installed at an angle beneath the BLIP facility to aid in the barrier integrity verification. Borehole logging was performed prior to the emplacement as a baseline and after emplacement to monitor changes in soil moisture and isotope concentrations. Any changes would most likely be a result of the barrier emplacement. The locations of the boreholes are shown in Figure 6-1.

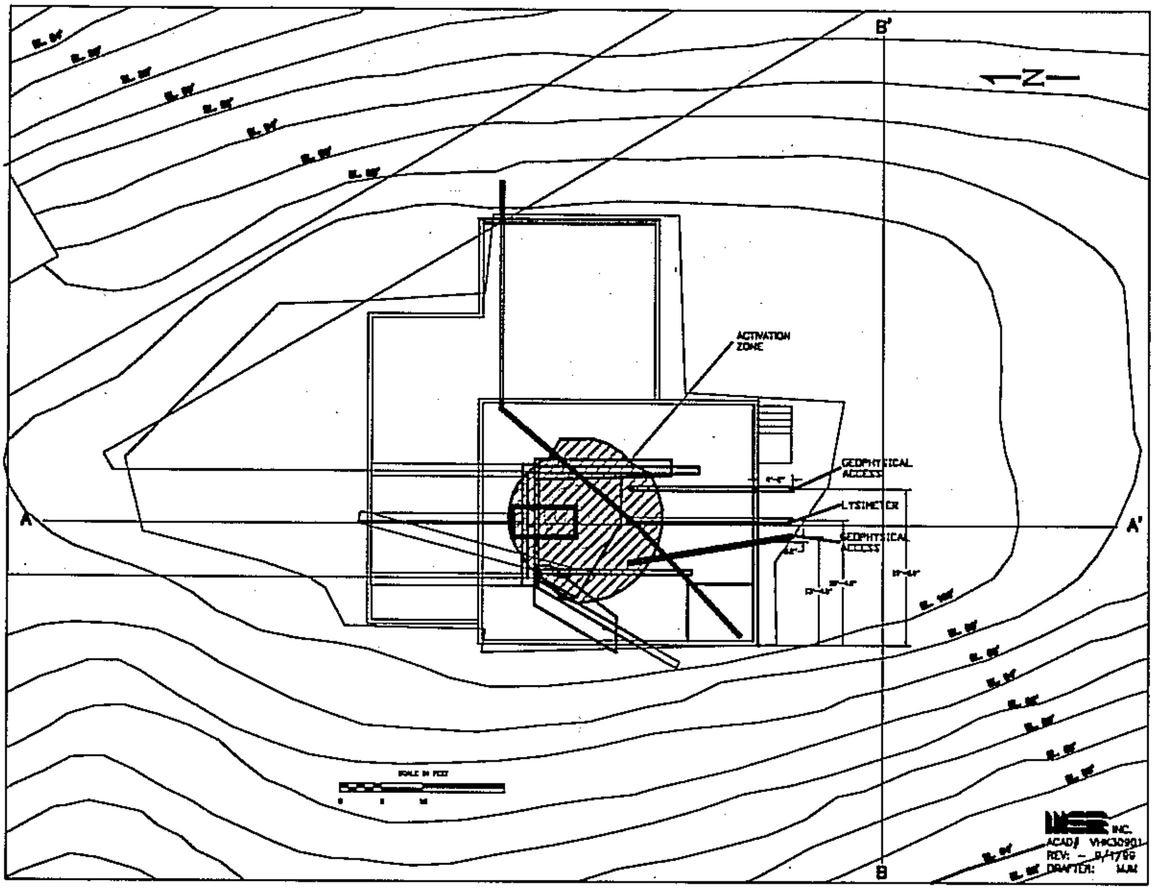

Figure 6-1. Top view of the BLIP site showing location of geophysical boreholes.

The boreholes were about 60 feet in length and installed at an angle of approximately 20 degrees from vertical (Figure 6-2).

Each borehole was completed using 2-inch-diameter polyvinyl chloride casing grouted into the borehole with a neat cement grout. Two boreholes, PM-02 and PM-04, were completed for the purpose of monitoring the site using borehole logging techniques, and the third borehole, PM-03, was equipped with a high-pressure vacuum lysimeter, approximately 50 feet bgs. With these boreholes in place, it was possible to monitor the isotope concentrations in the pore water and soil moisture beneath the VLB and BLIP.

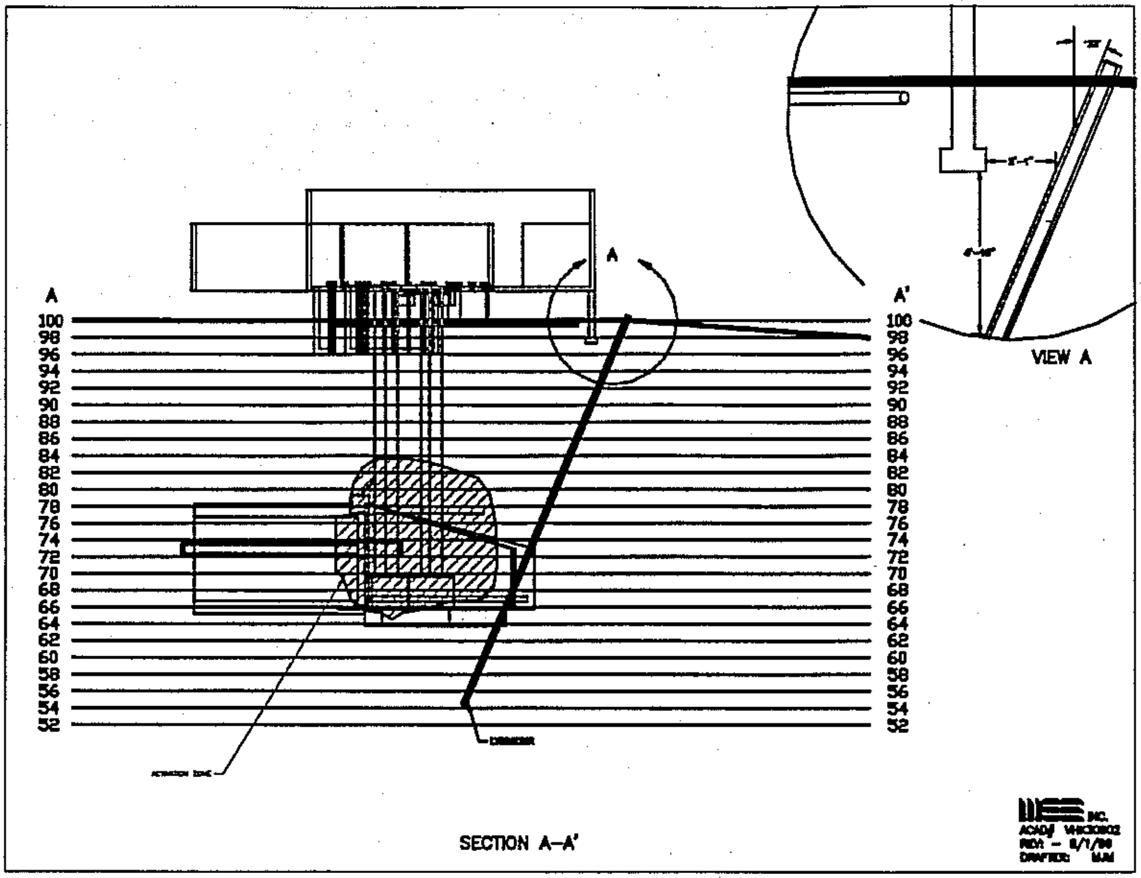

Figure 6-2. Side view of the BLIP site showing location of geophysical boreholes.

6.1 VISCOUS LIQUID BARRIER GEOPHYSICAL BOREHOLE LOGGING

6.1.1 Data Acquisition

A suite of geophysical logs was acquired in boreholes PM-02 and PM-04 on four occasions. Data were acquired twice prior to the VLB installation to establish a baseline, once within a few days after completing the VLB installation and once approximately 60 days after the VLB installation. The data acquired during these logging events included borehole deviation (first logging event only), electromagnetic (EM) conductivity, neutron–soil moisture, and spectral gamma (including total gamma). From the spectral gamma logs, the gamma ray energies associated with the ^{7}Be and ^{22}Na isotopes were extracted and plotted. Two sets of logs were acquired in each borehole during each logging event to provide independent data sets for QC.

6.1.2 Baseline Analysis

Baseline data were acquired in November 1999 and in May 2000. The resulting baseline data from boreholes PM-02 and PM-04 are shown in Figures 6-3 and 6-4, respectively.

Neutron, conductivity, and total gamma logs from May 2000 are almost identical to those acquired in November 1999. In addition, the ^{7}Be and ^{22}Na energies show no significant change.

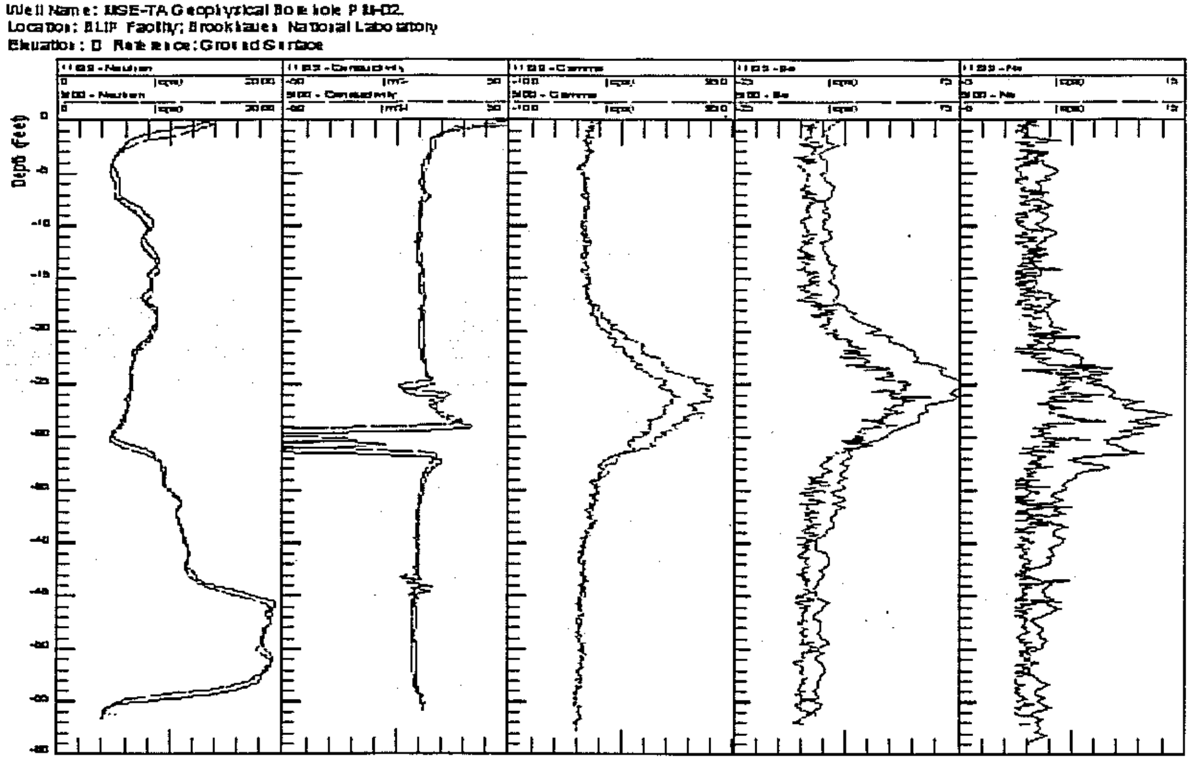

Figure 6-3. Baseline borehole logging data for geophysical borehole PM-02.

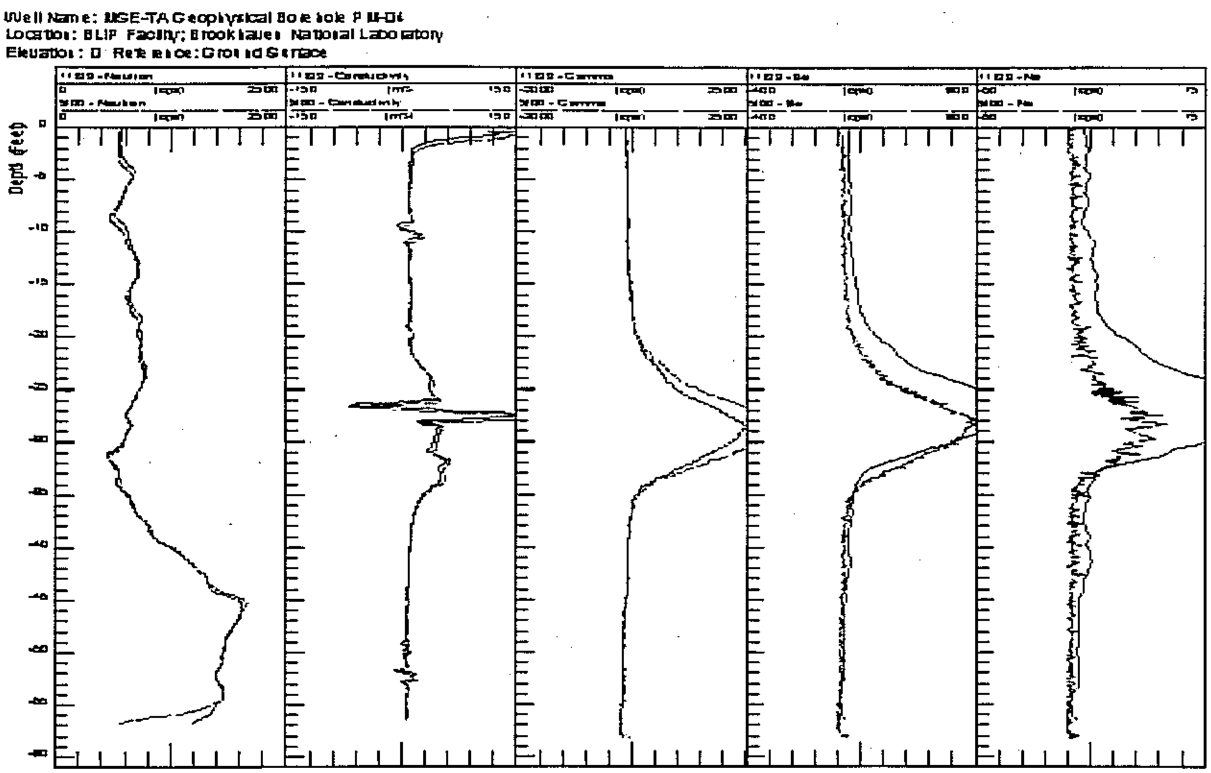

Figure 6-4. Baseline borehole logging data for geophysical borehole PM-04.

The baseline total gamma and spectral data show an area between 20 feet and 30 feet down the boreholes (corresponding to about 19 feet to 28 feet vertical depth) with a significant increase in counts per second. This indicates an increase in concentration of gamma-emitting isotopes.

The neutron logs indicate the soil moisture is fairly constant from the surface to a borehole depth of about 30 feet. From 30 feet to about 45 feet the soil moisture decreases steadily before leveling off. The neutron tool bombards the formation(s) with high-energy neutrons. Energy is lost when the neutrons collide with nuclei of comparable mass, primarily hydrogen. As a result, a lower energy reading indicates more pore fluid (water).

With the exception of a pronounced anomaly, which is seen in both boreholes (about 30 feet in PM-02 and 27 feet in PM-04), the conductivity remains fairly constant along the length of the borehole. This indicates the subsurface material is most likely consistent from the surface down to total depth.

Because of budget constraints, geophysical logging data could only be acquired twice prior to the VLB installation. Consequently, it is difficult to conclude that the two independent sampling events are representative of what occurs throughout the course of a year. To minimize the uncertainty in the baseline data, it was determined that portions of the post-VLB installation data could be used to support the two baseline data sets. The upper and lower sections of the post-installation logs should not be affected by the VLB. As a result, any changes seen in these sections could be attributed to possible seasonal affects (i.e., infiltration) in the area.

6.1.3 Post-Viscous Liquid Barrier Installation Analysis

Following the VLB emplacement, two more sets of logging data were acquired. The baseline results are shown along with both post-VLB emplacement data sets in Figures 6-5 and 6-6. The first sets of post-installation data were acquired in June 2000 (red, dashed line), within a few days of completing the VLB. The final geophysical borehole logging event was completed in August 2000 (green, dotted line), approximately 60 days after the VLB installation.

Post-installation data acquired in June 2000 (red, dashed line) show common responses in boreholes PM-02 and PM-04. Data from PM-02 show changes in the formation responses from approximately 22 feet to 35 feet (vertical depth of 21 feet to 34 feet bgs), and data from PM-04 show changes in the curves over a borehole depth of approximately 21 feet to 41 feet (vertical depth of 19 feet to 37 feet bgs). These depths correspond to the zone in which the VLB was installed.

The June 2000 neutron data indicate that soil moisture increased slightly. Conductivity and gamma logs (including the ^{7}Be and ^{22}Na energies) from the first post-installation logs also increased compared to the baseline data. These variations are most likely a result of the VLB injection. The grout used to construct the VLB is extremely conductive. As it is pumped into the formation, the grout pushes the occupying pore fluid out, closer to the geophysical boreholes. In addition, the pore fluid most likely contains some amount of contamination (gamma-emitting isotopes) from the activated zone.

The August 2000 post-installation logging results (green, dotted line) indicated there was little change in the subsurface since June 2000. In both boreholes, the two post-injection data sets are very similar in magnitude and shape, showing the same trends when compared to the pre-injection data. Additional borehole logging after an extended period of time may provide different results that could aid in effectively monitoring the barrier performance.

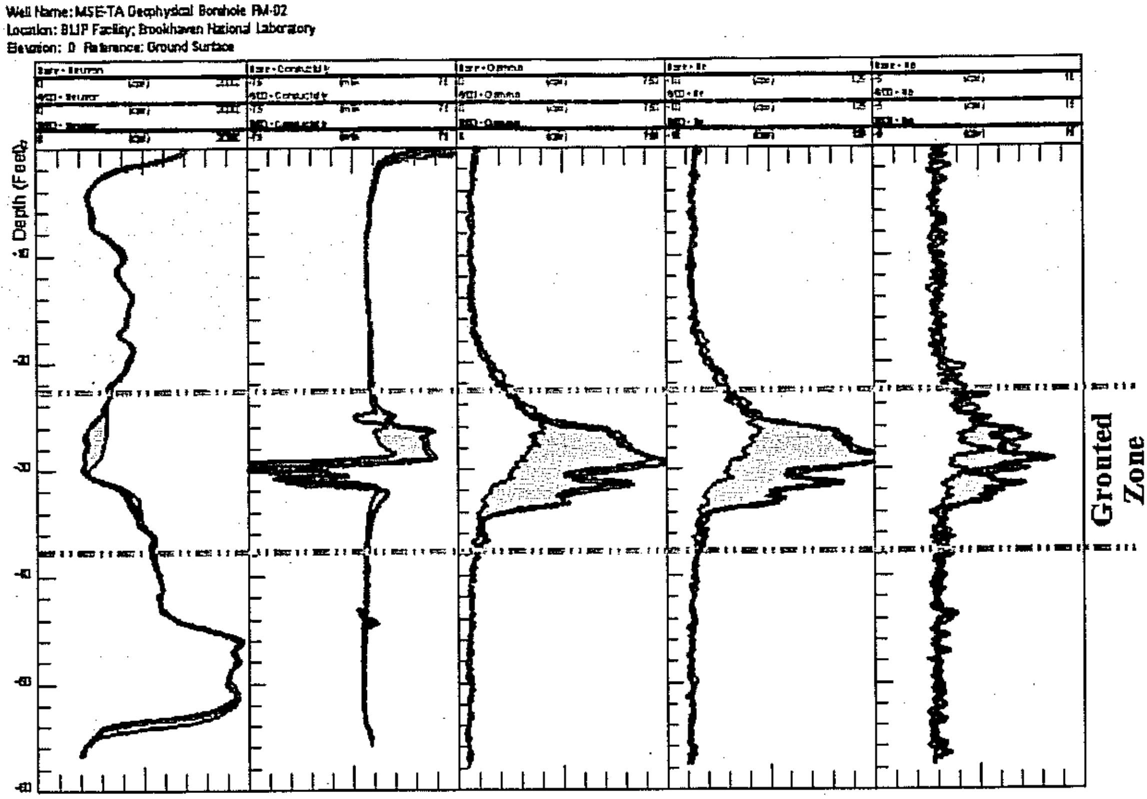

Figure 6-5. Post-VLB installation borehole logging data and baseline borehole logging data for geophysical borehole PM-02.

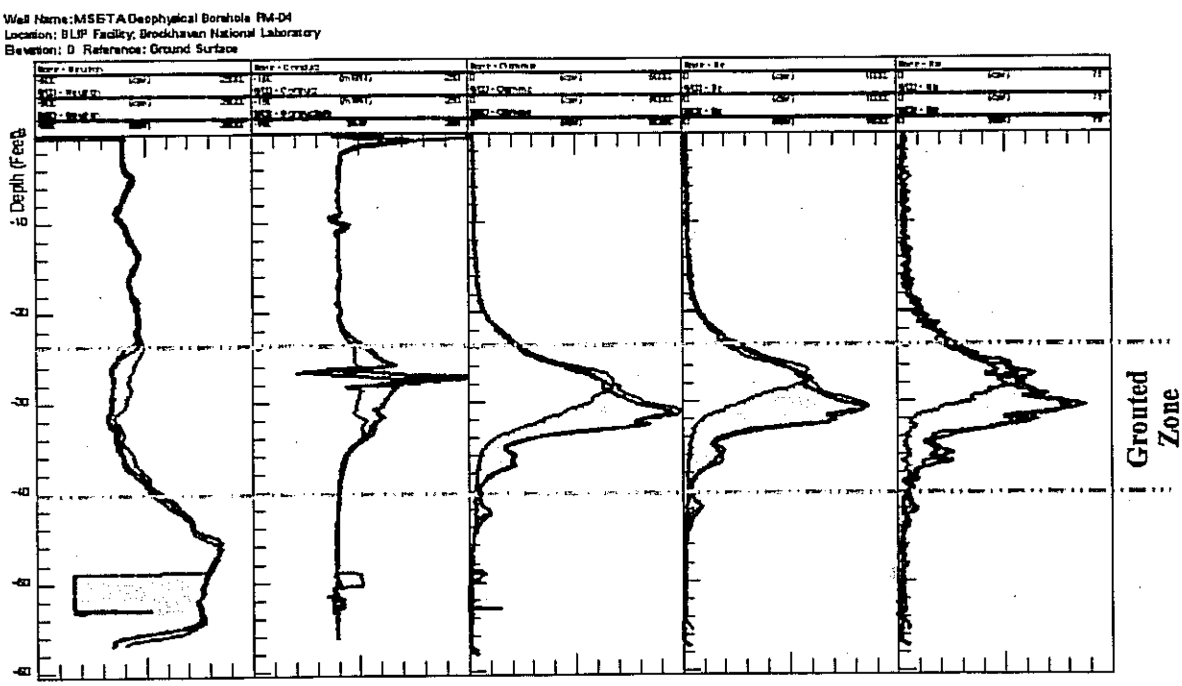

Figure 6-6. Post-VLB installation borehole logging data and baseline borehole logging data for geophysical borehole PM-04.

6.1.4 Geophysical Borehole Logging of the Viscous Liquid Barrier Test Panel

6.1.4.1 Geophysical Borehole Logging of the VLB Test Panel

In August 2000, after the initial permeameter testing, borehole EM conductivity data were acquired in two test holes drilled in the VLB test panel. The data were acquired from holes A and #3 of the test panel (Figure 6-7).

Test hole A was drilled to a depth of approximately 20 feet; and test hole #3 was drilled to a depth of approximately 21 feet. The EM conductivity borehole logs acquired along these test holes are shown in Figure 6-8.

The data from ground surface to about 7.5 feet bgs correspond to data from the upper portion of borehole PM-02 and PM-04 and are considered to represent background (ungrouted) conductivities. The EM logs show conductivity values above background (ungrouted soil) starting at approximately 7.5 feet bgs. Conductivity measurements peak approximately 9.5 feet bgs, near the center of the upper grout bulbs. Conductivity decreases but does remain higher than background readings over the remainder of the boreholes. It was expected that the conductivity measurements would remain fairly constant along the grouted zone. The notable conductivity changes seen in the borehole logs may be a result of grout material being "washed out" of the formation from the excessive amount of rain received in the weeks prior to the borehole logging, the addition of water into the formation during the permeameter tests, or a combination of both.

Permeameter test results (discussed in Section 6.2.3 of this report) for the test panel show agreement with the conductivity data (i.e., the hydraulic conductivity values are lower for the upper regions corresponding with the shallowest grout bulbs, indicating an area of more complete grouting).

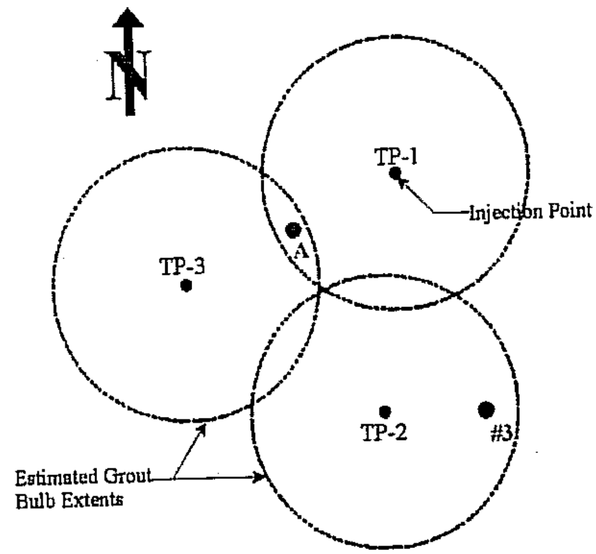

Figure 6-7. VLB test panel injecting and sampling locations.

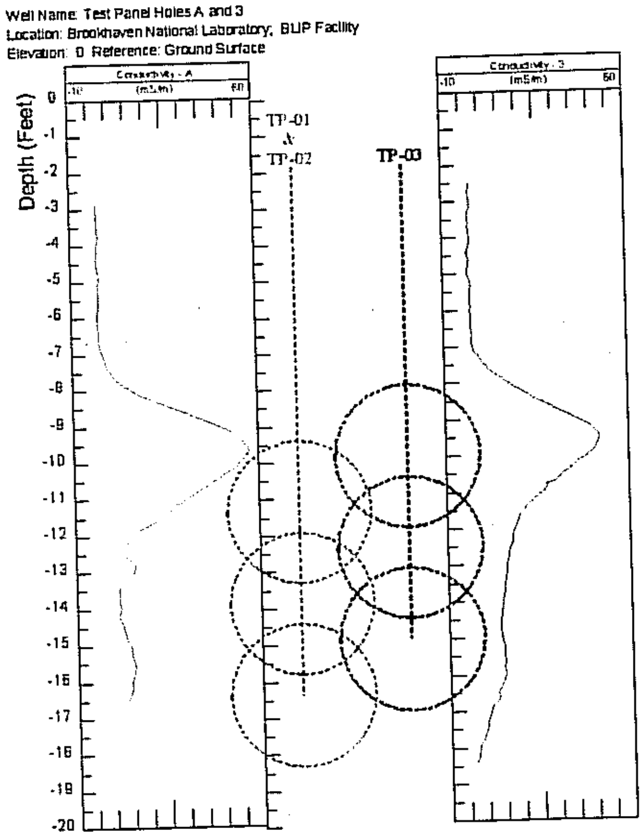

Figure 6-8. EM conductivity borehole logging data from VLB test panel test holes A and #3.

6.1.5 Lysimeter Sampling

A porous cup lysimeter was installed at approximately 46 feet along borehole PM-03. No samples could be obtained from the lysimeter over the course of the project. It is believed that the lysimeter was damaged during installation.

6.2 BROOKHAVEN LINAC ISOTOPE PRODUCER GUELPH PERMEAMETER TESTS

The in situ hydraulic conductivity of the BLIP test panel was determined using Guelph permeameters. The Guelph permeameter is a constant head device that operates on the Mariotte siphon principle and provides a method to measure saturated in situ hydraulic conductivity.

6.2.1 Guelph Permeameter Locations

6.2.1.1 August 2000

The performance monitoring plan for the BLIP designated 13 possible test locations (Figure 6-9) where the Guelph permeameters could be used. Locations A, B, C, and D are located inside the overlap zone of the grout bulbs, whereas locations 1 to 9 are outside the overlap zone, approximately 18 inches from the injection point. The permeability of the test panel was measured at three different horizons, at 10 feet, 12.67 feet, and 15.33 feet bgs. Four different boreholes were randomly selected to test at each horizon: one from inside the overlap zone and three from outside the zone. This selection process resulted in a total of 12 different permeability tests performed at 7 different locations in August 2000.

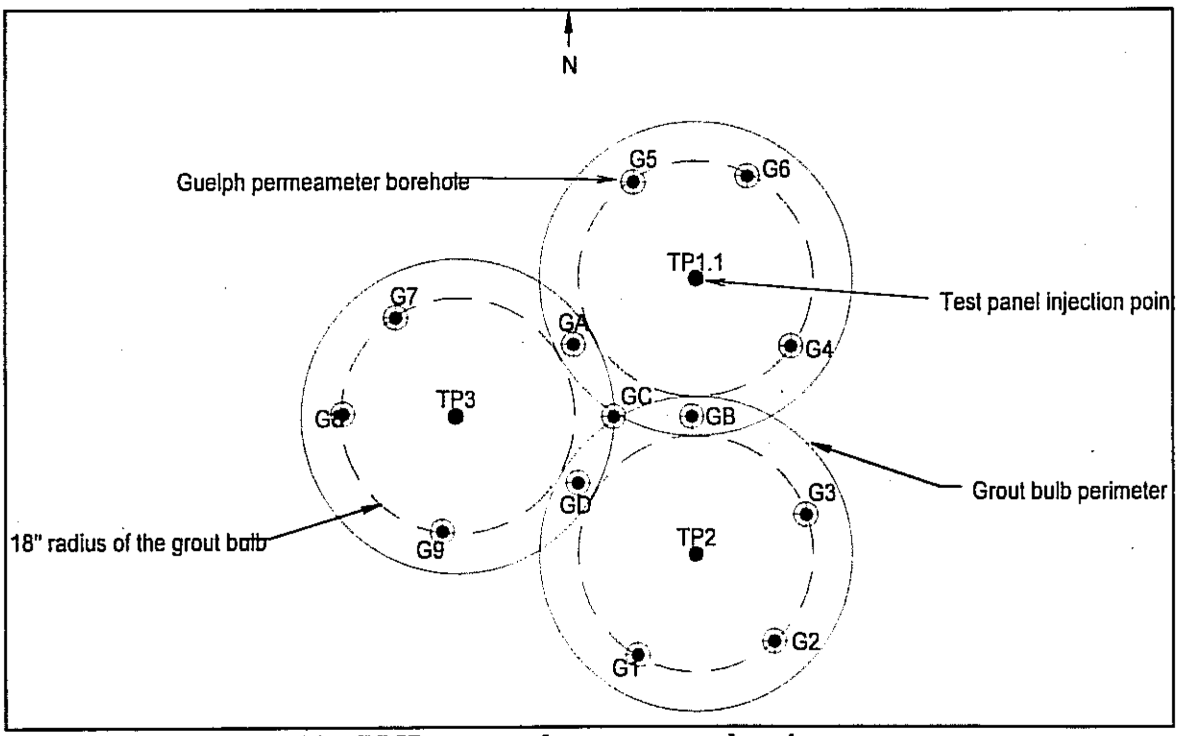

Figure 6-9. August 2000—BLIP test panel permeameter locations.

6.2.1.2 December 2000

As a consequence of the earlier Guelph permeameter testing, space for additional boreholes was limited. Boreholes for the December testing were placed where interference from the completed boreholes and simultaneous permeameter tests would be minimized. Again, the permeability of the test panel was measured at three different horizons, at 10 feet, 12.67 feet, and 15.33 feet bgs. This resulted in a total of 11 different permeability tests performed at 7 different borehole locations, both within the grout bulbs and where the grout bulbs overlap. Figure 6-10 shows the locations of all the Guelph permeameter locations, as well as the test panel injection locations.

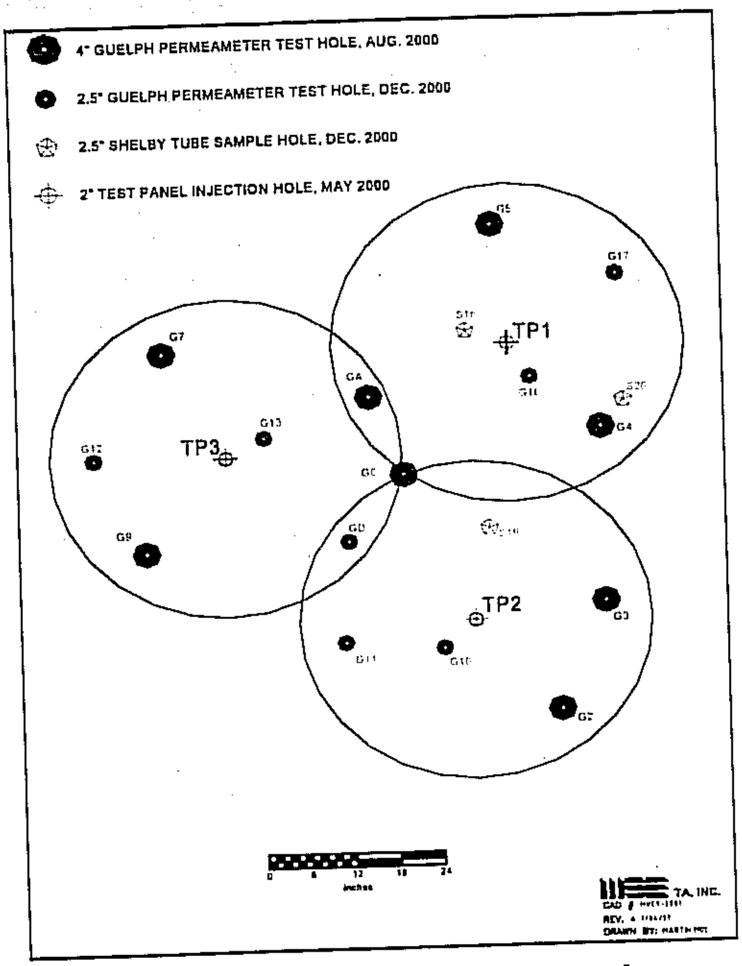

Figure 6-10. December 2000—BLIP test panel permeameter locations.

6.2.2 Guelph Permeameter Installation

Once the BLIP test panel was marked and the test holes were located (Figure 6-11), the Guelph permeameters were installed in boreholes that were drilled with a 4-inch solid-stem auger to within one foot of the test horizon. The last foot of each borehole was hand-drilled with a 2.5-inch bucket auger, then prepared by sizing the hole with a Guelph sizing auger and removing the smear layer with a well preparation brush. The effluent end of the Guelph permeameter was then placed at the bottom of the borehole and stabilized to prevent shifting during the test. Figure 6-12 shows four Guelph permeameters during testing of the BLIP test panel.

Table 6-2. BLIP test panel hydraulic conductivity values for December 2000.

Horizon	Borehole ID	Hydraulic Conductivity (cm/sec)
10 ft.	12	2.17×10^{-5}
	13	1.39×10^{-6}
	16	5.25×10^{-7}
	10	5.91×10^{-6}
12.67 ft.	10	5.30×10^{-4}
	17	1.95×10^{-4}
	D	5.17×10^{-4}
	12	4.54×10^{-4}
15.33 ft.	11	1.68×10^{-3}
	16	1.70×10^{-4}
	13	6.88×10^{-4}
Geometric mean of hydraulic conductivity values = 7.54×10^{-5} cm/sec		

The results from the permeameter testing conducted in August and December were combined and a geometric mean was calculated for each of the test horizons. The geometric mean hydraulic conductivities are 5.28×10^{-6} cm/sec, 2.77×10^{-4} cm/sec, and 3.63×10^{-4} cm/sec for 10 feet, 12.67 feet, and 15.33 feet bgs, respectively.

6.3 BROOKHAVEN LINAC ISOTOPE PRODUCER GROUNDWATER MONITORING

Note: The following section, Section 6.3, was authored by personnel from the BNL Environmental and Waste Technology Center and is included in this report to satisfy the requirements documentation for BNL.

Description of Groundwater Quality

Both tritium and ^{22}Na have been detected in the groundwater downgradient of the BLIP facility. In 1998, tritium concentrations exceeded New York Safe Drinking Water Standards (NYSDWS) in wells located directly downgradient of BLIP. However, following the implementation of the corrective measures, the tritium concentrations have dropped to well below NYSDWS.

Criteria for Selecting Sample Locations

The predominant direction of groundwater flow in the BLIP facility area is to the south-southeast. The BLIP facility is monitored using two upgradient wells (54-61 and 064-46) and seven downgradient wells (064-47, 064-48, 064-67, AGS-07, 064-49, 064-50, and 064-02). The wells are screened from 5 feet above to 10 feet below the water table. These screen positions are required because the wells are installed very close to suspected tritium source areas and will allow for the sampling of uppermost few feet of the aquifer following seasonal fluctuations in water table position. The recent detection of high levels of tritium within the uppermost 3 to 4 feet of the aquifer downgradient of the HFBR, BLIP, and g-2 Experiment facilities has underscored the need to perform routine monitoring of groundwater quality at the water table. These wells are used to verify that the engineering controls implemented at the BLIP are effective in preventing additional groundwater contamination.

Sampling Frequency and Analysis

The wells will be monitored four times per year. Three of the existing downgradient wells (064-02, 064-49, and 064-50) will be kept in reserve and only sampled as required. Samples will be collected quarterly and analyzed for the contaminants of concern, i.e., tritium and ^{22}Na.

Description and Technical Basis

During 1999, BNL installed six new monitoring wells to evaluate the effectiveness of the impermeable cap and new operational controls employed at BLIP. In early 2000, one additional downgradient well was installed to ensure that the facility could be adequately monitored under a variety of groundwater flow direction patterns. Based upon detailed knowledge of the types of radionuclides that are created near the BLIP target vessel, the only contaminants of concern that could impact groundwater quality are tritium and ^{22}Na. Therefore, the need to assess gross radioactivity levels (by using gross alpha/gross beta analyses) is no longer warranted. Although groundwater monitoring results from calendar year 1999 and the first half of calendar year 2000 indicate that tritium and ^{22}Na concentrations have fallen to levels of less than one-quarter of the drinking water standards, monitoring at this facility will remain on a quarterly schedule for at least one more year.

Data Quality Objective Analysis

Secondary particles created at the BLIP target vessel have activated some of the soils that surround portions of the vessel. BNL has been taking steps to prevent the leaching of these materials to groundwater by improving rainwater management. Rainwater management initiatives included the reconnection of the building's rain gutters, sealing paved areas, and the construction of an impermeable cap. In conjunction with the Environmental Restoration program, CS grout was injected into the activated soil area to reduce the permeability of the soils. Another potential source of groundwater contamination is the inadvertent release of activated water from the BLIP's primary cooling water system.

The collection of groundwater samples from wells located downgradient of BLIP is required to demonstrate that the operational and engineered controls are effective in protecting groundwater quality. These controls include:

- limiting the amount of soil activation by use of internal shielding material and beam focusing;
- primary cooling water management;
- reducing the permeability of the activated soils using CS grout;
- installation and maintenance of impermeable caps (geomembrane, gunnite, etc.); and
- stormwater management.

The decision for this monitoring program is:

- Are the operational and engineered controls employed at BLIP effective at preventing additional releases of tritium and ^{22}Na to groundwater at concentrations that exceed drinking water standards at the point of assessment, i.e., the closest downgradient well(s)?

Figure 6-11. BLIP test panel layout.

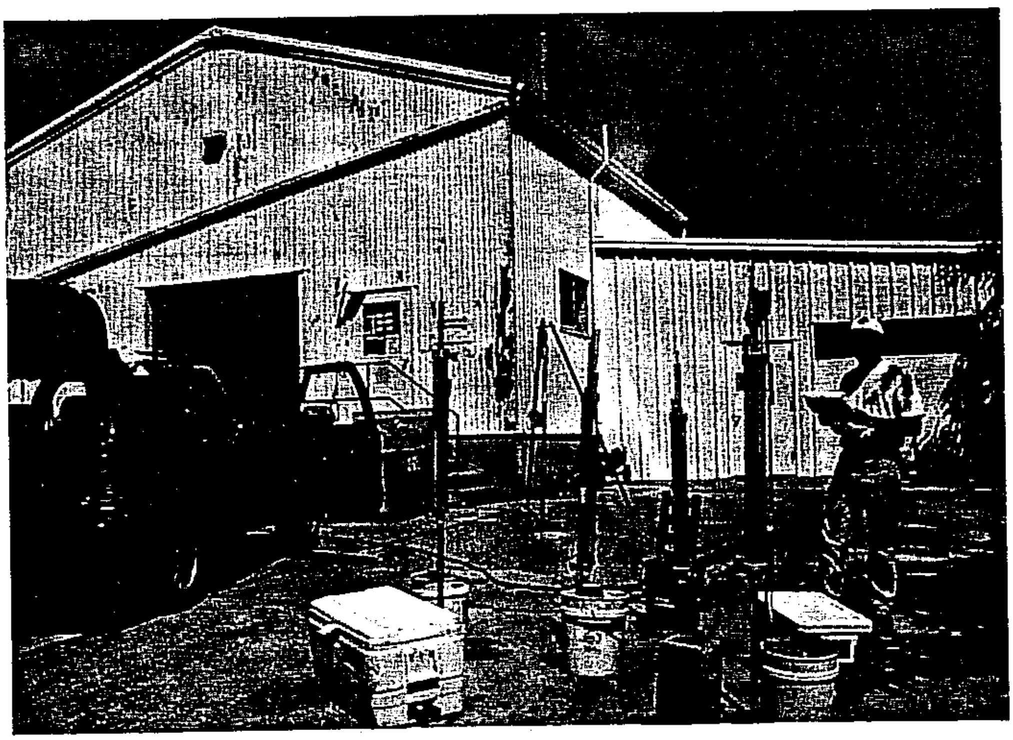

Figure 6-12. Guelph permeameter testing of BLIP test panel.

6.2.3 Guelph Permeameter Results

The Guelph permeameter data were analyzed using the single-head analysis method (Ref. 10), which uses steady-state flow rates from one constant head setting. Guelph permeameter testing was conducted in August 2000 and again in December 2000. The results are summarized below.

6.2.3.1 Permeameter Test Results–August 2000

During the early permeameter testing conducted approximately 60 days after the barrier emplacement, the permeability of the test panel was measured in four different boreholes at three different horizons, at 10 feet, 12.67 feet, and 15.33 feet bgs. This resulted in a total of 12 different permeability tests performed at 7 different locations, both within and outside of the grout bulb overlap zone.

Table 6-1 displays the locations, horizons, and permeameter test results determined using the single-head analysis method. While the hydraulic conductivity values ranged from 3.09×10^{-6} cm/sec to 1.50×10^{-3} cm/sec, the geometric mean hydraulic conductivity of the BLIP test panel was calculated at 7.63×10^{-5} cm/sec. (The in situ hydraulic conductivity of the native sands at BNL is approximately 1×10^{-3} cm/sec.)

Table 6-1. BLIP test panel hydraulic conductivity values for August 2000.

Horizon	Borehole ID	Hydraulic Conductivity (cm/sec)
10 ft.	A	3.09×10^{-6}
	7	5.06×10^{-5}
	3	4.21×10^{-6}
	2	8.88×10^{-6}
12.67 ft.	C	3.07×10^{-4}
	9	6.01×10^{-4}
	5	3.07×10^{-5}
	2	2.53×10^{-4}
15.33 ft.	A	1.50×10^{-3}
	7	1.35×10^{-5}
	5	1.14×10^{-3}
	3	1.84×10^{-4}
Geometric mean of hydraulic conductivity values = 7.63×10^{-5} cm/sec		

6.2.3.2 Permeameter Test Results–December 2000

The final permeameter testing was conducted approximately 6 months after the barrier emplacement, the permeability of the test panel was measured at three different horizons, at 10 feet, 12.67 feet, and 15.33 feet bgs. This resulted in a total of 11 different permeability tests performed at 7 different locations, both within and outside of the grout bulb overlap zone.

Table 6-2 displays the permeameter test results determined using the single-head analysis method. While the hydraulic conductivity values ranged from 5.25×10^{-7} cm/sec to 1.68×10^{-3} cm/sec, the mean hydraulic conductivity of the BLIP test panel was calculated at 7.54×10^{-5} cm/sec.

The inputs necessary for the decision include:

- Current and planned operations at BLIP
- Direction and velocity of groundwater flow
- Tritium and ^{22}Na concentrations in groundwater
- Locations of background and downgradient wells relative to each identified soil activation area
- Regulatory requirements (DOE Order 5400.1)
- Action levels (as described in the Groundwater Contingency Plan)
- Analytical methods and detection limits (as described in the Environmental Monitoring Plan)
- Tritium – EPA Method 906
- Gamma spectroscopy – EPA Method 901

The decision for this monitoring program applies to the area in the immediate vicinity of BLIP. The period for which decisions are made is 90 days. This timeframe is based upon the following:

- The time required for tritium and ^{22}Na to migrate through the vadose zone and reach the groundwater table (by means of rainwater leachate) is likely to be on the order of 30 to 60 days.
- Once the radionuclides have migrated to groundwater, the typical travel time to the nearest downgradient well (i.e., point of assessments, which are located approximately 50 feet from the source) is on the order of 75 days.
- A decision period of 90 days is required to evaluate the effectiveness of new engineered and operational controls that have been implemented in the past 3 years.

The sample results will be evaluated in context with historical data. As part of the evaluation, circumstances that would require the implementation of the Groundwater Contingency Plan (either response Category 4 or Category 3 of the plan) would be ascertained for each sampled well or set of wells. Examples of such circumstances are unusually high contaminant concentrations, detection of previously undetected contaminants, and the detection of contaminants in previously "clean" wells.

<u>Decision Rule for a Category 4 Response:</u>

If for any monitoring well:

- the tritium or ^{22}Na concentrations exceed the applicable drinking water standards (and this result is confirmed by resampling); or
- tritium or ^{22}Na concentrations indicate a new release, an unexpected release rate, or previously unknown source (and this result is confirmed by resampling); or
- if tritium or ^{22}Na concentrations increase by greater than 10 times the established baseline concentration for an existing plume,

then implement actions as prescribed in the BNL Groundwater Contingency Plan for a Category 4 response.

Decision Rule for a Category 3 Response:

If for any monitoring well:

- the tritium or ^{22}Na concentrations are greater than 50% but less than 100% of the applicable drinking water standards (and this result is confirmed by resampling); or
- tritium or ^{22}Na concentrations indicate a new release, an unexpected release rate, or previously unknown source (and this result is confirmed by resampling); or
- if tritium or ^{22}Na concentrations increase by greater than 5 times but less than 10 times the established baseline concentration for an existing plume,

then implement actions as prescribed in the BNL Groundwater Contingency Plan for a Category 3 response.

There are no potential receptors (i.e., potable water supply wells) located immediately downgradient of BLIP, and groundwater travel time to the nearest potential downgradient receptor (Potable Well 4) is greater than 5 years. Due to these factors, it is very unlikely that a decision error will result in adverse consequences to human health. Consequences associated with decision errors for this program relate primarily to possible enforcement actions for environmental degradation, erosion of stakeholder trust, and loss of BNL credibility. Ultimately, a decision error could result in degradation of groundwater quality to such an extent as to require additional remedial actions.

The wells located near the BLIP are biased toward detecting contamination originating from activated soils adjacent to the target vessel and to evaluate potential contamination that could originate from upgradient sources such as the LINAC. The downgradient wells are located as close as possible to the BLIP building to allow for early detection of contaminant releases. The current approved monitoring network is considered adequate for meeting the acceptable risk levels of stakeholders. Because the groundwater flow direction has been relatively constant in this area in recent years and the relatively small size of the potential source, no refinements are recommended.

6.4 BARRIER PERFORMANCE VERIFICATION

As mentioned in Section 3 of this report, during the sand tank testing phase of the project, grout was injected into sand tanks under simulated subsurface conditions. Grouted sand tank samples were collected and analyzed, and hydraulic conductivity data and soil moisture characteristic curves were developed for the grouted materials. Data/fitting parameters from the soil moisture characteristic curves and field parameters from the site were inputted into PORFLOW™ modeling software to simulate the flux through a 1-radian portion of the barrier. The results of the flow simulation were analyzed with respect to the barrier performance goal to reduce the flux through the barrier from 30 cm/yr to 4 cm/yr. Considering that the cross-sectional area of a 1-radian portion of the barrier is 5.61 m^2, the flux of 4 cm/yr corresponds to an outflow from the modeled region of 0.22 m^3/yr.

Total outflow from the solidified medium predicted by the model ranges from 0.00005 m^3/yr to 0.5 m^3/yr depending on the soil moisture characteristic curve used for the modeling. Modeled outflow appears to be related to the values of saturated hydraulic conductivity (Figure 6-13). This power-function relation needs to be considered site specific as the magnitude of the outflow from the solidified region depends on the mutual relationship of water retention curves for the native and the silica solidified sand. The outflow from the solidified region, if calculated using the power function relationship shown in Figure 6-12, is 0.15 m^3/yr, 0.12 m^3/yr, and 0.0077 m^3/yr for the hydraulic conductivities of 3.6×10^{-4} cm/s, 2.8×10^{-4} cm/s and 5.3×10^{-6} cm/s, respectively. This calculation indicates that the test panel (and thus the CS barrier) meets the BNL performance goal, i.e., flux through the barrier will be less than 4 cm a year or 0.22 m^3/yr.

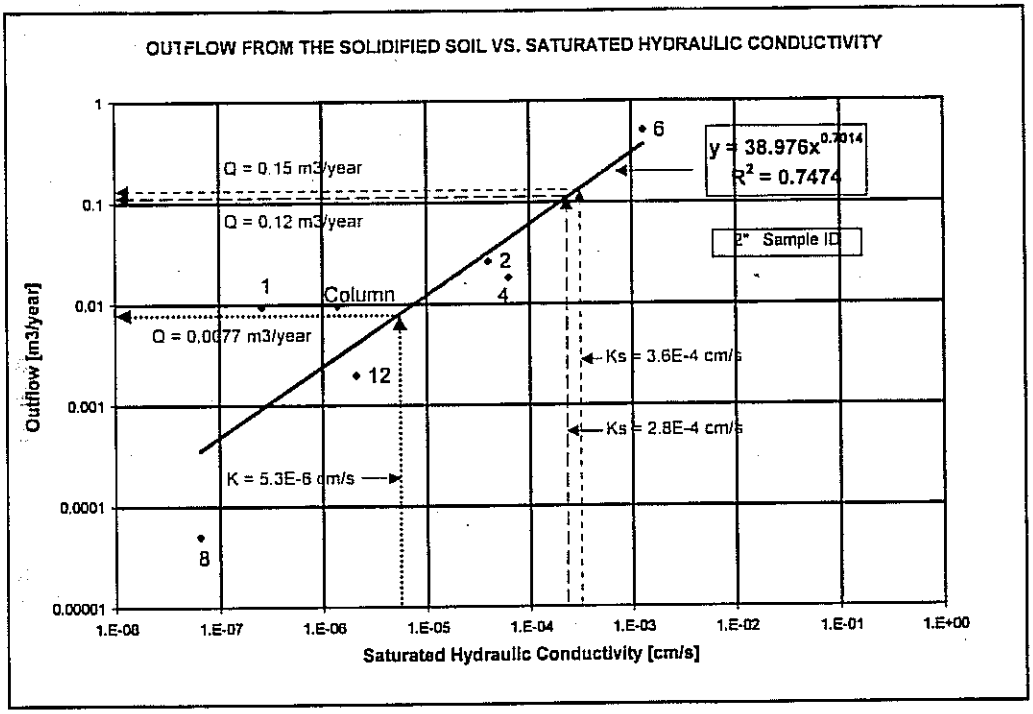

Figure 6-13. Plot of saturated hydraulic conductivity (cm/sec) vs. outflow (m^3/yr).

7. CONCLUSIONS

The primary objective of the deployment of the VLB was to construct and verify the performance of a subsurface hydraulic barrier emplaced using a viscous liquid chemical grout material (i.e., CS) and downstage permeation grouting methods at the BNL BLIP site. The overall performance objective for the BLIP site was to emplace the VLB to reduce the contaminant flux originating at the activated zone below the BLIP to the groundwater (i.e., to cause a reduction in the rate at which water moves through the soils, thereby reducing the amount of contaminants transported to the water table). The performance requirement set by BNL was to reduce the flux through the contaminated soils from 30 cm/yr to a maximum of 4 cm/yr.

The different tasks discussed in this report follow the sequence of activities that supported the overall completion of the VLB emplacement and integrity verification. After the site was selected, the site characterization followed to provide necessary data for the laboratory work. Once the laboratory grout selection and optimization testing were completed, the results were used as input to the model that simulated the subsurface response to the grout injections in a soil similar to BNL. The model predictions were favorable with respect to the performance goal developed by BNL, and all documentation to support the emplacement was reviewed and approved by the necessary regulatory agencies and the end user; consequently, the project was advanced to the field implementation stage. The field preparations, the VLB emplacement, and the associated health and safety and QA/QC activities were accomplished at the site. DOE's Brookhaven Area office was responsible for the successful regulator approval and also funded the site management activities, while BNL's Environmental and Waste Technology Center coordinated the site logistical support, completed all permitting, and managed the radiological testing. The actual deployment progressed smoothly and was accomplished earlier than anticipated due to the combined efforts of BNL and MSE.

In situ permeameter testing was conducted on the VLB test panel in August and December. The geometric means of the hydraulic conductivity results for the three different horizons (10 feet, 12.67 feet, and 15.33 feet bgs) are 5.28×10^{-6} cm/sec, 2.77×10^{-4} cm/sec, and 3.63×10^{-4} cm/sec. From past modeling of hydraulic conductivity values from BNL sands solidified with CS, a power-function relationship between the outflow and the saturated hydraulic conductivity was defined. Using the geometric means of the field measured hydraulic conductivities, the total outflow/flux from the barrier was calculated as $0.0077 m^3/yr$, $0.12 m^3/yr$, and $0.15 m^3/yr$, respectively. These results indicate that the test panel, and thus the CS barrier, meets the BNL performance goal of less than 4 cm/yr or $0.22 m^3/yr$ of flux through the barrier.

The BLIP remediation objective to remove or stabilize activated soil such that contaminants do not reach the aquifer at levels in excess of the drinking water standards (Ref. 1) has been met with an exception. Several months after the barrier emplacement, elevated levels of ^3H (in excess of the drinking water standards) were detected at monitoring wells downgradient of the BLIP. As anticipated and modeling as predicted, the emplacement of the VLB displaced the pore water from the contaminated soils, which then traveled down to the water table and was subsequently detected at the downgradient monitoring wells. The monitoring at the downgradient wells was increased to monitor the changes in the ^3H levels, and the levels have since fallen below the DWS for ^3H. The emplacement of the barrier materials caused this event, which is a one-time occurrence. The two actions, VLB containment and gunnite cap, are working together to prevent the leaching of ^3H and ^{22}Na from the activated soils surrounding the BLIP target area into the groundwater while allowing continued operation of the BLIP facility.

Per the March 10, 2000, Action Memorandum, the major threat to the environment is the contamination of groundwater because the groundwater beneath BNL is designated as a sole-source aquifer under the Safe

Drinking Water Act; it is classified as a source of potable drinking water, and it is the primary source of drinking water in the area.

While the flux through the contaminated zone and the contaminant migration to the groundwater are being reduced, these cost-effective actions are providing protection to human health and the environment.

The CERCLA removal action goal of keeping the groundwater contamination levels below the drinking water standards is being met. The VLB and cap remedial actions are consistent with the future use of BNL and are steps toward the overall remediation goals of the site.

8. LESSONS LEARNED

There were numerous lessons learned throughout the implementation of the VLB project; the primary lessons learned are categorized below.

Programmatic and Project Level

- There should be full circle communication between the technology providers, the representatives from the demonstration host site, and the regulatory community. This would enable more complete information exchange and alleviate miscommunication concerns.

- Flow through the vadose zone is much different than in the saturated zone; therefore, barrier and/or containment performance must be judged differently. Within the vadose zone, it is appropriate for the performance criteria to be based upon the resulting flux through the zone of concern rather than based on the resulting (saturated) hydraulic conductivity of the grouted area because flux through the vadose zone is dependent on soil moisutre and matric potential rather than permeability.

- The grouting contractor and equipment is crucial to the success of the barrier installation; they must be familiar with the CS grout and sensitive to its attributes and idiosyncrasies.

Technical Laboratory and Field Level

- The up-front laboratory work was critical to the material selection process and should be included in the initial testing for all future VLB projects. The testing demonstrated that the CS variants with a wide particle size distribution did not cure (i.e., strength) as fast as those with a narrower particle size range. The particle size distribution of the CS makes a difference in the ability to seal certain soil types; although they are all in the colloidal silica family, their sealing ability changes depending upon the soil type.

- Sand tank testing:

  - Native sands from the BNL site were used for all of the testing to ensure grout and emplacement compatibilities and/or problems.
  - A load cell was used to simulate subsurface conditions (higher pressures experienced at depths), which provided the opportunity to inject the grout under these conditions and experience problems that may arise during those conditions.
  - Sheet drain material was used on the side walls and bottom of the tank so the grout would not be injected under boundary conditions.
  - Weep holes were drilled in the bottom of the tank to allow drainage of displaced pore fluids, and the fluids were collected and monitored at these locations. This also proved beneficial because it alerted project personnel to the pore water displacement issues.
  - Samples were collected from the grouted sand tanks for the development of soil moisture retention curves, which were later used in the verification of barrier performance. More emphasis should be put on generating these curves early on for grout modified soils.

- The pilot hole drilling technique proved to be a good approach, especially at a radiologically contaminated site. This pilot hole provided a "catch basin" for grout that may have otherwise come up the annulus to the surface. Because of the pilot hole, personnel were not exposed to the risk of contaminated material coming to the surface and there were not the added waste disposal issues. (Less than 2 gallons of grout came to the surface during the entire emplacement.)

- Flow controllers purposely kept the grout flowing while advancing the rod string to the next injection horizon, in order to keep the injection holes from being plugged with formation sediments.

- Proper rod seals are very important. The seal at the rod connections is critical. If a connection is leaking:

  - the location of the leakage cannot be determined without retraction of the drill string;
  - leaking grout may go into undetermined subsurface areas and the amount of actual grout being delivered to the desired location cannot be determined; and
  - enough grout may leak into the annulus and come to the surface where workers may be exposed.

- Continuous grout QA/QC was necessary to maintain the grout quality and desired gel times.

- The use of the deviation tool and the near real-time as-builting were crucial to the success of the emplacement. It was not time consuming to run the tool once each grout string was completed, and it provided the exact location of the bottom of the injection hole. This allowed the near-time as-builting to be more accurately completed in the field as both a QC check and to provide design modifications when necessary. It provided the documentation of the delivery of grout to each particular location.

- The pore water displacement experienced in the sand tank testing was also an important issue. Due to the emplacement of an encapsulating barrier that encompassed the contaminated soils (as opposed to a containment barrier that would surround contaminated soils), the pore water from the contaminated soils was displaced and subsequently migrated to the groundwater. The travel time to the groundwater of the displaced pore water was modeled, and the results were consistent with the actual arrival time of the contaminants at the downgradient monitoring wells.

- Outside influences such as major rain events may have an effect on the emplaced grout in an area unprotected from these influences (e.g., grout injected 20 to 40 feet bgl directly beneath a building would not likely be affected by a rain event, whereas grout injected 10 to 15 feet bgl in a unprotected /uncapped area may be adversely affected (washed out).

9. TECHNICAL ISSUES AND GAPS

Extensive work has been performed to support the VLB technology development and deployment. Some recommendations to further advance the technology for future use throughout the Complex include the following.

- The following suggestion was made by Lead Lab member Wayne Martin of Pacific Northwest National Laboratory at the SCFA Midyear Review in Atlanta, Georgia. The VLB deployment at the BLIP site should be further tested in the future to provide more thorough results for the technology advancement and regulatory acceptance. The routine groundwater monitoring downgradient of the BLIP site will continue, but added monitoring and future sampling and laboratory testing would provide more thorough results of the emplacement (i.e., additional geophysical logging of the test panel, and additional permeameter testing).

- Other viscous liquid grout materials (e.g., polysiloxane) need to be further tested in different subsurface environments, with different contaminants and geochemical conditions. For example, CS does not perform well under high pH conditions, but there is a real need within the DOE Complex for a grout that can be emplaced in areas with subsurface infrastructure and high pH contaminants. To date, colloidal silica is the only viscous liquid tested on a demonstration scale; one small-scale injection of polysiloxane was conducted at Los Banos, California, by LBNL.

- Currently, there is no simple, inexpensive, and reliable, method to test in situ hydraulic conductivities in the field. The field method used for this project, Guelph permeameter measurements, may not be sensitive enough for the lower hydraulic conductivities (i.e., the hydraulic conductivities being measured may be near or beyond the limits of the apparatus, $< 10^{-6}$ cm/sec). Although we recommend that flux be used to evaluate barrier performances in the vadose zone, there needs to be some field measurement of saturated hydraulic conductivity to be used in the modeling to determine the flux, or there needs to be a field measurement to directly determine flux.

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APPENDIX A

MSE Drawings

NOTE

A: NOT ALL INTERIOR OR EXTERIOR FEATURES OF BUILDING 931B ARE SHOWN. ONLY FEATURES DEEMED NECESSARY FOR THIS PROJECT AND REPRESENTED ON DRAWINGS RECEIVED FROM BROOKHAVEN ARE ILLUSTRATED.

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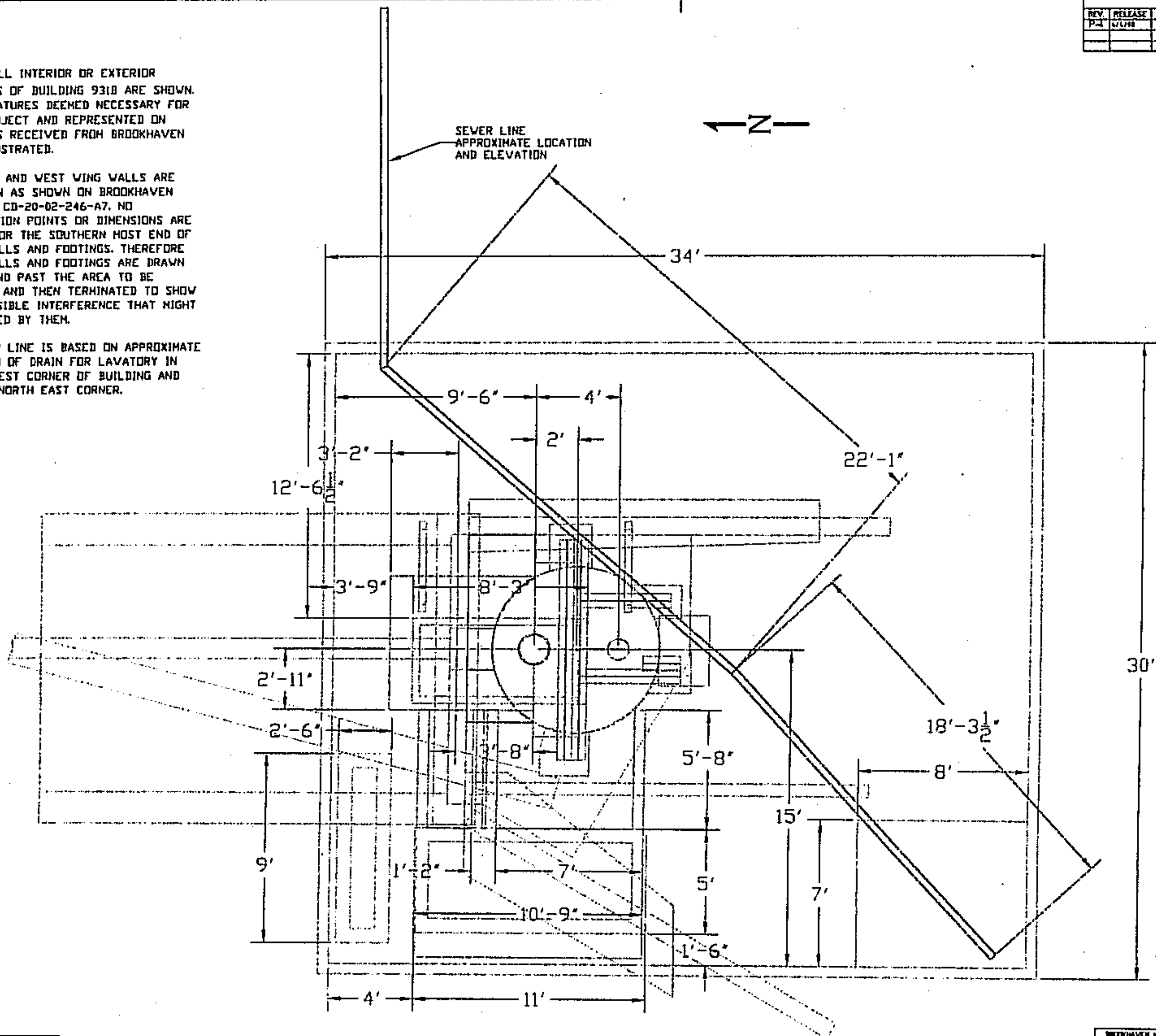

REVISIONS

REV.	RELEASE	DESCRIPTION	DFTR	R.ENG	C.ENG	P.ENG	P.MGR	CK
P-1	4/1/98		HJH				N/A	N/A
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							N/A	N/A

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LINAC ISOTOPE PRODUCER SITE

MSE TA, INC.
MSE TECHNOLOGY APPLICATIONS, INC.
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Butte, MT 59702

BLIP SITE
VISCOUS LIQUID BARRIER DEMONSTRATION,
PLAN VIEW BUILDING 931B
DIMENSIONS AND UNDERGROUND UTILITIES

DWG. NO. VHE-10AR-0004
REV. P-1
CAD # VHE10AR0004
SHEET 1 OF 100
GROUP AR-5
SPEC # SPEC
SCALE: NONE

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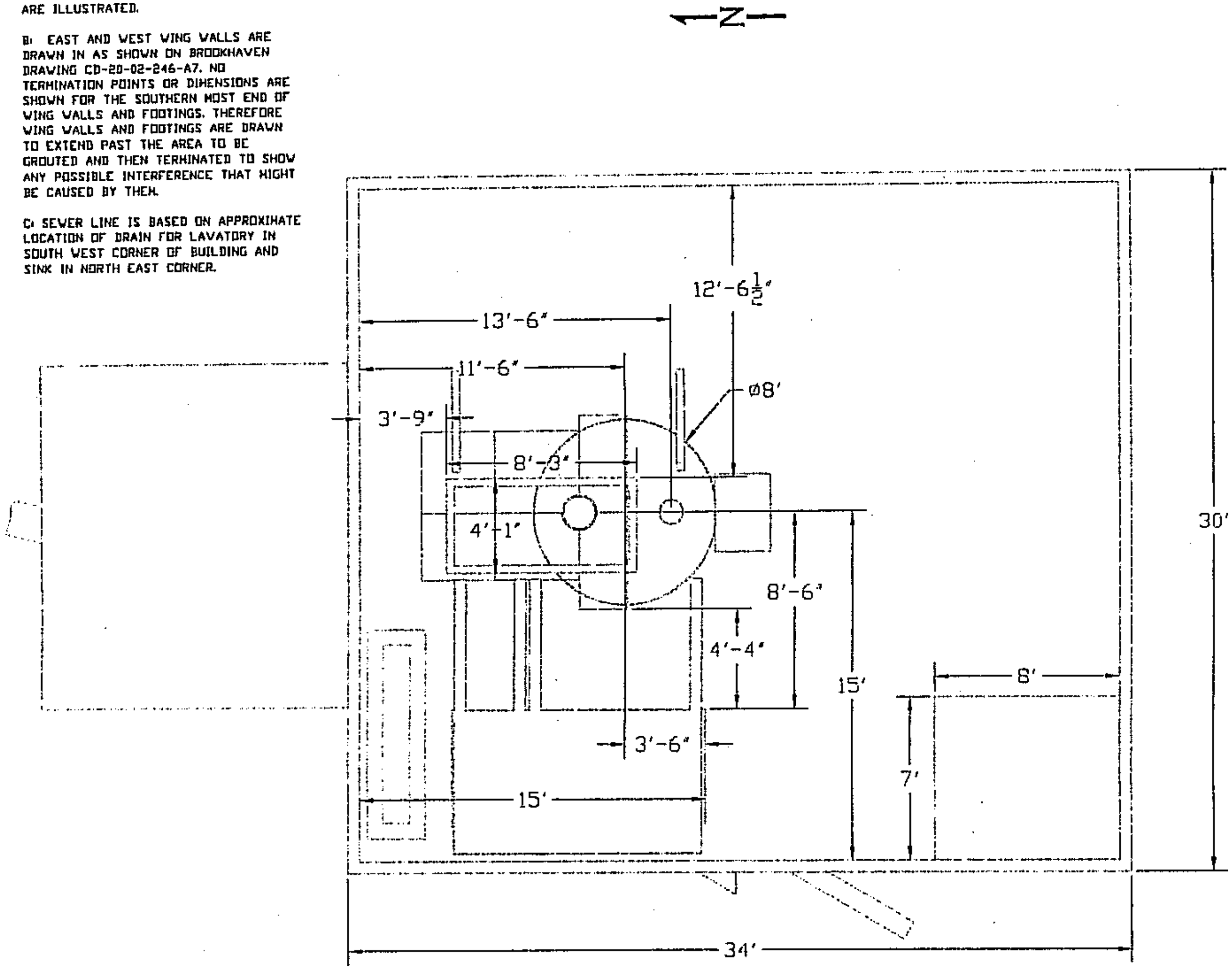

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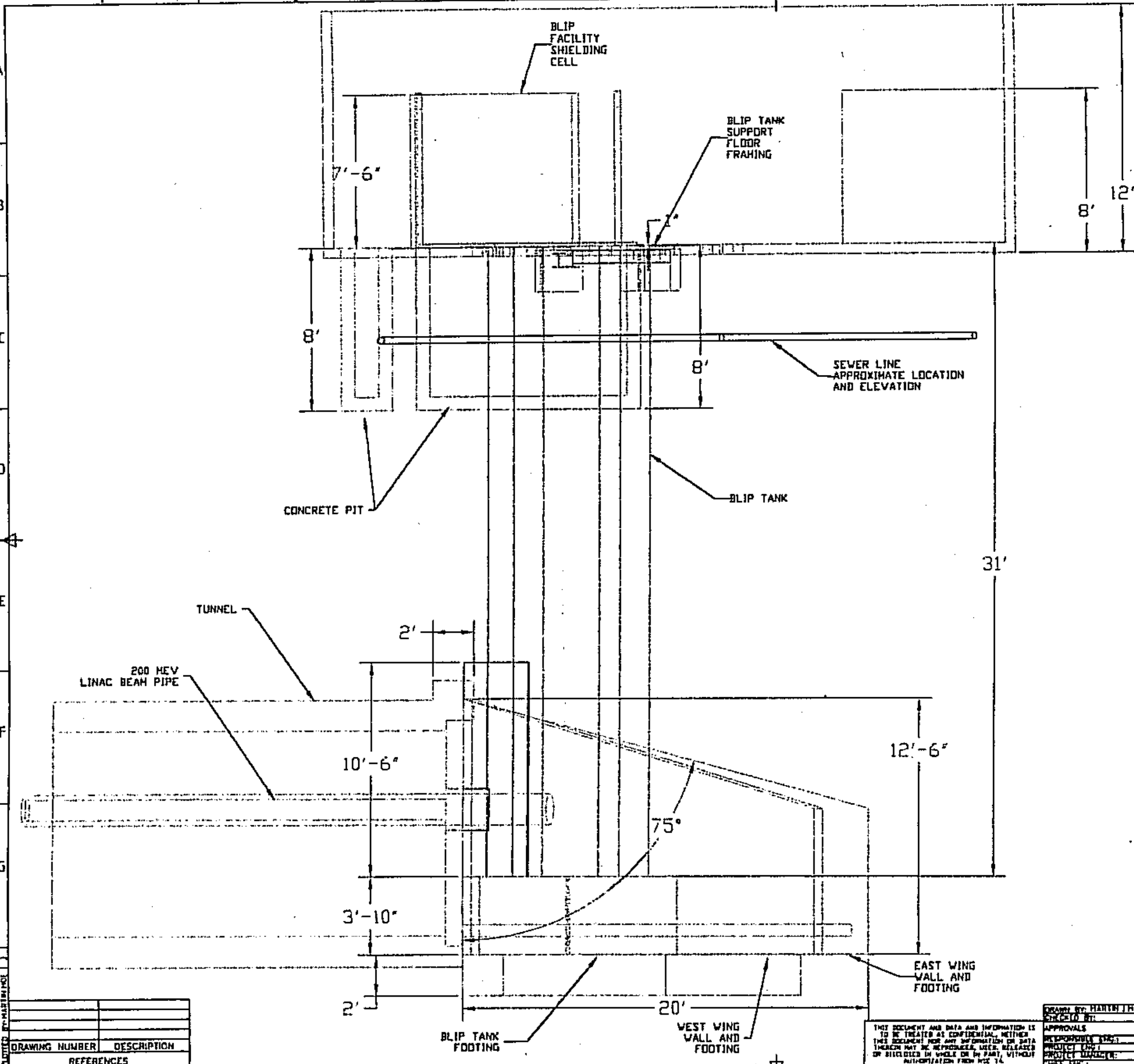
BLIP SITE
VISCOUS LIQUID BARRIER DEMONSTRATION
BUILDING 931
INSIDE LAYOUT PLAN VIEW

DWG. NO. VHE-10AR-0005 | REV. P-4
CAD # VHE10A-0000 | SHEET 1 OF 100 | GROUP AR-6
SPEC # SPEC | SCALE: NONE



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BLIP SITE, VISCOUS LIQUID BARRIER DEMONSTRATION, ELEVATION VIEW LOOKING WEST TO EAST SHOWING BUILDING 931B BLIP AND TUNNEL FOR 200 MEV LINAC BEAM

DWG. NO. VHE-10AR-0002 · REV. P-4
CAD # VHE10AR0002 · SHEET 1 OF 100 · GROUP AR-3
SPEC # SPEC · SCALE: NONE

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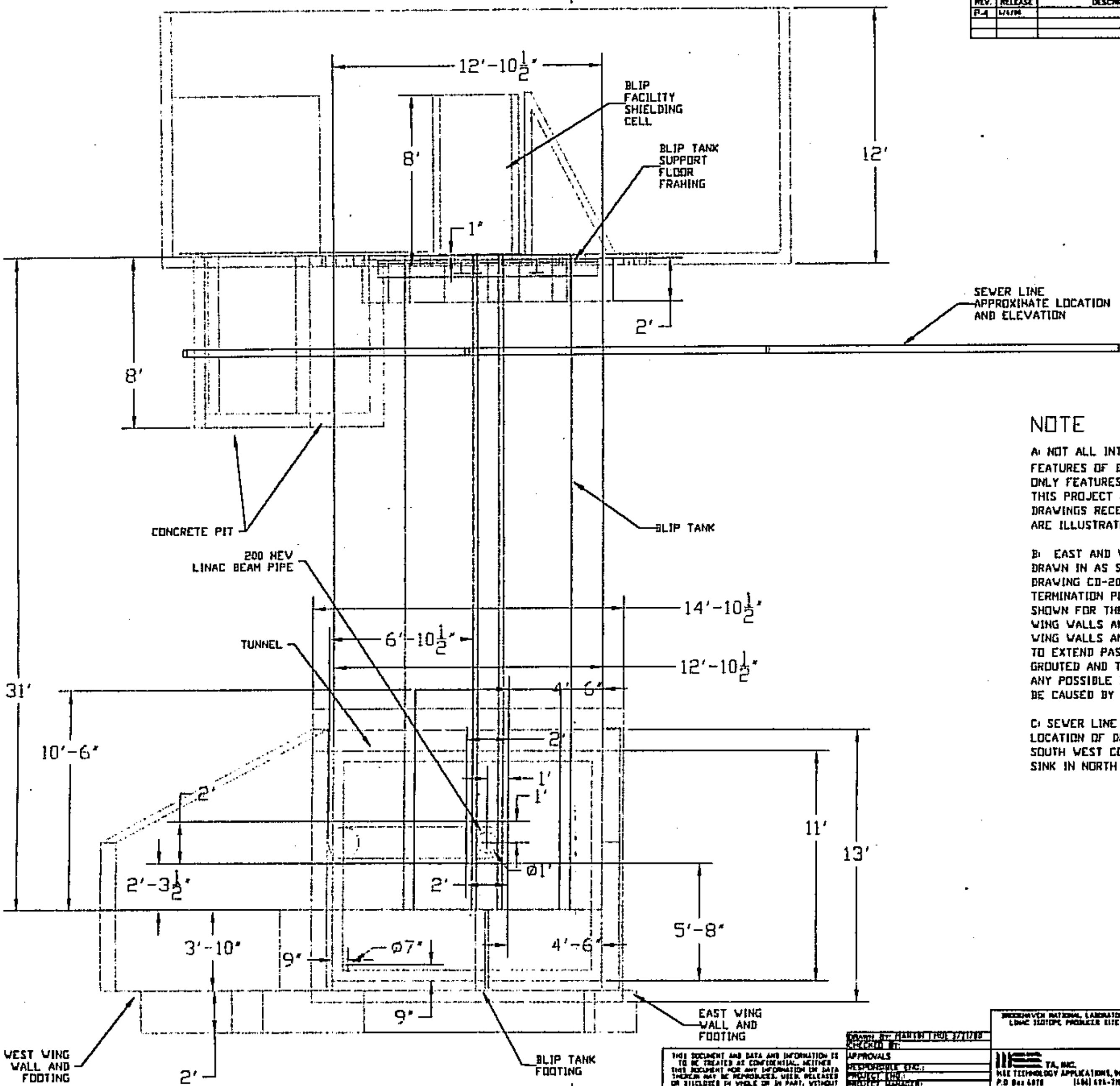

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BROOKHAVEN LINAC ISOTOPE PRODUCER SITE, VISCOUS LIQUID BARRIER DEMONSTRATION ELEV. VIEW LOOKING SOUTH TO NORTH SHOWING BUILDING 931B BLIP AND TUNNEL FOR 200 MEV LINAC BEAM

DWG. NO. VHE-10AR-0003 | REV. P-4
CAD # VHE10AR0003 | SHEET 1 OF 1 | GROUP AR-4
SPEC # SPEC | SCALE: NONE

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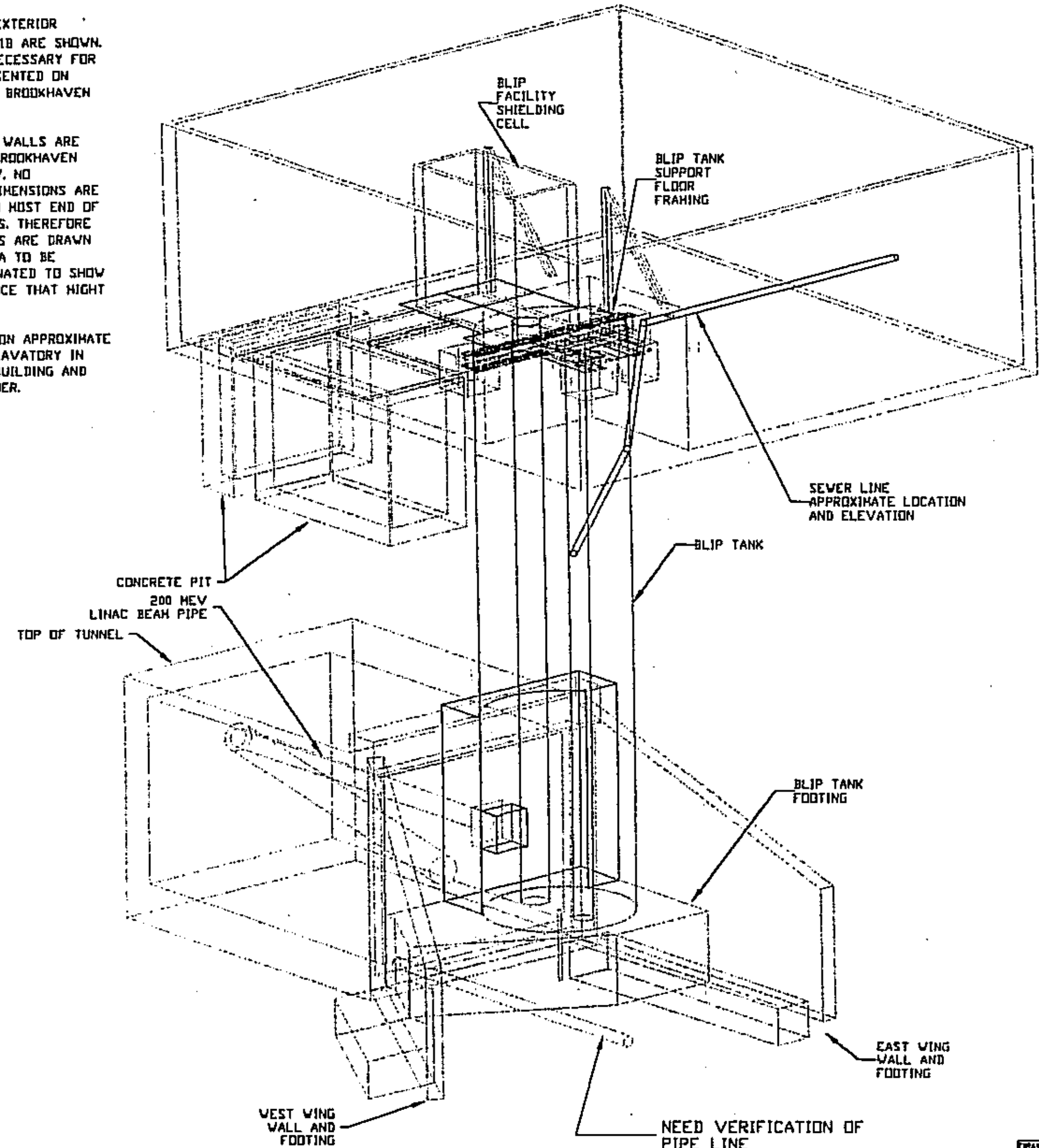

VHE-10AR-0001	PLAN VIEW SHOWING ELEVATION VIEW ORIENTATION & DIRECTION
VHE-10AR-0002	ELEVATION VIEW LOOKING WEST TO EAST SHOWING BUILDING 931B BLIP AND TUNNEL FOR 200 MEV LINAC BEAM PIPE DETAIL AND DIMENSIONS
VHE-10AR-0003	ELEVATION VIEW LOOKING SOUTH TO NORTH SHOWING BUILDING 931B BLIP AND TUNNEL FOR 200 MEV LINAC BEAM PIPE DETAIL AND DIMENSIONS
VHE-10AR-0004	PLAN VIEW BUILDING 931B BLIP DIMENSIONS AND UNDERGROUND UTILITIES AND STRUCTURES
VHE-10AR-0005	PLAN VIEW BUILDING 931B BLIP EXISTING FEATURES LAYOUT AND DIMENSIONS
VHE-10AR-0006	PLAN VIEW BUILDING 931B BLIP EXISTING UNDERGROUND FEATURES LAYOUT AND TUNNEL FOR 200 MEV LINAC BEAM PIPE

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BLIP SITE VISCOUS LIQUID BARRIER DEMONSTRATION, ISOMETRIC OF STRUCTURE AND BUILDING 931B

DWG. NO. VHE-10AR-0000 REV. P-4
CAD # VHE10AR0000 SHEET 1 OF 100 GROUP AR-1
SPEC # SPEC SCALE: NONE

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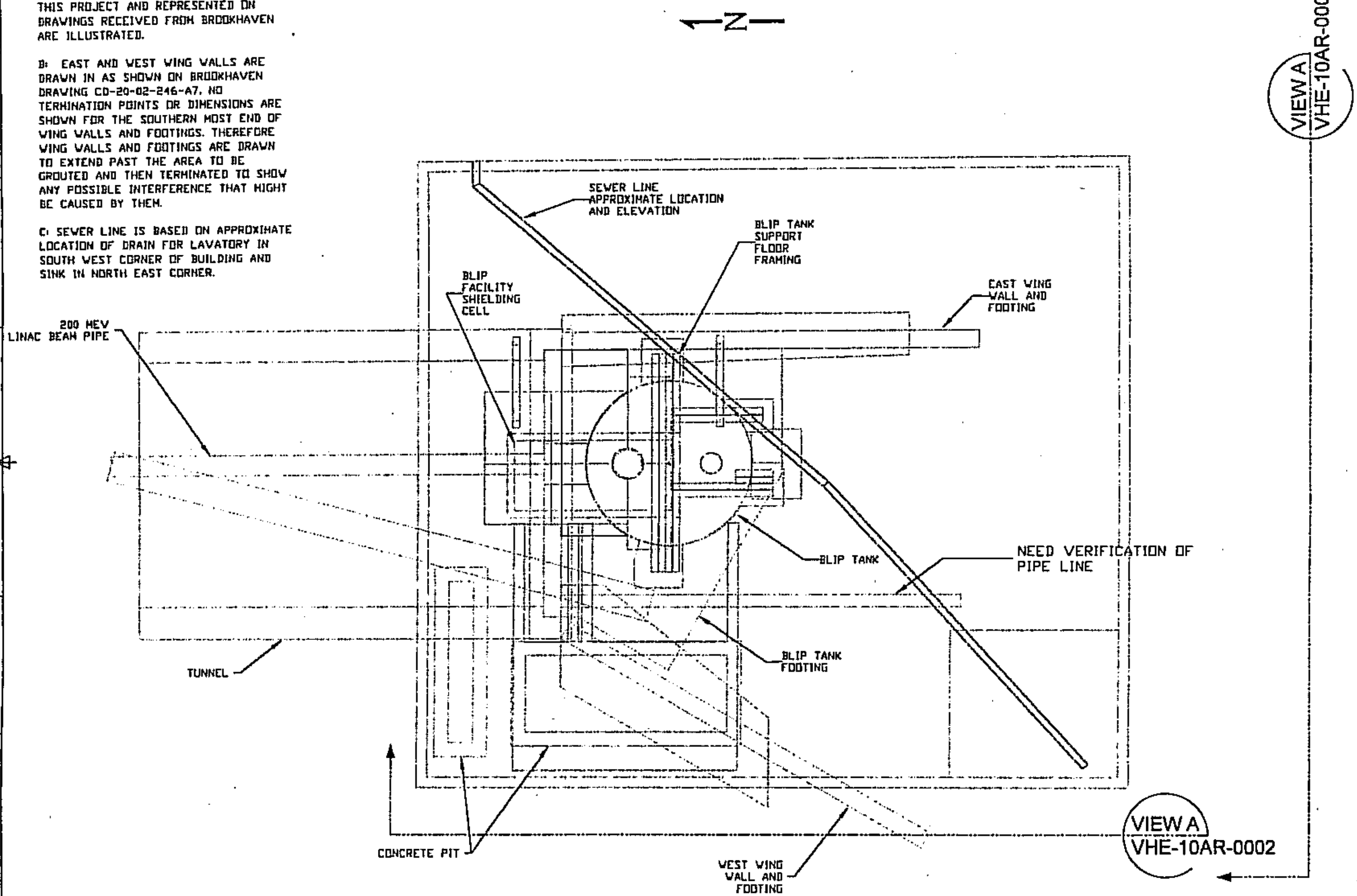

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DWG. NO. VHE-10AR-0001 REV. P-4
CAD # VHEIGA0001 SHEET 1 OF 100 GROUP AR-2
SPEC # SPEC SCALE: NONE

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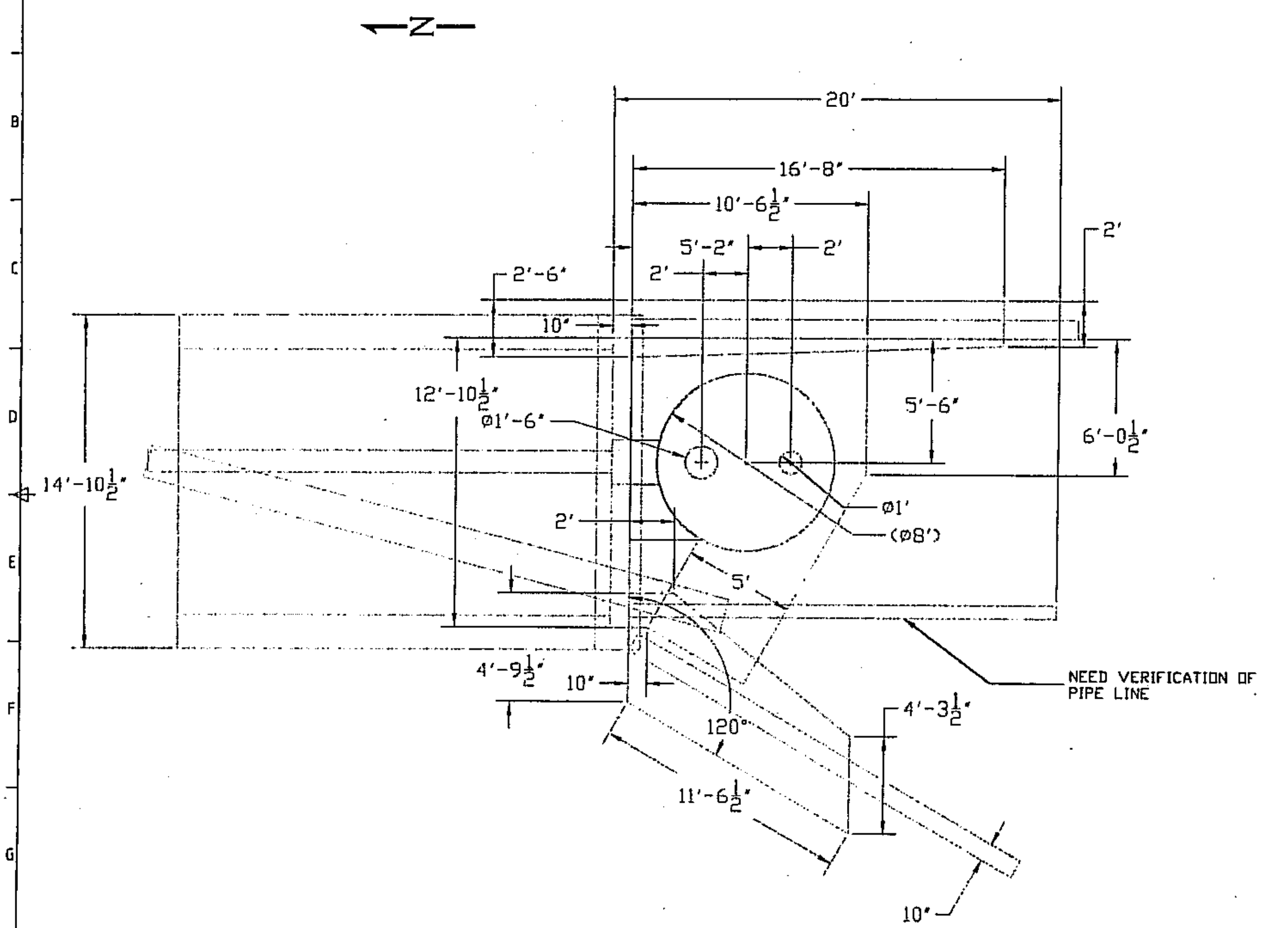

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REV.	RELEASE	DESCRIPTION	DFTR	R.ENG	C. ENG	P. ENG	F. MGR	CX
P-1	6/6/98		MJM				N/A	N/A
							N/A	N/A
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BLIP SITE
VISCOUS LIQUID BARRIER DEMONSTRATION, PLAN VIEW SHOWING BUILDING 931B BLIP EXISTING UNDERGROUND FEATURES

DWG. NO. VHE-10AR-0006 | REV. P-4
CAD # VHE10A0006 | SHEET 1 OF 100 | GROUP AR-7
SPEC # SPEC | SCALE: NONE

APPENDIX B

BROOKHAVEN
NATIONAL LABORATORY

Brookhaven Linear Isotope Producer (BLIP)

Groundwater Status Report

September 14, 2001

Drew B. Bennett
Douglas Paquette
Environmental Services Division

Brookhaven National Laboratory
Operated by
Brookhaven Science Associates
Upton, NY 11973

Under Contract with the United States Department of Energy
Contract No. DE-AC02-98CH10886

GW82ER.01

Brookhaven Linear Isotope Producer (BLIP)
Groundwater Status Report
September 14, 2001

Brookhaven National Laboratory's (BNL) Environmental Management System includes a comprehensive groundwater protection program that relies primarily on pollution prevention -- using operational and engineered controls to prevent contamination from entering the groundwater. Since BNL is situated over a sole source aquifer, it is a priority for BNL to protect that resource. Since 1997, BNL has been conducting a systematic and comprehensive evaluation of its active research and support facilities for their potential to impact groundwater quality and to identify any necessary corrective actions.

The primary concern in the Collider-Accelerator Facility areas is the potential activation of soils used as shielding material near 23 accelerator beam stop and target areas. Rainwater infiltrating these soils has the potential to leach tritium and sodium-22 into groundwater. See the BNL website http://www.esh.bnl.gov/esd/gw.htm for more details on groundwater protection programs at these facilities.

One facility in the Collider-Accelerator Facility area is the Brookhaven Linear Isotope Producer (BLIP). BLIP is an active facility used to make medical isotopes by hitting targets with high-energy protons. These interactions, along with producing the isotopes, release neutrons that penetrate the shielding material and cause activation of the soil surrounding the BLIP target. In the past, nearby groundwater monitoring wells helped determine that rainwater was coming in contact with these activated soils and leaching tritium and Na-22 into the groundwater at concentrations greater than drinking water standards. A detailed groundwater investigation in that area in 1998 detected tritium concentrations of 52,000 pCi/L. The drinking water standard for tritium is 20,000 pCi/L.

In response to the 1998 groundwater investigation, BNL began to take action to improve water management on the surface by diverting rainwater away from the activated soil region and installing a cement (gunite) cap. According to the 1999 and early 2000 groundwater monitoring data, these actions were effective in controlling this source of groundwater contamination. In September 1999, an Engineering Evaluation/Cost Analysis (EECA) was completed. This analysis recommended that the activated soil zone near the BLIP target be stabilized with colloidal silica grout as an additional remedial action. The purpose of the grout injection was to reduce the permeability of the activated soil to minimize leachate generation.

A Viscous Liquid Barrier (VLB) technology was selected and deployed through DOE's Subsurface Contaminants Focus Area (SCFA). The VLB technology was deployed for the first time at BLIP and helped SCFA achieve the first hot deployment of a technology whose development and demonstration the SCFA has supported since 1996.

The viscous liquid barrier was installed at BLIP in May/June 2000 by MSE, Inc. In July 2000, the quarterly groundwater monitoring program at BLIP did not detect tritium in excess of the drinking water standard. In the next sampling period, October 2000, one of three wells 40 feet downgradient from the BLIP detected a tritium concentration of 56,000 pCi/L, which is in excess of the drinking water standard. The other two wells had tritium concentrations that were less than 5,000 pCi/L. Because the aquifer is a sole source aquifer, exceeding the drinking water standard again in October 2000 triggered a number of actions at the BNL site including implementation of BNL's Groundwater Protection Contingency Plan. The groundwater contingency plan is implemented to address off-normal groundwater monitoring data and includes a series of near and long-term actions and communications to address the groundwater issue detected. It is a serious step that reflects the BNL stakeholder concerns over protecting the environment. This plan requires a number of formal actions including notification of BNL management, DOE and BNL regulators as well as development of strategies to address the issue.

The following is a chronology of the BLIP groundwater issue and a comprehensive summary of actions to date:

- 1998 - Detailed groundwater characterization study. The highest tritium and sodium-22 concentrations (52,000 pCi/L and 151 pCi/L, respectively) were detected in wells installed approximately 20 feet downgradient of the BLIP. This tritium contamination was probably due to rainwater coming in contact with activated soils near the BLIP target.
- 1998 - Repaired roof drains, sealed pavement, and constructed gunnite cap over the target area to prevent infiltration of rainwater. These actions prevent rainwater from entering the soil and moving contaminants into the groundwater.
- March 1999 - Enhancements to the groundwater-monitoring program used to verify that the operational and engineered controls of the source area are effective.
- May through June 2000 - Injected silica grout into the area of activated soil. This grout is designed to solidify and "lock" contaminants in place so they cannot migrate into the groundwater. This process was performed as an innovative technology demonstration project. (http://www.dne.bnl.gov/ewtc/blip.htm)
- October 11, 2000 - Detection of tritium at a concentration of 56,000 pCi/L 40 feet downgradient of the source triggered BNL's Groundwater Protection Contingency Plan. (This tritium contamination was due to the silica grout injection process.)
- November 1, 2000 - More frequent groundwater sampling was initiated.
- October 2000 – February 2001 - Several site inspections and technical meetings were held including technical assistance from DOE's Subsurface Contaminants Focus Area. The review concluded that the use of the innovative VLB technology likely displaced some soil pore water contaminated with tritium into the groundwater. The magnitude of this displacement was not expected.

The tritium release from the grout injection is expected to be a one-time event and will dissipate relatively quickly in the aquifer. This information is being used to improve this innovative grouting technology. Groundwater monitoring continues to ensure that the source controls remain effective and the one-time tritium release is dissipating in the aquifer.

This status report provides a summary of the groundwater monitoring data since the VLB deployment. **Figure 1** shows the location of groundwater monitoring wells used to monitor BLIP. A comparison of the BLIP monitoring well locations with BNL's quarterly water table maps has confirmed that the wells are still located properly to detect releases to groundwater from the BLIP facility.

Table 1 is a summary of the monitoring well data since mid-2000. Of the 6 wells in the monitoring system, only two wells have detected tritium above drinking water standards. They are wells 64-67 and 64-50. These wells are located 40 and 150 feet downgradient of the contaminant source. **Figure 2** shows the tritium activity with time at these two wells. Tritium concentrations in the remaining BLIP monitoring wells remained at activities less than 25% of the drinking water standard.

BNL's conclusions from this data are

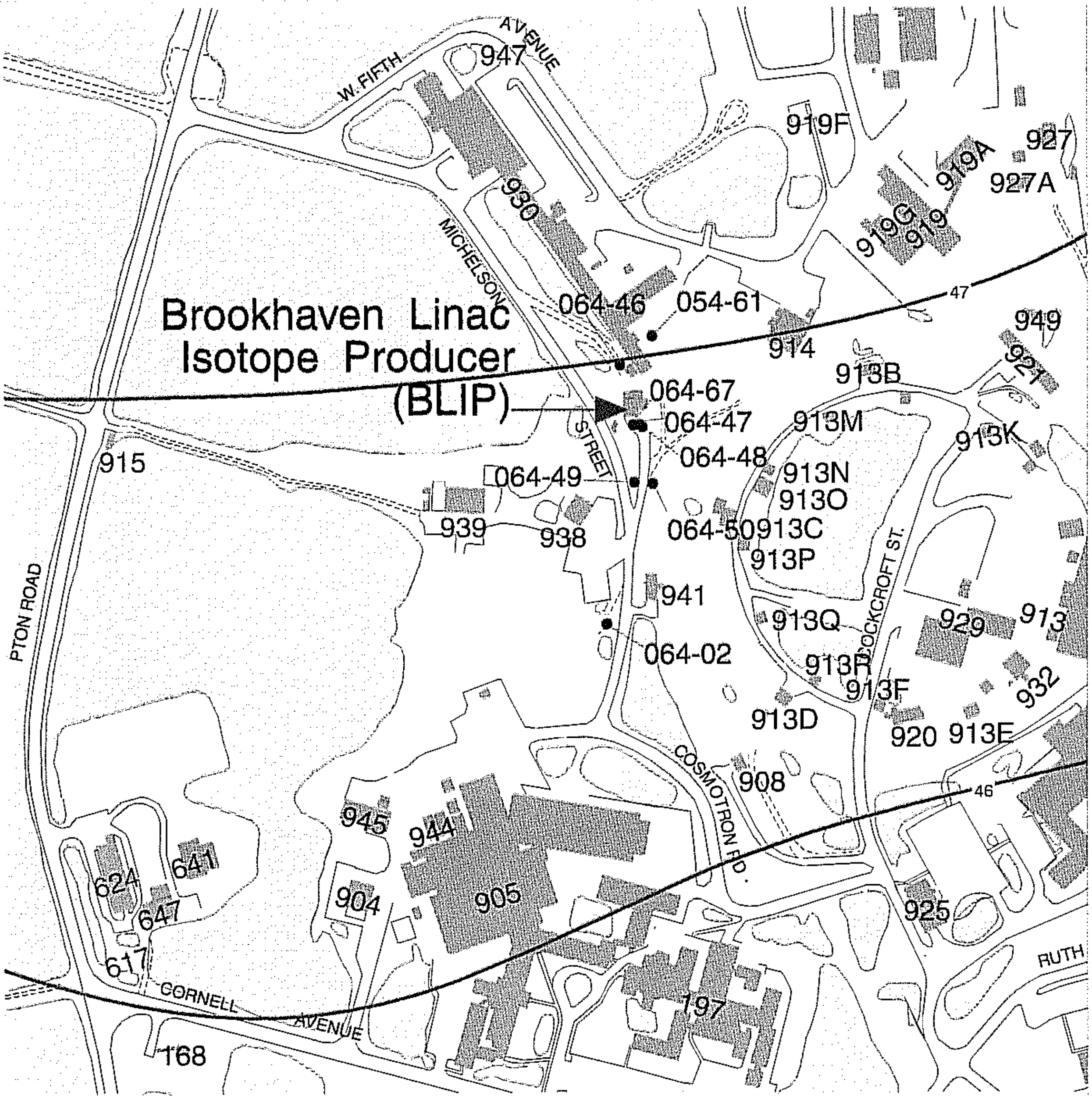
- The engineered and operational source controls remain effective. The elevated tritium detected in groundwater following the VLB grout injection was a one-time release caused by the grout displacement of the activated soil pore water.
- The size of this slug of tritium contamination (where concentrations could exceed drinking water standard) is estimated to be 150 feet long by 15 feet wide.
- Based upon an estimated groundwater flow rate of 0.45 ft/day, the slug has migrated about 200 feet downgradient of the source.
- The first detection above drinking water standards post VLB injection (detected on October 11, 2000 in well 64-67) did not ideally sample the highest activity area of the plume. This was due to the timing of the sample.
- The peak activity in the slug should be detected at well 64-50 sometime between July and October 2001.
- This slug of contamination is not expected to affect existing BNL or offsite water supplies.

Path Forward

- Monthly monitoring of well 64-50 is planned to continue through the remainder of 2001. The remaining 5 wells (which remain below 5,000 pCi/L will continue to be sampled on a quarterly basis as part of BNL's routine environmental surveillance monitoring. The next update report is scheduled for late November 2001, unless unusual or off-normal results are detected. Those types of results would be expeditiously forwarded to the regulatory stakeholders in accordance with BNL's Groundwater Protection Contingency Plan.

- Conduct routine, long-term groundwater monitoring to confirm the effectiveness of the cap.

- Continue to inspect and maintain the cap system.



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Environmental Services Division

Figure 1

Environmental Surveillance Monitoring Well Locations BLIP Facility Area

LEGEND

- Monitoring Well
- Wooded Areas
- Buildings, Facilities
- June 2000 Groundwater Elevation (ft AMSL)

SCALE

Meters

0 10 20 30 40 50 60 70

0 100 200

Feet

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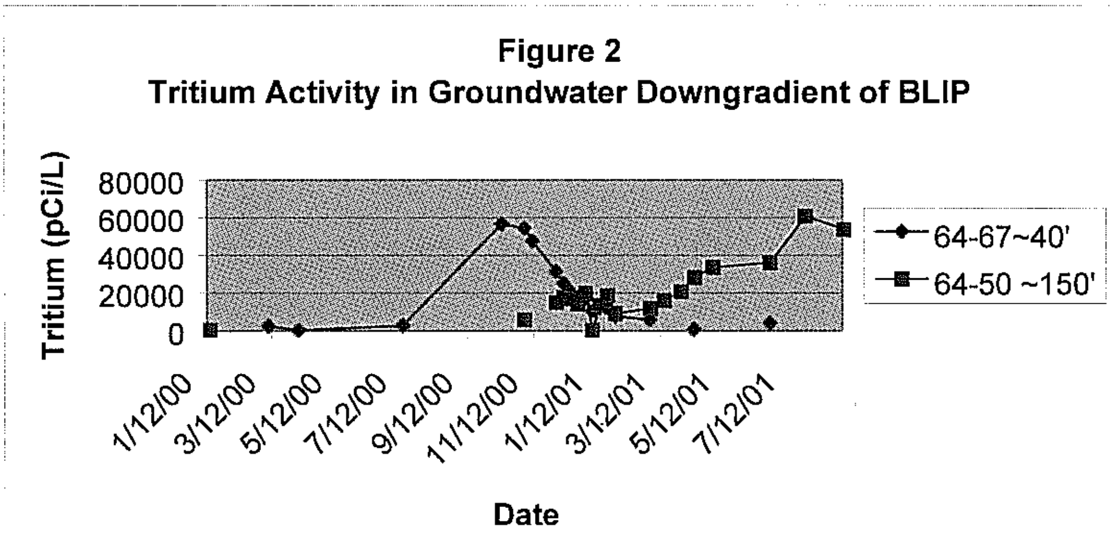

Note 1: Monitoring well 64-67 is located 40 feet downgradient of the BLIP target area. The timing of the October 2000 sampling of that well probably did not measure the peak activity in the plume at that time. The peak activity probably passed through well 64-67 in September 2000. That is the likely explanation for the peak tritium concentrations in monitoring well 64-50 in July 2001, located 150 feet downgradient of the BLIP target, being slightly higher than those measured in well 64-67.

Note 2: The drinking water standard for tritium is 20,000 pCi/L.

BNL Facility Groundwater Monitoring Program

Brookhaven LINAC Isotope Producer (BLIP)
Summary of Tritium and Sodium-22 Results for CY 2000 - 2001
(pCi/L)

Well	Radionuclide	January 12, 2000	March 7, 2000 (a)	April 4, 2000	July 11, 2000
64-46 (upgradient)	Tritium Sodium-22	<316 ND	NS	<331 ND	<356 3.7 +/- 1.3
54-61 (upgradient)	Tritium Sodium-22	<343 ND	NS	<331 ND	<356 ND
64-47 (~40 feet downgradient)	Tritium Sodium-22	<343 1.2 +/- 0.9	NS	<331 ND	5,700 +/- 412 57.1 +/- 6.9
64-48 (~40 feet downgradient)	Tritium Sodium-22	495 +/-215 2.6 +/- 1.4	NS	<331 ND	3,630 +/- 351 23.7 +/- 3.3
64-67 (~40 feet downgradient)	Tritium Sodium-22	NI	2,290 +/-281 2.1 +/-1.2	<331 ND	2,820 +/- 318 19.0 +/- 2.8
64-49 (~150 feet downgradient)	Tritium Sodium-22	<343 ND	NS	NS	NS
64-50 (~150 feet downgradient)	Tritium Sodium-22	<343 ND	NS	NS	NS
64-02 (~450 feet downgradient)	Tritium Sodium-22	NS	ND	NS	NS

ND: Radionuclide not detected.
NS: Well not sampled during this period.
NI: Well not installed before this period.
(a): Initial sampling of new Well 064-67.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

BNL Facility Groundwater Monitoring Program

Brookhaven LINAC Isotope Producer (BLIP)

Summary of Tritium and Sodium-22 Results for CY 2000 - 2001

(pCi/L)

Well	Radionuclide	October 11, 2000	November 1, 2000	November 9, 2000	December 1, 2000
64-46 (upgradient)	Tritium Sodium-22	<320 2.3 +/- 1.2	<321 ND	NS	NS
54-61 (upgradient)	Tritium Sodium-22	<320 ND	<321 2.5 +/- 1.2	NS	NS
64-47 (~40 feet downgradient)	Tritium Sodium-22	<320 2.5 +/- 1.0	445 +/- 231 6.1 +/- 1.7	<328 ND	471 +/- 227 ND
64-48 (~40 feet downgradient)	Tritium Sodium-22	2,440 +/- 303 14.0 +/- 2.2	4,680 +/- 392 30.3 +/- 3.3	5,610 +/- 416 54.3 +/- 5.1	3,650 +/- 355 10.7 +/- 1.7
64-67 (~40 feet downgradient)	Tritium Sodium-22	56,500 +/- 1,160 (b) 88.0 +/- 7.8	54,200 +/- 1,120 219 +/- 17.8	47,400 +/- 1,080 233 +/- 18.8	31,100 +/- 875 299 +/- 24
64-49 (~150 feet downgradient)	Tritium Sodium-22	NS	<321 ND	NS	NS
64-50 (~150 feet downgradient)	Tritium Sodium-22	NS	5,800 +/- 414 ND	NS	14,900 20.0 +/- 2.5
64-02 (~450 feet downgradient)	Tritium Sodium-22	NS	<321 5.1 +/- 1.2	NS	NS

ND: Radionuclide not detected.
NS: Well not sampled during this period.
NI: Well not installed before this period.
(b): To confirm initial results, the November 1, 2000 sample was reanalyzed. Reanalysis indicated tritium concentrations of 57,800 +/- 1,180 pCi/L and 58,700 +/- 1,200 pCi/L.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

BNL Facility Groundwater Monitoring Program

Brookhaven LINAC Isotope Producer (BLIP)
Summary of Tritium and Sodium-22 Results for CY 2000 - 2001
(pCi/L)

Well	Radionuclide	December 8, 2000	December 15, 2000	December 21, 2000	December 28, 2000
64-46 (upgradient)	Tritium	NS	NS	NS	NS
	Sodium-22				
54-61 (upgradient)	Tritium	NS	NS	NS	NS
	Sodium-22				
64-47 (~40 feet downgradient)	Tritium	454 +/- 232	366 +/- 209	396 +/- 230	377 +/- 216
	Sodium-22	ND	ND	ND	ND
64-48 (~40 feet downgradient)	Tritium	3,210 +/- 341	2,080 +/- 284	1,380 +/- 277	1,660 +/- 278
	Sodium-22	12.4 +/- 1.8	15.4 +/- 2.1	13.6 +/- 2.1	11.3 +/- 1.9
64-67 (~40 feet downgradient)	Tritium	25,100 +/- 788	20,300 +/- 682	15,800 +/- 642	16,500 +/- 644
	Sodium-22	255 +/- 21	248 +/- 20	188 +/- 15.9	185 +/- 15.0
64-49 (~150 feet downgradient)	Tritium	NS	NS	NS	NS
	Sodium-22				
64-50 (~150 feet downgradient)	Tritium	17,600 +/- 672	16,900 +/- 635	14,400 +/- 602	20,000 +/- 710
	Sódium-22	20.9 +/- 2.5	19.7 +/- 2.3	23.3 +/- 2.7	25.5 +/- 3.1
64-02 (~450 feet downgradient)	Tritium	NS	NS	NS	NS
	Sodium-22				

ND: Radionuclide not detected.
NS: Well not sampled during this period.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

BNL Facility Groundwater Monitoring Program

Brookhaven LINAC Isotope Producer (BLIP)
Summary of Tritium and Sodium-22 Results for CY 2000 - 2001
(pCi/L)

Well	Radionuclide	January 4-5, 2001	January 11, 2001	January 18, 2001	January 25, 2001
64-46 (upgradient)	Tritium Sodium-22	<324 ND	NS	NS	NS
54-61 (upgradient)	Tritium Sodium-22	<308 ND	NS	NS	NS
64-47 (~40 feet downgradient)	Tritium Sodium-22	508 +/- 212 ND	701 +/- 245 2.8 +/- 1.5	629 +/- 243 2.0 +/- 0.9	646 +/- 212 3.2 +/- 1.1
64-48 (~40 feet downgradient)	Tritium Sodium-22	977 +/- 223 9.4 +/- 1.6	1,530 +/- 283 9.9 +/- 1.7	1,760 +/- 297 9.9 +/- 1.7	1,580 +/- 251 10.8 +/- 1.8
64-67 (~40 feet downgradient)	Tritium Sodium-22	10,400 +/- 499 149.0 +/- 11.2	12,200 +/- 585 132.0 +/- 10.2	11,700 +/- 577 111.0 +/- 8.8	7,790 +/- 445 99.8 +/- 7.8
64-49 (~150 feet downgradient)	Tritium Sodium-22	<308 ND	NS	NS	NS
64-50 (~150 feet downgradient)	Tritium Sodium-22	<308 23.7 +/- 2.7	13,500 +/- 613 26.7 +/- 2.8	18,600 +/- 710 27.7 +/- 3.1	9,100 +/- 485 24.6 +/- 2.8
64-02 (~450 feet downgradient)	Tritium Sodium-22	NS	NS	NS	NS

ND: Radionuclide not detected.
NS: Well not sampled during this period.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

BNL Facility Groundwater Monitoring Program

Brookhaven LINAC Isotope Producer (BLIP)
Summary of Tritium and Sodium-22 Results for CY 2000 - 2001
(pCi/L)

Well	Radionuclide	February 27, 2001	March 12, 2001	March 28, 2001	April 10, 2001
64-46 (upgradient)	Tritium Sodium-22	NS	NS	NS	<323 ND
54-61 (upgradient)	Tritium Sodium-22	NS	NS	NS	NS
64-47 (~40 feet downgradient)	Tritium Sodium-22	574 +/- 238 8.0 +/- 1.8	NS	NS	348 +/- 226 14.9 +/- 1.9
64-48 (~40 feet downgradient)	Tritium Sodium-22	2,050 +/- 308 12.8 +/- 2.1	NS	NS	3,900 +/- 377 74.8 +/- 6.7
64-67 (~40 feet downgradient)	Tritium Sodium-22	5,730 +/- 437 106.0 +/- 8.4	NS	NS	751 +/- 246 32.4 +/- 3.7
64-49 (~150 feet downgradient)	Tritium Sodium-22	NS	NS	NS	NS
64-50 (~150 feet downgradient)	Tritium Sodium-22	11,700 +/- 582 24.8 +/- 2.8	16,000 +/- 631 30.6 +/- 3.3	20,700 +/- 737 64.8 +/- 5.9	28,300 +/- 872 101 +/- 8.3
64-02 (~450 feet downgradient)	Tritium Sodium-22	NS	NS	NS	NS

ND: Radionuclide not detected.
NS: Well not sampled during this period.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

BNL Facility Groundwater Monitoring Program
Brookhaven LINAC Isotope Producer (BLIP)
Summary of Tritium and Sodium-22 Results for CY 2000 - 2001
(pCi/L)

Well	Radionuclide	April 27, 2001	June 20, 2001	July 23, 2001	August 28, 2001
64-46 (upgradient)	Tritium Sodium-22	NS	<337 ND	NS	NS
54-61 (upgradient)	Tritium Sodium-22	NS	NS	NS	NS
64-47 (~40 feet downgradient)	Tritium Sodium-22	NS	<337 6.9 +/- 1.4	NS	NS
64-48 (~40 feet downgradient)	Tritium Sodium-22	NS	4,640 +/- 427 22 +/- 2.6	NS	NS
64-67 (~40 feet downgradient)	Tritium Sodium-22	NS	3,920 +/- 402 15.6 +/- 2.1	NS	NS
64-49 (~150 feet downgradient)	Tritium Sodium-22	NS	NS	<364 ND	NS
64-50 (~150 feet downgradient)	Tritium Sodium-22	33,700 +/- 837 143 +/- 10.9	35,800 +/- 1,040 188 +/- 14.6	60,800 +/- 1,300 304 +/- 25	53,500 +/- 1,100 337 +/- 24
64-02 (~450 feet downgradient)	Tritium Sodium-22	NS	NS	<365 ND	NS

NA: Data not available at this time.
ND: Radionuclide not detected.
NS: Well not sampled during this period.
Note: Drinking water standard for tritium = 20,000 pCi/L; for sodium-22 = 400 pCi/L.

APPENDIX C

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managed by Brookhaven Science Associates
for the U.S. Department of Energy

Memo

Date: October 11, 2001

To: Drew Bennett

From: Terry Sullivan

Subject: Revised Modeling of the BLIP tritium plume

Background

Use of the BLIP causes soils near the target area to become activated producing H-3, Na-22, and other radionuclides. When rainwater flows through this activated zone, contaminants are leached from the soils and are carried down through the vadose zone and into the aquifer. In February 1998, H-3 was detected in groundwater at a level of 52,000 pCi/L at approximately 40 feet downgradient from the source area. In the summer of 1998, BNL took corrective actions to prevent rainwater from entering the soils surrounding the BLIP facility. These actions included the resealing of paved areas, construction of a gunnite cap placed over the ground surface surrounding the BLIP facility and the redirection of the building's downspouts to route stormwater runoff away from the area.. Groundwater monitoring demonstrated that these modifications were effective in preventing the leaching of the contamination from the activated soils and into the groundwater. As an added level of protection, a colloidal silica barrier was injected into the activated soil region during May 29 -June 12, 2000. The barrier has lowered the hydraulic permeability of the soil shielding, thereby reducing the ability of water to flow through the activated zone in case the surface water management controls become ineffective.

Groundwater Monitoring Results (1998-2001)

After the surface water management controls were installed in 1998, H-3 levels in the three monitoring wells 40 feet downgradient from the source region were typically a few thousand pCi/L or less. However, following the colloidal silica grout injection, a marked increase in tritium concentrations was observed in several of these monitoring wells. On July 11, 2000 these wells were sampled and all three had concentration values between 2000 and 6000 pCi/L. On October 11, 2000, one well, 64-67, had H-3 concentrations of 56,500 while the other wells 64-48 and 64-47, had concentrations of 2440 and less than 320 pCi/L, respectively. These wells are all approximately 40 feet downgradient from the activated soil region and are separated by approximately 12 feet with well 64-48 being the middle well. In accordance with the BNL Groundwater Protection Contingency Plan, the detection of H-3 above the drinking water standard of 20,000 pCi/L triggered more frequent sampling of the groundwater monitoring wells, and an investigation into the cause of the tritium release.

Potential causes for the increase in H-3 in the wells near the BLIP were investigated and it was determined that the most likely cause was the displacement of contaminated pore water from the activation zone during injection of the colloidal silica. Modeling studies were performed in January, 2001 (Sullivan, 2001) to estimate the source strength, source width, and concentrations at well 64-50, 150 feet downstream from the source. The model was calibrated to the existing data and assumed water pore velocity, 0.61 ft/d. The model predictions suggested that the peak concentrations would be measured in well 64-50 around March, 2001 and would be approximately 16,000 pCi/l.

During 2001, tritium concentrations in well 64-50 (located approximately 150 feet downgradient of BLIP) increased steadily, with levels reaching 35,800 pCi/l in June 2001. This suggested that the original estimate of the groundwater pore velocity (0.61 ft/d) was higher than in the field and that the estimated source strength was too low. The modeling was refined by increasing the estimated source strength by a factor of 2 and examining water velocities of 0.45 ft/d and 0.31 ft/d. Assuming a flow rate of 0.45 ft/d led to a peak concentration at well 64-50 of 55,000 pCi/l in May 2001, while a flow rate of 0.31 ft/d led to a peak concentration of 54,500 pCi/l in November, 2001.

Continued monthly monitoring of well 64-50 during July through September,2001 showed tritium values of 60,800, 53,500, and 36,400 pCi/l, respectively. The objective of this study was to estimate the groundwater pore velocity that best matched the data. Additional calculations were performed to estimate the time and peak concentrations of the plume as it continued migrating.

Modeling Approach

The modeling approach and equations were presented in Sullivan, 2001. The foundation of the model is the 3-D advective dispersion equation which was solved for a constant source lasting for 60 days. Groundwater pore velocities and dispersivity values are held constant during a single simulation. It was assumed that the contaminated pore water driven out of the region near the BLIP reached the water table at June 1, 2000. This is the start of the injection period for the colloidal silica barrier and represents the earliest possible time that contamination resulting form emplacement of the barrier could have reached the aquifer.

Parameter Assumptions

The following parameter values were used for the baseline calculations.

Parameter	Value	Justification
Water Pore Velocity (Vx)	0.31 - 0.45 ft/day	Range tested to find the best fit to the data.
Vertical Velocity (Vz)	0.01 ft/day	Low-end of range for HFBR tritium plume data.
Transverse Velocity (Vy)	0.0 ft/day	Model is calibrated to direction of flow.
Longitudinal Dispersivity (Dx)	3 ft	Best fit HFBR tritium plume data at a distance of 280 ft (Sullivan & Cheng, 1997).
Transverse Dispersivity(Dy)	0.3 ft	Best fit HFBR tritium plume data at a distance of 280 ft (Sullivan & Cheng, 1997)..
Vertical Dispersivity (Dz)	0.005 ft	Best fit HFBR tritium plume data at a distance of 280 ft (Sullivan & Cheng, 1997)..

Source Length	10 ft.	Best fit to observed data at well 64-47.
Source Strength	0.00004 Ci/d	Best fit to observed data at well 64-50.

More detailed discussion of the choice of parameters is found in Sullivan, 2001.

Best Fit Estimate of Groundwater Pore Velocity

Attempts to estimate the groundwater pore velocity consistent with the data were performed through varying the velocity and holding all other parameters constant. Figure 1 presents predicted concentrations as a function of two flow rates (0.31 ft/d, and 0.38 ft/d) and compares these to the measured values.

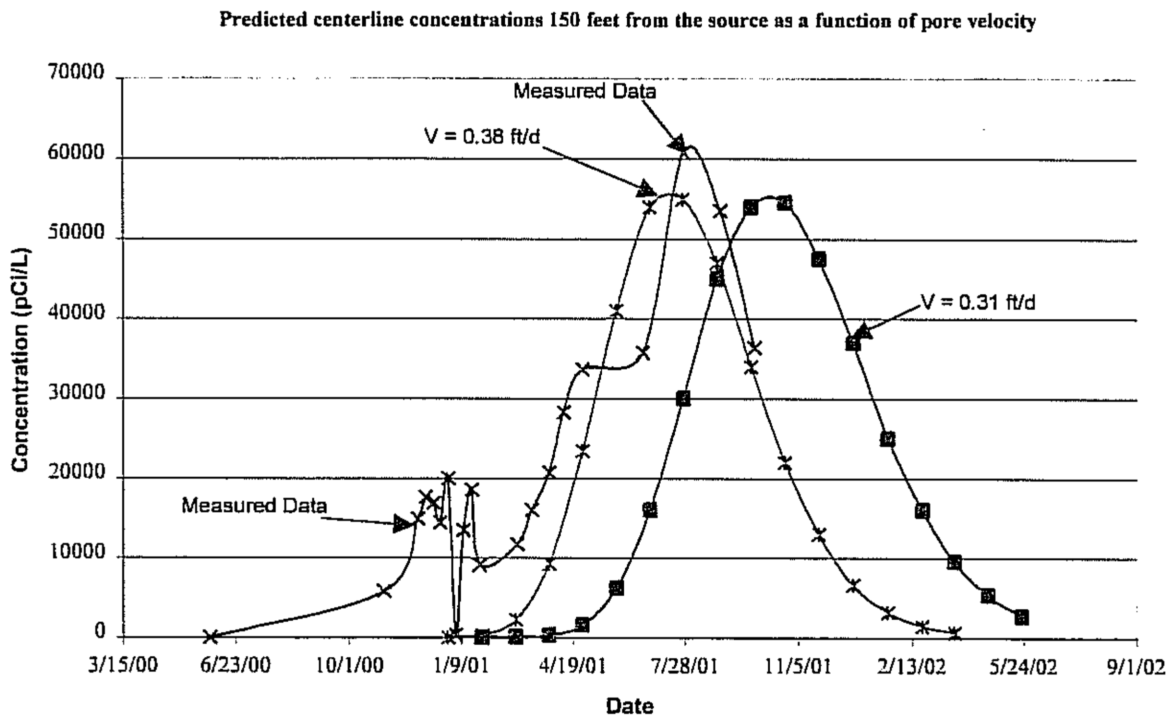

Figure 1 Comparison between predicted and measured concentrations 150 feet downgradient from the source.

The flow rate of 0.38 ft/day matches the measured data and the trends in the data reasonably well from the period of March 2001 through October 2001. At a flow rate of 0.31 ft/d, the predicted concentrations increase at much later times than the measured data. Similarly, at a flow rate of 0.45 ft/d (not shown in the graph), predicted concentrations increase much earlier than the measured data.. The predicted peak (55,000 pCi/l) and the measured peak (60,800 pCi/l) are also in reasonable agreement.

Estimate of Distance from the Source that will Eventually Exceed the Drinking Water Standard (20,000 pCi/L)

Using the best fit parameters in Table 1 and a groundwater pore velocity of 0.38 ft/d the peak concentration as a function of distance was estimated. Figure 2 presents this information along with the approximate date of arrival.

The model predicts that the peak concentration in the plume will drop below the drinking water standard (20,000 pCi/l) at all locations by September 2002. The maximum distance from the source that will experience concentrations in excess of the standard is approximately 300 feet.

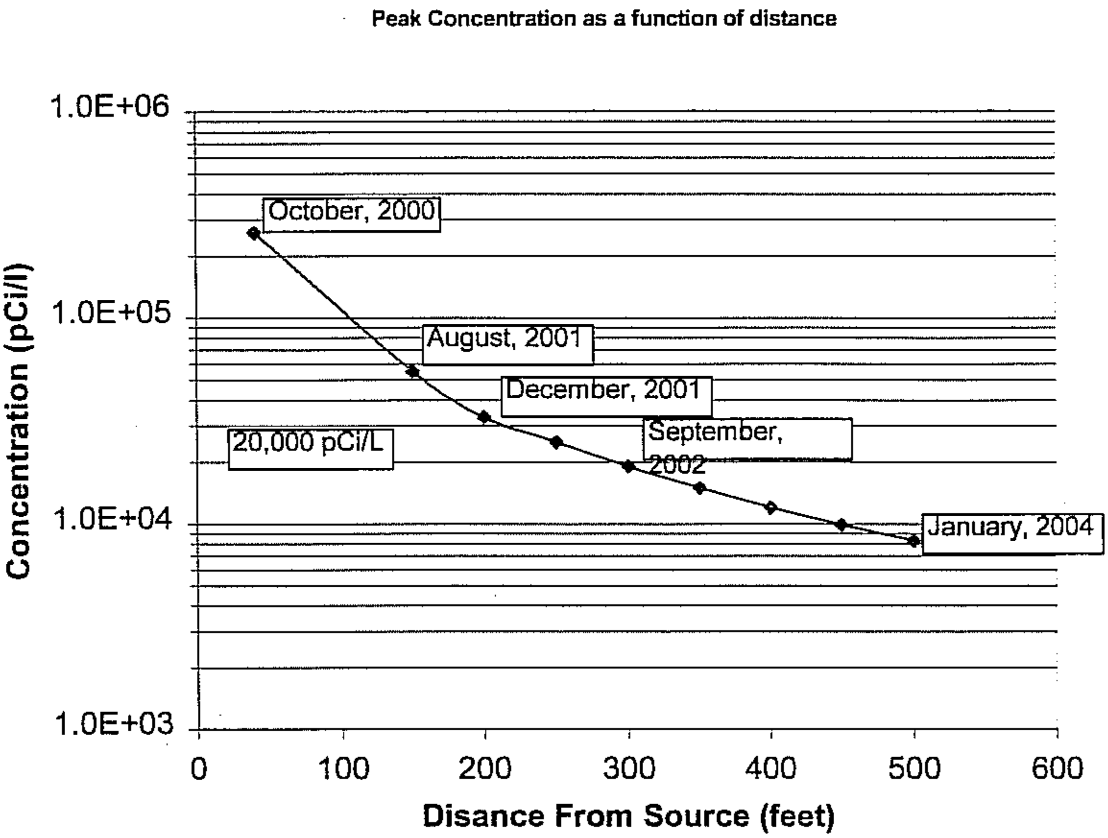

Figure 2 Predicted peak concentration as a function of distance and time.

The model predictions are based on the best fit to the data collected at 150 feet. They do not match the data at 40 feet in terms of peak concentration. The predicted peak concentration 40 feet from the source was 260,000 pCi/l (October 2000), while the measured peak concentration was a factor of 4.6 lower at 56,500 pCi/l. Some possible reasons for this discrepancy are the spatial gradients in concentration near the source and the timing of the sample collection in October 2000. It is clear that the peak concentration was not measured 40 feet downgradient from the source, as the peak measured value at this distance is less than at 150 feet. For this reason, the data collected at 150 feet are more reliable for determining best fit parameters.

The best fit model parameters are based on the assumption that the observed values represent the concentration at the centerline of the plume (i.e. maximum concentrations at a given distance). If the measurements are not on the centerline, the actual peak concentration could be higher than the measured value. Not measuring the exact peak could be addressed by increasing the estimated source strength in the model by a factor of 2. This is equivalent to assuming that the measured concentration is a factor of 2 lower than the exact peak concentration. Doing so, while holding all other model parameters to their previous best estimate values, would lead to a prediction that all points in the aquifer would be below the drinking water standard by September, 2003 and that the maximum distance that would experience concentrations above the standard would be 450 feet.

References:

Sullivan and Cheng, 1997.
T.M. Sullivan and L.Y. Cheng, "Modeling Analysis Performed to Estimate the Leak Rate, Source, and Duration of the Tritium Plume Observed South of the High Flux Beam Reactor," Brookhaven National Laboratory Memo to File, March 10, 1997.

Sullivan, 2001
T.M. Sullivan, "Modeling Analysis Performed to Estimate the Source Strength and Duration for the Tritium Plume Observed South of the Brookhaven Linear Isotope Producer (BLIP) facility.", Brookhaven National Laboratory Memo to Drew Bennett, January 10, 2001.

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