ACTION MEMORANDUM
BROOKHAVEN LINAC ISOTOPE PRODUCER (BLIP)
REMOVAL ACTION

March 10, 2000

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ACTION MEMORANDUM

I. PURPOSE

The purpose of this Action Memorandum is to document the decision by the U.S. Department of Energy (DOE) to conduct a removal action at the Brookhaven Linear Accelerator Isotope Producer (BLIP) which is designated as sub-Area of Concern (AOC) 16K. The action is part of the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) process for environmental restoration.

The selected removal action alternative is Alternative 4 "Close Proximity Containment Using Colloidal Silica Grout" to remediate contaminated soils and prevent additional groundwater contamination. The action involves installation and of a colloidal silica grout, maintenance of the existing cap and continued groundwater monitoring.

This action is being undertaken as a non-time-critical removal action in accordance with the Interagency Agreement between DOE, the U.S. Environmental Protection Agency (EPA) and the New York State Department of Environmental Conservation (NYSDEC) and will be consistent with the final remedial action selected for this AOC. Work will be conducted in accordance with the National Oil and Hazardous Substance Pollution Contingency Plan (40 CFR 300).

II. SITE CONDITIONS AND BACKGROUND

A. SITE DESCRIPTION

1. Physical Location

BNL is located in the geographical center of Suffolk County on Long Island, New York in the Town of Brookhaven (Figure 1). The present site contains 5,265 acres, of which 75 percent are wooded. The remainder is developed and contains office buildings, various large research facilities, parking lots, etc. The BLIP is located in the northwestern section of the BNL property, near the Linear Accelerator (LINAC) and the Alternating Gradient Synchrotron (AGS) ring (Figures 2 and 3).

The BNL site is underlain by approximately 1,600 feet of unconsolidated sediments, which rest on bedrock, and by an aquifer system designated by the EPA as a Sole Source Aquifer, pursuant to Section 1424(e) of the Safe Drinking Water Act. This aquifer system contains the primary sources of drinking water for Nassau and Suffolk Counties. The groundwater table is located approximately 55 feet below the ground surface beneath the BLIP building. South of the building, in the direction of the groundwater flow, the water table is approximately 40 feet below the ground surface.

The BNL site, formerly Camp Upton, was occupied by the U.S. Army in World Wars I and II, and was subsequently transferred to the Atomic Energy Commission in 1947 for use as a national laboratory. BNL carries out basic and applied research in the fields of high-energy nuclear and solid state physics; fundamental material and structure properties and the interaction of matter; nuclear medicine; biomedical and environmental sciences; and selected energy technologies. Major operating facilities include the High Flux Beam Reactor, the Brookhaven Medical Research Reactor, the National Synchrotron Light Source and the Alternating Gradient Synchrotron. BNL is a government-owned, contractor-operated facility of the DOE. BNL is operated and managed by Brookhaven Science Associates (BSA) under contract to DOE.

2. Removal Site History

The BLIP, which is considered an accelerator facility, has operated from 1972 to the present. 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 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. 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.

The target area of the BLIP, the drive assembly and the cooling system are contained in a vertical 34 feet long, 16 inch diameter, stainless steel tube. This tube is filled with 300 gallons of deionized water, to cool the target and provide neutron shielding, and is surrounded by an eight feet diameter tank (Figure 4). The target area extends about 28 feet below the concrete floor of the BLIP facility. There are generally eight targets of different materials. The proton beam generated by the LINAC penetrates the stack of targets but does not reach the soil berm, having been stopped by the targets and the water. 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 waste water 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.

The operation of the BLIP facility over the years has resulted in the activation and radiological contamination of soil located in the vicinity of the BLIP target. Some of the radionuclides are very short-lived but others, particularly tritium and sodium-22, are longer lived 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. 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 contaminants subsequently entered the soil through cracks in the concrete. The leak was repaired and the cracks in the pit patched and sealed. In February 1998, elevated levels of tritium and sodium-22 were noted in monitoring well 064-02, approximately 240 feet downgradient of the BLIP (see Figure 3) and are described in Section 3.

3. Release or Threatened Release into the Environment of a Hazardous Substance, or Pollutant or Contaminant

The primary radioisotopes of concern in the soil berm at the BLIP are tritium, with a half-life of 12.3 years, and sodium-22, with a half-life of 2.6 years. 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 iron-55 (half-life 2.7 years) and manganese-54 (half-life 312.5 days), but in smaller concentrations.

The major threat to public health or welfare and the environment from the radioactive contamination in the soil berm comes from migration of the isotopes into the surrounding soils and groundwater, and ultimately into the underlying aquifer.

Additional information concerning the concentrations of the radioisotopes at various locations in the soil berm and the results of modeling estimates indicating the rates of migration and concentration levels over time are contained in the Engineering Evaluation/Cost Analysis Report [CDM Federal, 1999].

B. ACTIONS TO DATE

1. Previous Actions

The BLIP has been in operation from 1972 to the present. During this period, the soil in the immediate vicinity of the BLIP has become activated and contaminated.

In February, 1988, perceptible losses of cooling water were noted during BLIP operations, resulting in a total loss of 100 to 150 gallons of water. In May, 1988, the leak was found to have originated at the primary recirculation pump located within a concrete pit in Building 931B. The contaminants subsequently entered the soil through cracks in the concrete. The leak was repaired, the cracks in the concrete were patched and sealed, and the pit was lined with stainless steel. 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 and has tracked changes in contaminant levels. In February 1998, elevated levels of tritium and sodium-22 were noted and subsequently confirmed through the installation of 13 additional Geoprobe groundwater samples in that area. The February 1998 monitoring well data revealed the groundwater concentration of tritium to be 14,000 pCi/l and that of sodium-22 43.6 pCi/l, both levels below the drinking water standards (20,000 pCi/l for tritium and 400 pCi/l for sodium-22). However, both values represented significant increases from previously measured values (up to 1400 pCi/l for tritium and up to 27 pCi/l for sodium-22). The maximum tritium concentration detected in the Geoprobes was 53,000p Ci/l in June 1998.

Response actions to these findings included re-routing of downspouts on Building 931B to improve stormwater runoff and drainage in the area; the placement of the gunnite cap over the entire target area to prevent infiltration of rainwater; and the installation of six additional monitoring wells. Also, the BLIP has been identified in the Operable Unit II Remedial Investigation Report [IT 1999] as requiring further action.

Data concerning the nature and extent of soil and groundwater contamination resulting from operation of the BLIP are summarized in the BLIP Engineering Evaluation/Cost Analysis [CDM Federal, 1999]. Recent soil sample data indicate that radiological soil contamination is more widely distributed, both vertically and horizontally, than was originally thought. The full extent of the soil activation will be established through additional sampling as part of the removal action design.

2. Current Actions

Additional investigations of the contaminant levels in the soil in the vicinity of BLIP have occurred. Soil sampling was performed in September 1998 and focused on four Geoprobe locations:

- one directly opposite the beam line within the area of activated soil, to determine the degree of activation
- two near this area, to determine the extent of soil contamination beyond the known activated area
- one outside the building in an area where no radiological contamination was expected.

Samples were collected from four locations at various depths. Generally, little contamination was detected at depths down to 20 feet but then concentrations increased significantly at lower depths. The highest concentration of tritium, 4,020 pCi/g, was found at a depth of 28 to 30 feet, as was that of sodium-22 (42,600 pCi/g). The peak concentrations of other radioisotopes, all found at the same depth, included 73,200 pCi/g (beryllium-7), 8,400 pCi/g (iron-55), 7800 pCi/g (manganese-54), 1840 pCi/g (europium-152), and 1,120 pCi/l (cobalt-60). Non-volatile beta was measured at a peak of 39,900 pCi/g and gross alpha at 765 pCi/l.

Using the soil data and adopting conservative modeling assumptions, it has been estimated that a three-meter high vertical cylinder of contaminated soil would need to be treated to insure that drinking water standards in the aquifer would not exceeded in the future by radionuclides leaching from the contaminated soil. . This cylinder would be centered on the axis of the proton beam and have a radius that extends two meters from the eight-feet diameter tank that houses the BLIP target (Figures 5 and 6). The model predicts that such a cylinder would capture 99.9 percent of the soil activation products.

Possible removal action alternatives for remediation of the contaminated soils were developed and are discussed in the Engineering Evaluation/Cost Analysis [CDM Federal, 1999]. These alternatives were evaluated using appropriate criteria concerning public health and safety protection, effectiveness, feasibility, and cost. The recommended alternative is close proximity containment of the activated soil using an injection of colloidal silica grout. Maintenance of the gunnite cap and monitoring of the groundwater will continue.

C. NATIONAL PRIORITIES LIST STATUS

BNL was added to the EPA's National Priorities List (NPL) in 1989. At that time, BNL was also on the NYSDEC list of Inactive Hazardous Waste Sites. An Interagency Agreement under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA) and applicable New York State regulations was negotiated between DOE, EPA and NYSDEC and become effective in May 1992. The Interagency Agreement governs the environmental restoration program at BNL. The BLIP Soil Removal Action, included as AOC 16K, is considered a non-time-critical removal action as defined in the National Contingency Plan.

D. PUBLIC COMMENT PERIOD

The BLIP Engineering Evaluation/Cost Analysis Report was issued for public review and comment from September 20, 1999 to October 20, 1999. No comments were received.

III. THREATS TO PUBLIC HEALTH OR WELFARE AND THE ENVIRONMENT, AND STATUTORY AND REGULATORY AUTHORITIES

A. THREATS TO PUBLIC HEALTH OR WELFARE

The potential threats posed by contamination from the operation of the BLIP facility are of a non-time-critical nature. That means no imminent or substantial endangerment to public health, welfare or the environment currently exists at this location that would necessitate remediation within six months. The appropriateness of a removal action is based on the following factor listed in the Code of Federal Regulations [40 CFR 300.415(b)(2)]:

Actual or potential contamination of drinking water supplies or sensitive ecosystems.

The groundwater beneath BNL is designated as a sole source aquifer by the EPA under the Safe Drinking Water Act and is classified Class GA by NYSDEC under New York State Codes, Rules and Regulations Part 703 (6 NYCRR Part 703). The best usage of Class GA groundwater is defined as a source of potable drinking water. The groundwater is the primary source of drinking water in the area and most residents immediately down gradient of BNL are now connected to the public water supply. To date, no contaminants presumed to originate from the BLIP location have been found in groundwater offsite.

B. THREATS TO THE ENVIRONMENT

The major threat to the environment is the contamination of groundwater.

IV. PROPOSED ACTIONS AND ESTIMATED COSTS

A. PROPOSED ACTION

1. Proposed Action Description

The removal action alternative selected to address the activated zone of soil adjacent to the target area of the BLIP involves continued maintenance of the existing gunnite cap and the injection of a colloidal silica grout barrier. The gunnite cap is constructed over the target area to prevent seepage of rainwater. Maintenance of the cap is anticipated to consist of application of asphalt sealer to the cap itself every five years and application of joint sealer to the building perimeter every year. Upon completion of the barrier, an operations and monitoring plan will be developed that outlines the specific activities. The colloidal silica barrier will contain the contaminated region and prevent further leaching to the sole source aquifer. The containment barrier will also act as a beam stop for the duration of research at the BLIP, thus reducing the amount of soil that may undergo spallation from continuing operations at the BLIP facility. Due the low-energy injection method employed, no drill spoils or associated potential work hazards are expected. However, because of the developmental nature of the technology, there is a small degree of uncertainty about the permanency of the containment. Thus a second injection of the silica grout may be needed after 25 years if the facility is in operation at that time.

2. Contribution to Remedial Performance

The Operable Unit II Remedial Investigation Report [February 1999] included sampling and analysis of soils, sediment and surface water, and a baseline risk assessment to determine long-term remediation requirements. The BLIP facility is included in this Operable Unit. The Removal Action contained in this Action Memorandum addresses source and migration control at the BLIP facility and groundwater monitoring. This Removal Action is consistent with the overall site cleanup strategy. The final remedial action will be documented in a future Record of Decision.

3. Description of Alternative Technologies

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:

1. No Action with Institutional Controls
2. Upgrade of Existing Cover
3. Close Proximity Containment Using Cement Grout
4. Close Proximity Containment Using Colloidal Silica Grout

5. Excavation of Activated Soil Zone and Install Beam Stop

Alternative 1 (No Action) would provide some protection to the groundwater via the gunnite and asphalt cap that was installed previously. Groundwater model predictions indicate that the activated soil is unlikely to continue to cause groundwater contamination in excess of drinking water standards if the cover is properly maintained over time. However, concerns regarding effectiveness exist because this alternative does not include the installation of a beam stop, without which soil activation will continue throughout the operational life of the BLIP. The activated soils represent a potential risk to the underlying sole source aquifer, particularly if a cooling system leak should occur.

Alternative 2 (Upgrade of Existing Cover) would provide more protection to the groundwater than Alternative 1 but would not eliminate concerns arising from the absence of a beam stop. That is, soil activation will continue during the operational life of the BLIP and present a risk to the underlying sole source aquifer, particularly in the event of a cooling system leak.

Alternative 3 (Close Proximity Containment Using Cement Grout), together with upgrade of the existing cover, would provide a demonstrated and permanent means of containing the activated soil in the subsurface. Cement grout would adequately contain the activated soil so that contaminants would not leach into the groundwater, in effect permanently stabilizing them. It would also function as a beam stop, thereby eliminating continued activation of the soil during BLIP operations. Against these advantages are three implementability concerns:

- the high pressures needed to inject the grout and the associated vibrations and potential soil compaction;
- the corrections necessary to remedy the damage resulting from high pressure, vibration and soil compaction could lead to potentially high worker exposure and costly schedule delays;
- the large size of the grouting equipment prevents its use within the confines of the BLIP building, thus necessitating some building dismantlement and reassembly.

Alternative 4 (Close Proximity Containment Using Colloidal Silica Grout), together with upgrade of the existing cover, would also provide containment of the activated soil. However, the developmental status of the technology means that the permanency of this type of barrier compared with that of cement grout is not known. The colloidal silica grout remains a gel and does not set like cement grout. Also, because the silica grout may desiccate slowly over time, a second injection may be needed after 25 years to ensure continuation of the containment. As with the cement grout, the silica grout would also act as a beam stop. On the other hand, the implementability problems associated with cement grouting virtually disappear with silica grout injection. The relatively low injection pressures (less than 5 percent of those required to inject cement grout) assure much less associated damage and the equipment can be used within the BLIP structure, removing the problem of building dismantlement and reassembly.

Alternative 5 (Excavation of Activated Soil Zone and Install Beam Stop) is a highly effective removal action but has several implementability and cost concerns. Implementation of a full scale tunneling-type excavation would increase the potential for increased worker exposure to radiologically activated soil and, at the same time, be complicated by the need to consider the presence of underground facilities in unspecified or uncertain locations. This Alternative would also take considerably longer to implement than the other Alternatives, and potentially cause significant disruptions to operations in the BLIP and other nearby facilities. Ultimately, radioactive waste will be generated and require offsite disposal. This would significantly increase the cost of the Alternative compared with those of the other Alternatives and simultaneously add to the risk of exposure to the public during the transportation of the waste to the disposal site.

The EE/CA recommended Alternative 4 "Close Proximity Containment Using Colloidal Silica Grout and Upgrade of the Existing Cover". Subsequent laboratory testing [MSE, 1999] performed after the EE/CA was finalized supports the use of Close Proximity Containment Using Colloidal Silica Grout. In addition, recent groundwater monitoring (see Appendix A) shows significant reduction in the contaminant levels found in the groundwater just south of BLIP. Sampling performed from February 1999 to January 2000 shows tritium levels in wells downstream (20 and 100 feet from the source) of the BLIP facility have fallen off to below detectable levels. This strongly indicates that the existing gunnite cap provides adequate coverage.

Based on the current groundwater monitoring data, it is recommended that the gunnite cap be left in its present configuration. The recommended action now involves the installation of the colloidal silica grout, maintenance of the gunnite cap, and groundwater monitoring. If groundwater monitoring indicates increasing contaminant levels, then the required actions will be reevaluated with the EPA and NYSDEC and the gunnite cap may be upgraded. This alternative reduces contaminant migration to the groundwater; is protective of human health and the environment; and is technically feasible cost-effective.

These remedial actions are consistent with the future use of BNL and are steps toward the overall remediation of the site.

4. Administrative Record

A copy of the Brookhaven LINAC Isotope Producer Engineering Evaluation/Cost Analysis Report [CDM Federal, 1999], is included in the Administrative Record. This Action Memorandum will also be included in the Administrative Record.

5. Applicable or Relevant and Appropriate Requirements

Implementation of Alternative 4 will satisfy Applicable or Relevant and Appropriate Requirements (ARARs), criteria and guidance. The principle ARARs pertaining to the BLIP radiologically-contaminated soils are as follows:

Safe Drinking Water Act (43 USC 300) and National Drinking Water Standards (40 CFR 141). This establishes federal drinking water standards that are relevant and appropriate for establishing goals for groundwater and soil remediation.

New York State Water Quality Standards (6 NYCRR Part 703): This requirement establishes standards of purity for groundwater. Standards for class GA waters are set at the drinking water standards.

Alternative 4 will stabilize the contaminated soils and prevent further leaching of contaminants into the groundwater. Groundwater monitoring will occur to ensure that contaminant levels reduce in time to meet the drinking water standards.

Non-promulgated guidance, also known as To-Be- Considered (TBC) was also evaluated. In that regard, the principle TBC identified for Alternative 4 is DOE Order 435.1 "Radioactive Waste Management". This Order describes the DOE requirements for radioactive waste management at DOE facilities. Radioactive wastes generated during installation of the colloidal silica grout will be disposed of in accordance with this Order.

6. Project Schedule

The proposed removal actions will be performed in accordance with the schedules established under the Interagency Agreement. The key tasks for the BLIP soil remediation include preparation of design specifications and work plans and installation of the colloidal silica barrier. Installation of the barrier is planned for the second quarter in calendar year 2000. The remedial action will be followed by the preparation of a close-out report.

B. ESTIMATED COSTS

The cost of Alternative 4 is estimated to be $591,200.

V. EXPECTED CHANGE IN THE SITUATION SHOULD ACTION BE DELAYED OR NOT TAKEN

A delayed action or no action will increase the potential for increased contamination of the soil and groundwater, and for migration of contaminants to the sole source aquifer. Delayed action will potentially increase the scope and cost of the project.

VI. OUTSTANDING POLICY ISSUES

None.

VII. ENFORCEMENT

The site is owned by DOE. Funding for this action will be provided entirely by DOE and the removal action will be conducted in accordance with CERCLA requirements, the Interagency Agreement, Executive Order 12580 and applicable New York State regulations.

VIII. RECOMMENDATION

This decision document represents the selected removal action for the BLIP radiologically contaminated soil area (AOC 16K) at BNL. These actions were developed in accordance with CERCLA as amended, and are consistent with the National Contingency Plan. This decision is based on information contained in the Administrative Record for the site.

IX. REFERENCES

Note: Administrative Record Citations, where available, are given in parenthesis.

1) [CDM Federal, 1999]. CDM Federal Programs Corporation. " Brookhaven LINAC Isotope Producer Engineering Evaluation/Cost Analysis." September 17, 1999.

2) [IT, 1999]. IT Corporation. "Operable Units II/VII Remedial Investigation Report." February, 1999.

3) [MSE, 1999]. MSE Technology Applications, Inc. Unsaturated Flow Simulation for the Brookhaven Linac Isotope Producer (BLIP) Viscous Liquid Barrier Demonstration at the Brookhaven National Laboratory. Dated September 1999.

X. ACRONYMS

AGS	Alternating Gradient Synchrotron
ALARA	As Low As Reasonably Achievable
ARAR	Applicable or Relevant and Appropriate Requirement
BLIP	Brookhaven Linear Accelerator Isotope Producer
BNL	Brookhaven National Laboratory
BSA	Brookhaven Science Associates
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CDM	CDM Federal Programs Corporation
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
LINAC	Linear Accelerator
NYSDEC	New York State Department of Environmental Conservation
NYCRR	New York State Codes, Rules, and Regulations
RCRA	Resource Conservation and Recovery Act

FIGURES

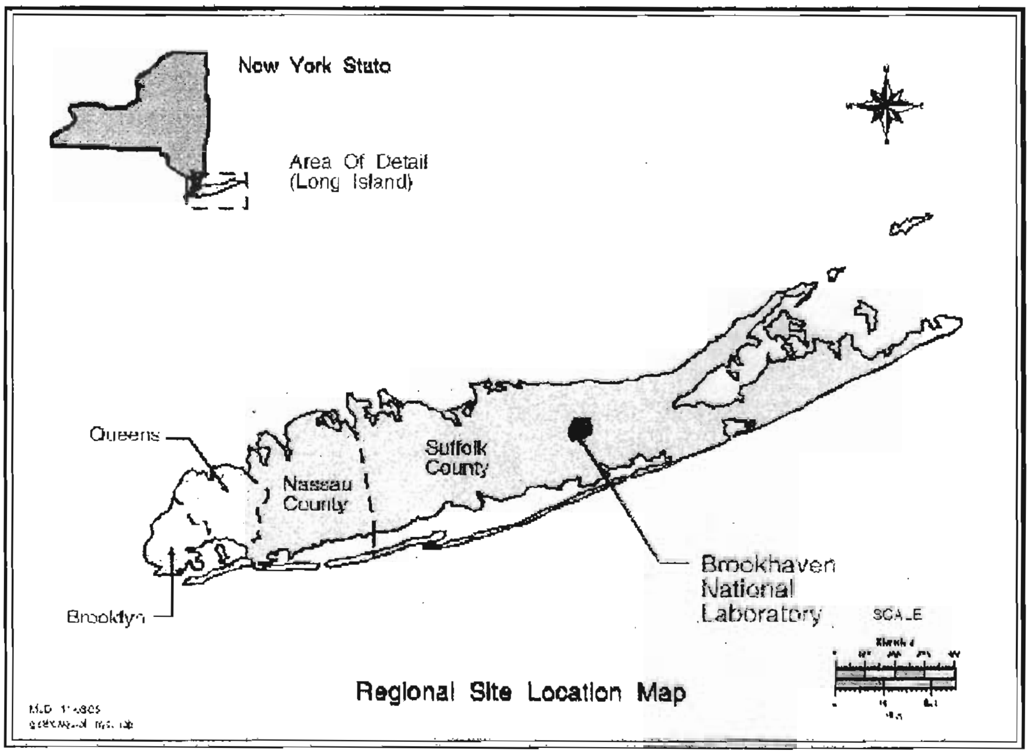

Figure 1 Regional Site Location Map

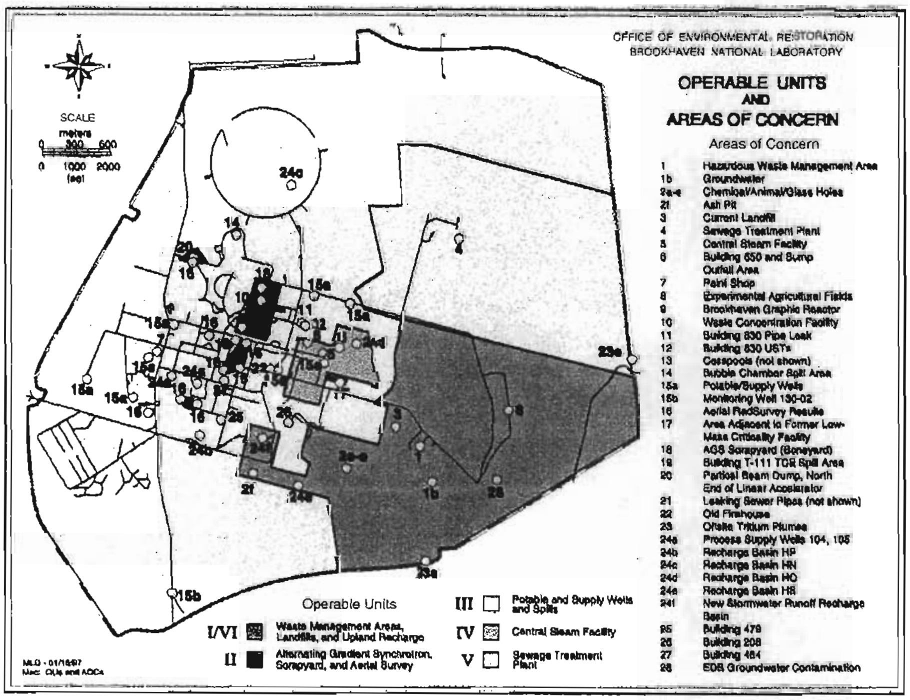

Figure 2 Location of the BLIP Facility within the BNL Site

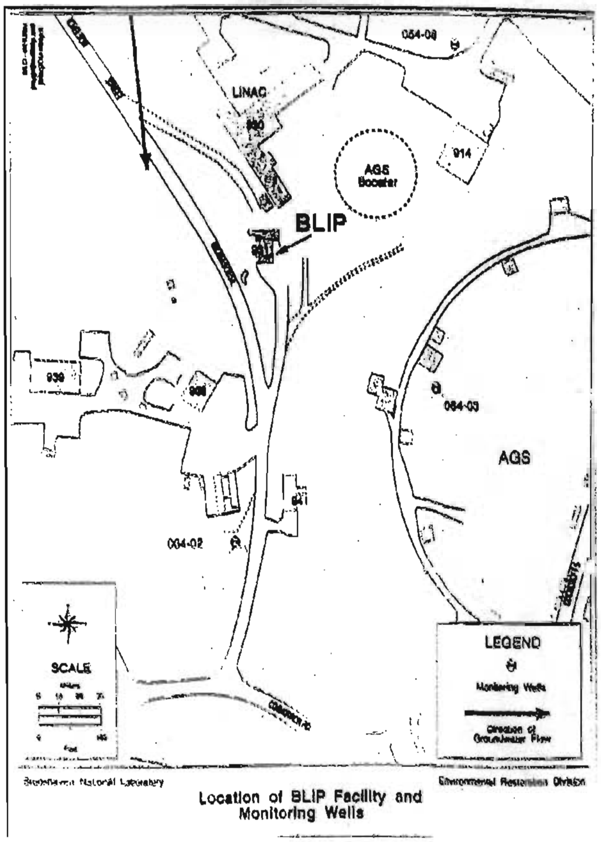

Figure 3 Location of BLIP Facility and Monitoring Wells

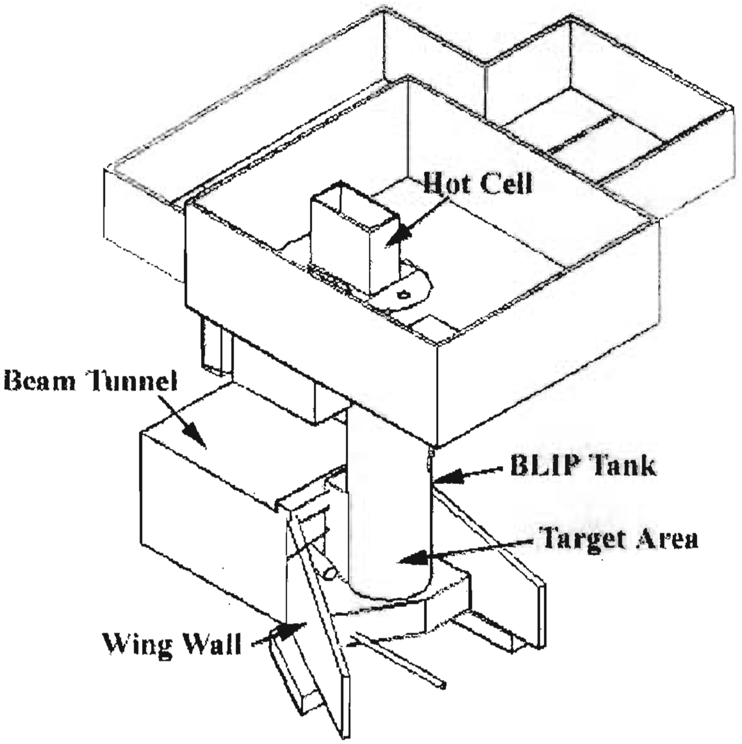

Figure 4 Cross-section View of the BLIP Building

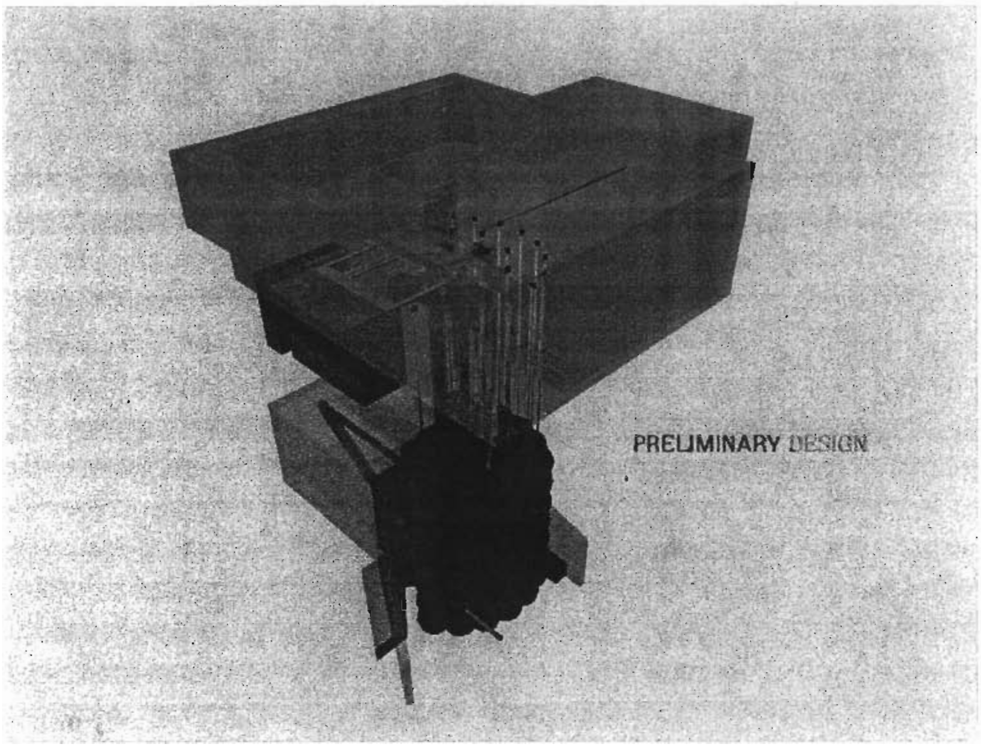

Figure 5 Activated Soil Zone Superimposed on Cross-Section View of the BLIP Building

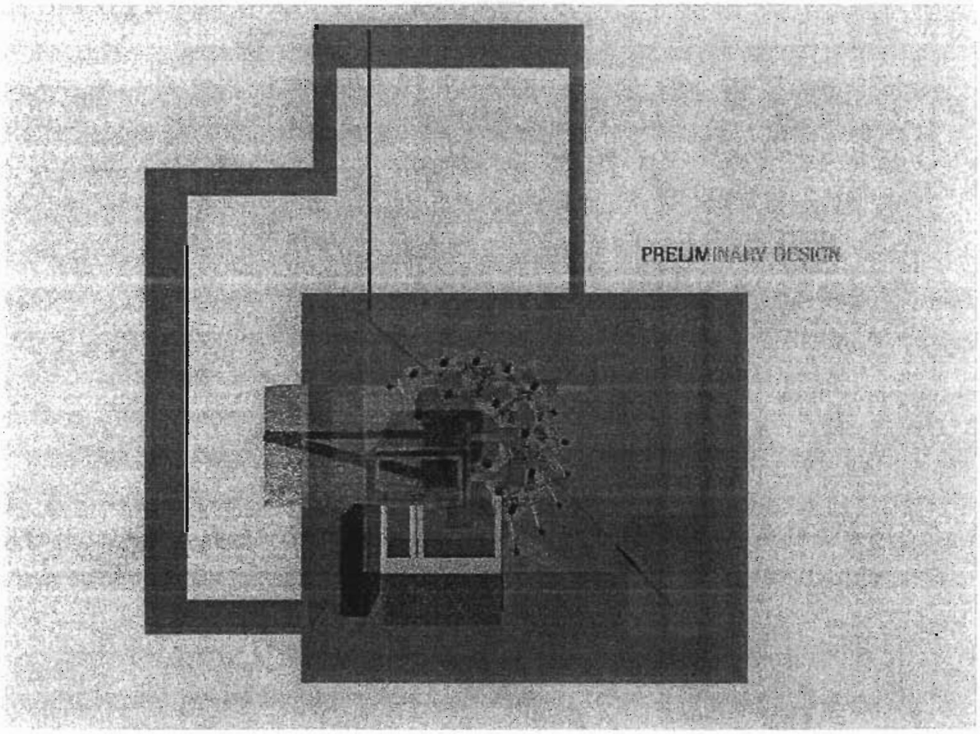

Figure 6 Plan View of Activated Soil Zone

APPENDIX A

Brookhaven National Laboratory
Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
February 25, 1999

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	< 317 (MDL = 317) ND
54-61 (upgradient)	Tritium Sodium-22	Well Not Available for Sampling
64-47 (~20 feet downgradient)	Tritium Sodium-22	<317 (MDL= 317) 4.9 +/- 1.6
64-48 (~20 feet downgradient)	Tritium Sodium-22	986 +/-235 (MDL = 317) 9.1 +/- 2.1
64-49 (~100 feet downgradient)	Tritium Sodium-22	<317 (MDL = 317) 6.67 +/- 1.4
64-50 (~100 feet downgradient)	Tritium Sodium-22	18,700 +/- 656 (MDL = 317) 7.21 +/- 0.8

Brookhaven National Laboratory
Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
April 7, 1999

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	< 370 (MDL = 370) ND
54-61 (upgradient)	Tritium Sodium-22	< 370 (MDL = 370) ND
64-47 (~20 feet downgradient)	Tritium Sodium-22	<370 (MDL=370) 2.8 +/- 1.3
64-48 (~20 feet downgradient)	Tritium Sodium-22	465 +/-230 (MDL = 370) 14 +/- 2.3
64-49 (~100 feet downgradient)	Tritium Sodium-22	<370 (MDL = 370) 2.21 +/- 1.0
64-50 (~100 feet downgradient)	Tritium Sodium-22	653 +/- 241 (MDL = 370) 38.4 +/- 4.8

Brookhaven National Laboratory
Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
July 9-21, 1999

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	<323 (MDL = 323) 2.7 +/- 1.3
54-61 (upgradient)	Tritium Sodium-22	<319 (MDL = 319) ND
64-47 (~20 feet downgradient)	Tritium Sodium-22	<323 (MDL = 323 ND
64-48 (~20 feet downgradient)	Tritium Sodium-22	2,450 +/- 310 (MDL = 323) 9.4 +/- 1.7
64-49 (~100 feet downgradient)	Tritium Sodium-22	<323 (MDL = 323) ND
64-50 (~100 feet downgradient)	Tritium Sodium-22	<323 (MDL = 323) 3.1 +/- 1.1

Brookhaven National Laboratory
Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
October 12-13, 1999

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	<306 (MDL = 306) ND
54-61 (upgradient)	Tritium Sodium-22	<306 (MDL = 306) ND
64-47 (~20 feet downgradient)	Tritium Sodium-22	<354 (MDL = 354) 1.3 +/-0.9
64-48 (~20 feet downgradient)	Tritium Sodium-22	Tritium Sample Broken 2.8 +/- 1.3
64-49 (~100 feet downgradient)	Tritium Sodium-22	<354 (MDL = 354) 0.95 +/- 0.9
64-50 (~100 feet downgradient)	Tritium Sodium-22	<354 (MDL = 354) ND

Brookhaven National Laboratory

Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
January 12, 2000

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	<316 (MDL =316) ND
54-61 (upgradient)	Tritium Sodium-22	<343 (MDL= 343) ND
64-47 (~20 feet downgradient)	Tritium Sodium-22	<343 (MDL= 343) 1.2 +/- 0.9
64-48 (~20 feet downgradient)	Tritium Sodium-22	495 +/-215 (MDL = 343) 2.6 +/- 1.4
64-49 (~100 feet downgradient)	Tritium Sodium-22	<343 (MDL = 343) ND
64-50 (~100 feet downgradient)	Tritium Sodium-22	<343 (MDL = 317) ND

Brookhaven National Laboratory

Brookhaven LINAC Isotope Producer
Groundwater Monitoring Program
Summary of Tritium and Sodium-22 Concentrations
March 7, 2000

Well	Radionuclide	Concentration (pCi/L)
64-46 (upgradient)	Tritium Sodium-22	NS
54-61 (upgradient)	Tritium Sodium-22	NS
64-47 (~20 feet downgradient)	Tritium Sodium-22	NS
64-48 (~20 feet downgradient)	Tritium Sodium-22	NS
64-67 (~20 feet downgradient)	Tritium Sodium-22	2,290 +/-281 (MDL=306) 2.1 +/-1.2
64-49 (~100 feet downgradient)	Tritium Sodium-22	NS
64-50 (~100 feet downgradient)	Tritium Sodium-22	NS

APPENDIX B

UNSATURATED FLOW SIMULATION FOR THE BROOKHAVEN LINAC ISOTOPE PRODUCER (BLIP) VISCOUS LIQUID BARRIER DEMONSTRATION AT THE BROOKHAVEN NATIONAL LABORATORY

Prepared by:

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Prepared for:

Brookhaven National Laboratory

September 1999

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ATTACHMENTS

1. MODELING OBJECTIVES

The objective of the modeling efforts described in this document was to predict the hydrologic regime within the unsaturated block of soil beneath the Brookhaven LINAC Isotope Producer (BLIP) at Brookhaven National Laboratory (BNL), after solidifying the block with colloidal silica (CS). The modeling efforts focused on the prediction of:

- Fluxes and flow coming in and going out of the solidified block of soil, and
- Flow paths within and in the vicinity of solidified region.

2. DATA USED

2.1 Data Source

The modeled domain was sized to fit predicted results of the solidification efforts, as described in the document prepared by MSE Technology Applications, Inc. (MSE) in September 1999 (MSE 1999). The soil parameters used for modeling efforts are based on the results provided by the Montana State University soils laboratory (MSU-Lab) in Bozeman, Montana. The MSU-Lab analyzed soil samples provided by MSE to determined soil moisture parameters (retention curve) for the native unsolidified soil and the solidified soil.

The native soil material tested by the MSU-Lab was collected at BNL from the same location as the material excavated to build the man-made mound, within which the BLIP is located.

2.2 Laboratory Consideration

The solidified material was extruded from a test column that included native material injected with CS at the MSE facility. This column was one of several that had been prepared in the MSE lab to test the performance of selected CS materials injected into the native soil at different pore volume (PV) ratios. The solidified material tested by MSU-Lab came from the column which was solidified using the CS selected for the BLIP barrier installation. This silica, variant MSE-6, was injected into a series of 10.16 cm high, 9.5 cm ID, columns at the PV ratios of 0.5, 1, 1.5, 2, and 2.5, as measured at the intake port located at the bottom of the column.

Because the bottom and top 1.25 cm of the column were filled with coarse sand, to facilitate an even distribution of CS across the native sand material, the total height of the solidified material was 7.5 cm. The MSU-Lab determined the retention curve for a one centimeter thick and five centimeter diameter sample extruded from the bottom portion of the 7.5 cm high column of solidified native material that was injected with 0.5 PV of CS.

PV refers to the volume of colloidal silica injected to a 10.16 cm high, 9.5 cm ID test column that was filled with a 7.5 cm of native sand outlined at its top and bottom with 1.25 cm thick coarse sand to facilitate an even distribution of CS across the native sand material. Injected volume of colloidal silica was measured at its injection point located at the bottom of the test column. One pore volume equals the volume of pores in the column calculated using total porosity, θ.

For constructing retention curves, measurements of water retention were conducted using two methods (Klute, 1986). 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 moisture retention curves, like volumetric moisture content, bulk density, saturated hydraulic conductivity and total porosity were obtained using appropriate ASTM lab procedures or methods of calculations. Certain explanations, however, are needed to qualify how the value of total porosity for the solidified material has been derived and used in the simulation of unsaturated flow.

- Determination of total porosity of a soil by drying it in the oven is a standard ASTM method. Unfortunately, drying a CS-solidified soil destroys the structure of the gel (present in pores) with evaporation of water. Thus the total porosity of a CS-solidified material, determined by drying the sample in the oven, will always be much greater than the actual total porosity of the moist sample.

- One way to compensate for this inevitable discrepancy is to treat the CS-solidified material similarly to clay, which also contains a significant amount of immobile water bound in very small pores. For clay, vanGenuchten (vanGenuchten 1980) fitting parameters take care of its retention curve, assigning a high porosity while high residual water content, θ_r, compensates for the immobile water content. The same model will be valid for a CS-solidified material and no error will be induced, especially at the high and medium ranges of soil saturation, the latter prevailing in the soil beneath the BLIP.

- The porosity of CS-solidified sand determined by drying it in an oven is reduced only by the volume of dry silica (SiO_2) that remains in pores. This volume can be approximately calculated from the percent of solids in the CS, the ratio of electrolyte to CS, and the molecular mass for water and silica. For the colloidal silica variant, MSE-6, whose percent solids (by mass) is 30 percent, the reduction of volume of the moist CS gel to dry silica (SiO_2), is 90 percent.

- It follows from the above, that if the native material of porosity 0.34 was fully saturated with CS, its porosity after oven drying would be 3.4 percent lower or 0.306. This value, however, was not used for the modeling. Instead, a more conservative value of 0.323, which was measured at the MSU-Lab, was used.

2.3 Moisture Retention Curves

The moisture retention curves were fitted to the laboratory data using vanGenuchten formulas. Details of the moisture retention curve and the MSU-Lab raw data for the solidified samples are included in Attachments A and B, respectfully. Details of the moisture retention curve and the MSU-Lab raw data for native (unsolidified) sand are included in Attachments C and D, respectfully. The soil retention curves were fitted to the laboratory data using a nonlinear optimization by least squares minimization, using the Levenberg-Marquardt algorithm (Wraith, 1998)[1]. A summary of the fitting parameters used for modeling efforts is given in Table 1.

Table 1 - Soil Parameters Used for Modeling.

Soil	θ (Total porosity - volumetric)	vanGenuchten fitting Parameters			θ_r (Residual moisture content - volumetric)	K_s (Saturated hydraulic conductivity) [cm/s]	Comments
		n	α [1/m]	S_r (Relative Residual Saturation)			
Native BLIP sand	0.341	2.306	3.257	0.117	0.040	2.3×10^{-2}	Based on MSU-Lab data. Used for PORFLOW simulations.
Solidified sand (0.5 pore volume)	0.323	1.409	3.215	0.316	0.102	1.35×10^{-6}	Based on MSU-Lab data. Used for PORFLOW simulations.

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[1] Dr. Jon M.Wraith is responsible for the MSU-Lab and has conducted soil analysis and fitted the soil retention curves for the MSE provided soil samples.

3. DESCRIPTION OF THE SOFTWARE USED

The simulation of unsaturated flow within a block of soil beneath the BLIP at BNL, after a portion of this block was solidified using CS, has been performed using PORFLOW™ software.

PORFLOW™ is a general purpose software developed by Analytic & Computational Research, Inc. (ACRi), for simulation of transient or steady state multi-phase fluid flow, heat, salinity and mass transport in multi-phase, variably saturated, porous or fractured media with dynamic phase change. The geometry of the modeled domain may be structured or unstructured, 2D, 3D, Cartesian, or cylindrical. The media modeled may be heterogenous and anisotropic, injection or pumping sources may be present and chemical reactions or radioactive decay may take place. From the numerical point of view, PORFLOW™ is a hybrid of a finite volume with a finite element mesh code written in FORTRAN.

PORFLOW™ has recently been enhanced with a Graphical User Interface (GUI), a preprocessor for entering geometry, boundary conditions; and flow, transport and dynamic phase change relationships. A post-processor, acrPLOT, generates charts, flow vectors, contours, grids, 3D surface plots and X-Y cross sections at any direction.

PORFLOW™ is a well recognized software successfully applied by nearly one hundred users (companies) based in USA, and other countries. In the USA, PORFLOW™ has been used by major consulting firms like Westinghouse, Battelle, and Woodward-Clyde as well as the government agencies including DOE, U.S. Army Engineers, U.S.G.S., etc.

4. MODELING EFFORTS

4.1 Boundary Conditions

The simulation of unsaturated flow within the unsaturated block of soil beneath the BLIP has been conducted using a simplified 3D 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 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 one radian portion of the cylindrical domain. This domain was discretized to 2,596 elements using structured, 61 (vertical) times 46 (horizontal), grid. Thus, there are 59 layers of elements in the model, each consisting of 44 elements. Each element is 0.3048 m high, 0.3048 m wide and has a length equal to the length of a one radian arch at the given radius. For example, the last element of each layer is 13.41 m long if measured along its outer side. A side view of such a cylindrical domain is presented in Figures 1, 2, 5 and 6. Because the software refers modeling results with respect to directions X-, X+, Y- and Y+, the same terminology is used in this documentation of the modeling efforts. The surfaces related to the X-, X+ and Y+ notations are marked in Figures 3 and 4 where they indicate:

- X- The upper surface (pie shape) for the solidified cylinder,
- X+ The lower surface (pie shape) for the solidified material, and
- Y+ A one radian portion of the side of the cylinder.

The coordinates Y- is placed along the axis of the cylinder, thus making a symmetrical boundary.

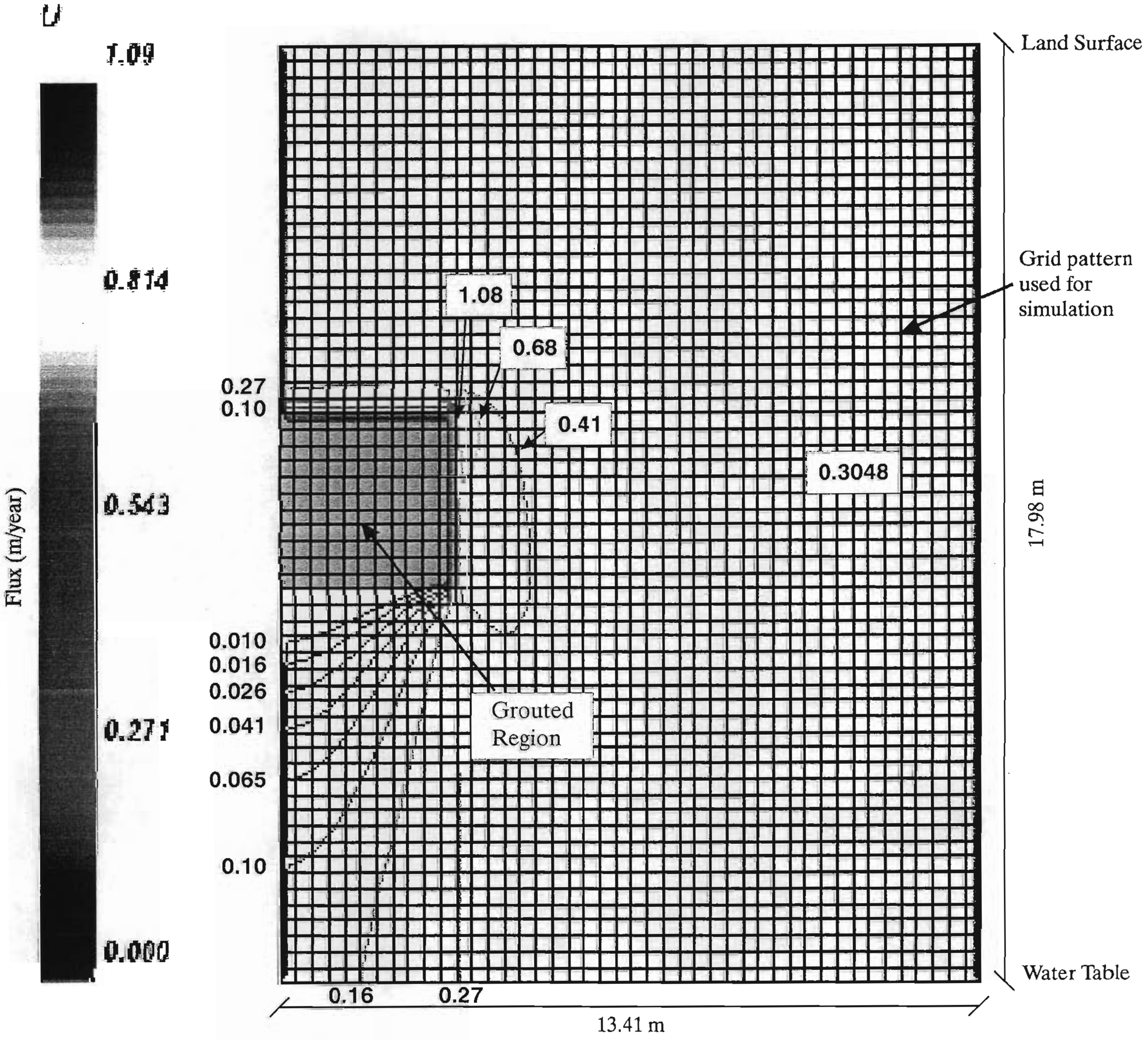
Boundary conditions for the simulated domain were set as:

- X- Constant flux boundary with 0.3048 m/year flux.
- X+ Constant pressure (hydraulic head) boundary of 0 value.
- Y- Constant flux boundary with 0 m/year flux
- Y+ Constant flux boundary with 0 m/year flux

These boundary conditions were used for the simulation of both a pre-injection flow regime and a post-injection flow conditions.

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 solidified sand was introduced in the modeled domain. Region2 is denoted in Figures 1 through 6 as Grouted Region. This cylindrical object is 3.35 meters high and has a radius of 3.35 meters.

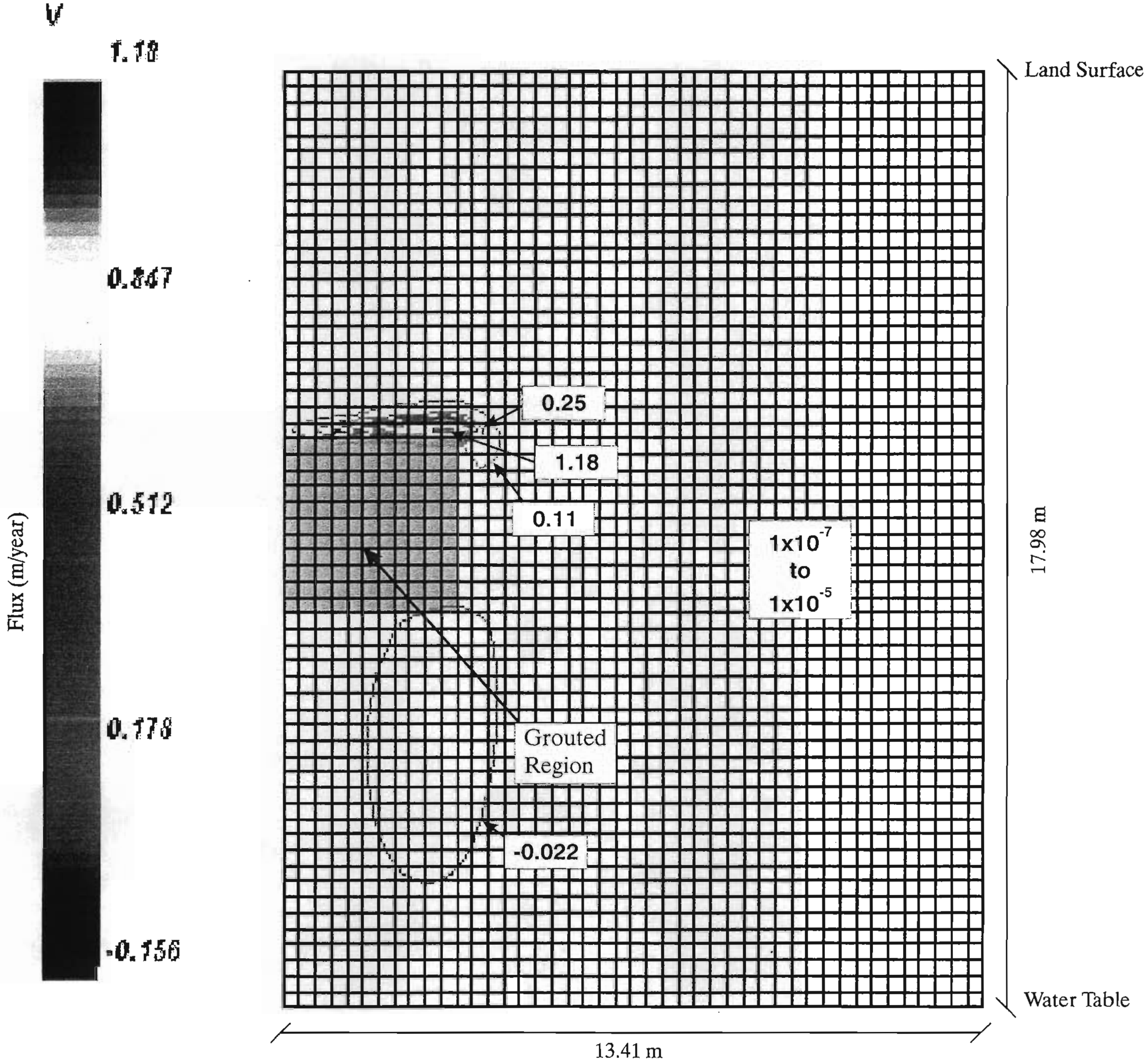
Distribution of the Vertical Component of Flux in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)



Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 1

Distribution of the Horizontal Component of Flux in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)

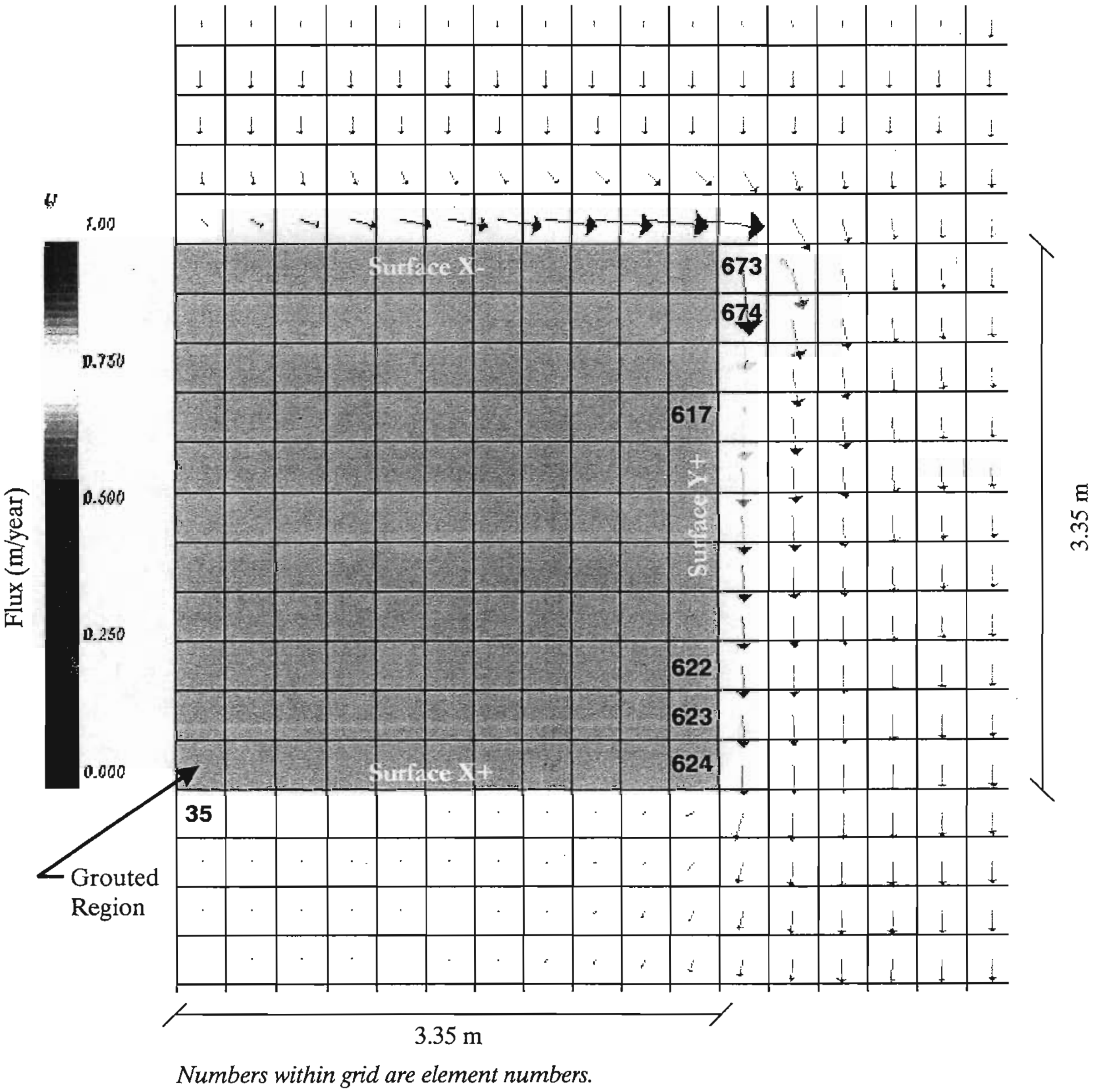


Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 2

Flow Vectors and their Vertical Components in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)

Colors indicate the vertical flow component.
Arrows indicate direction and magnitude
of total flow.



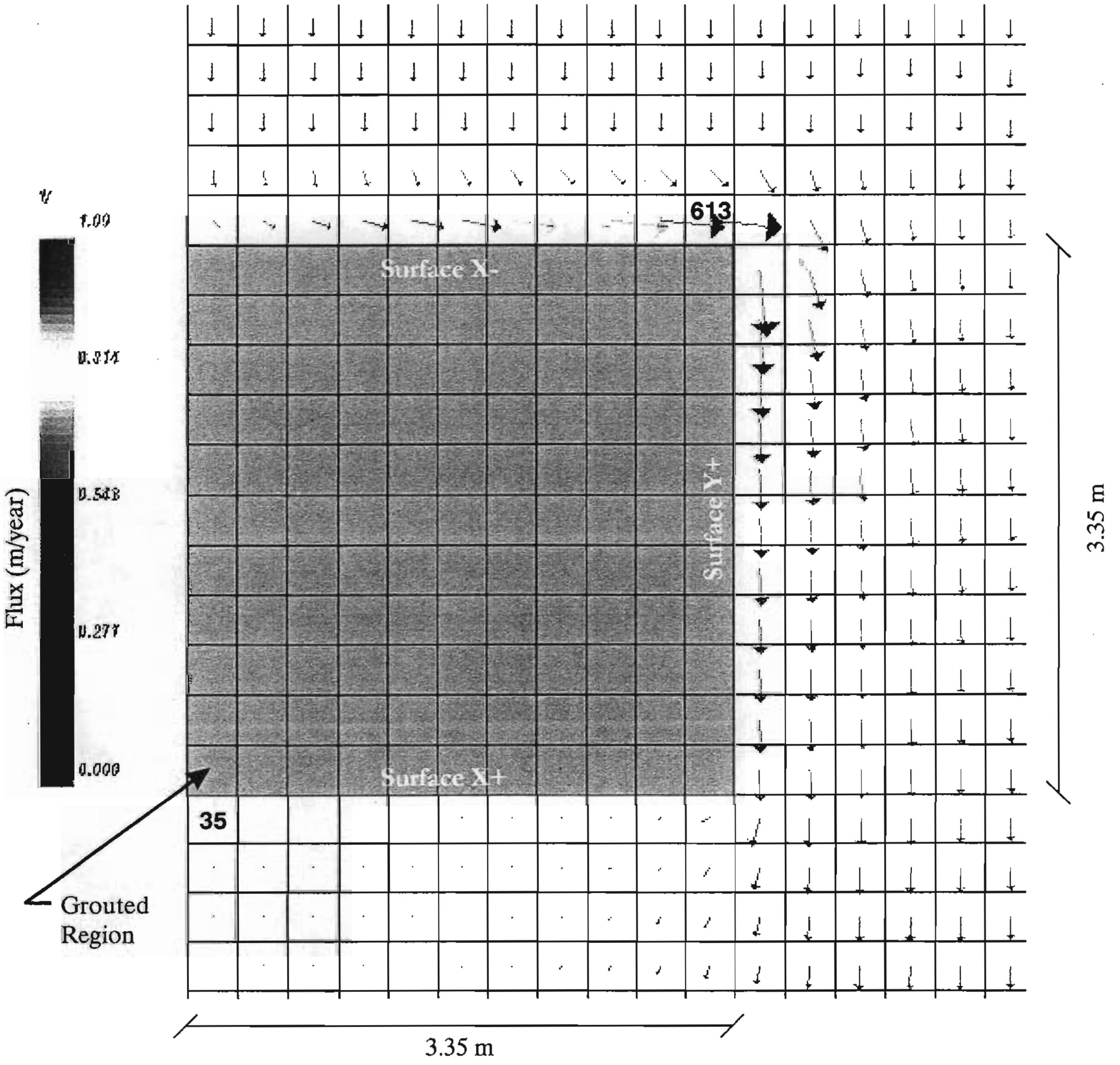
Numbers within grid are element numbers.

Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 3

Flow Vectors and their Horizontal Components in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)

Colors indicate the horizontal flow component.
Arrows indicate direction and magnitude
of total flow.

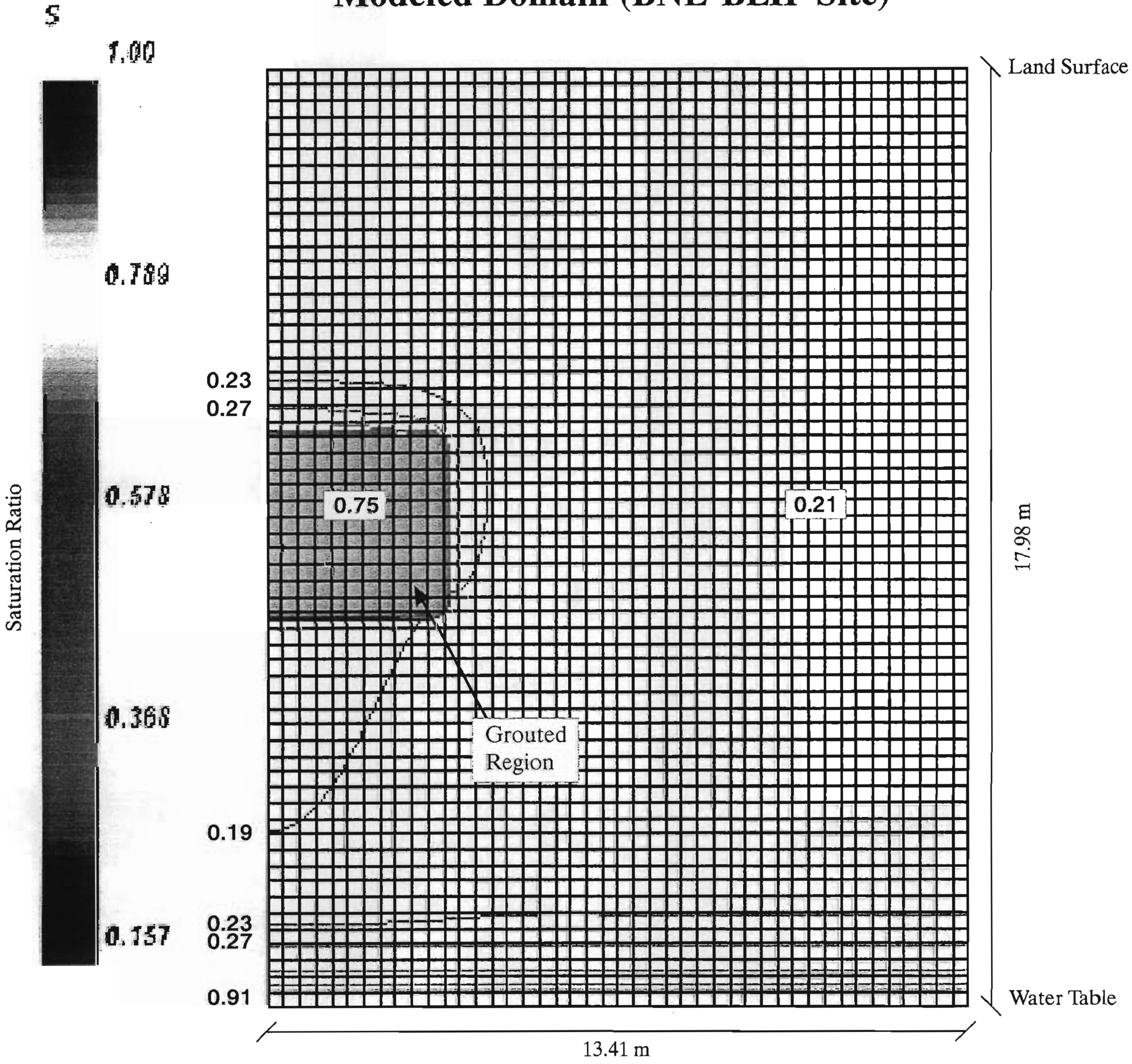


Numbers within grid are element numbers.

Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 4

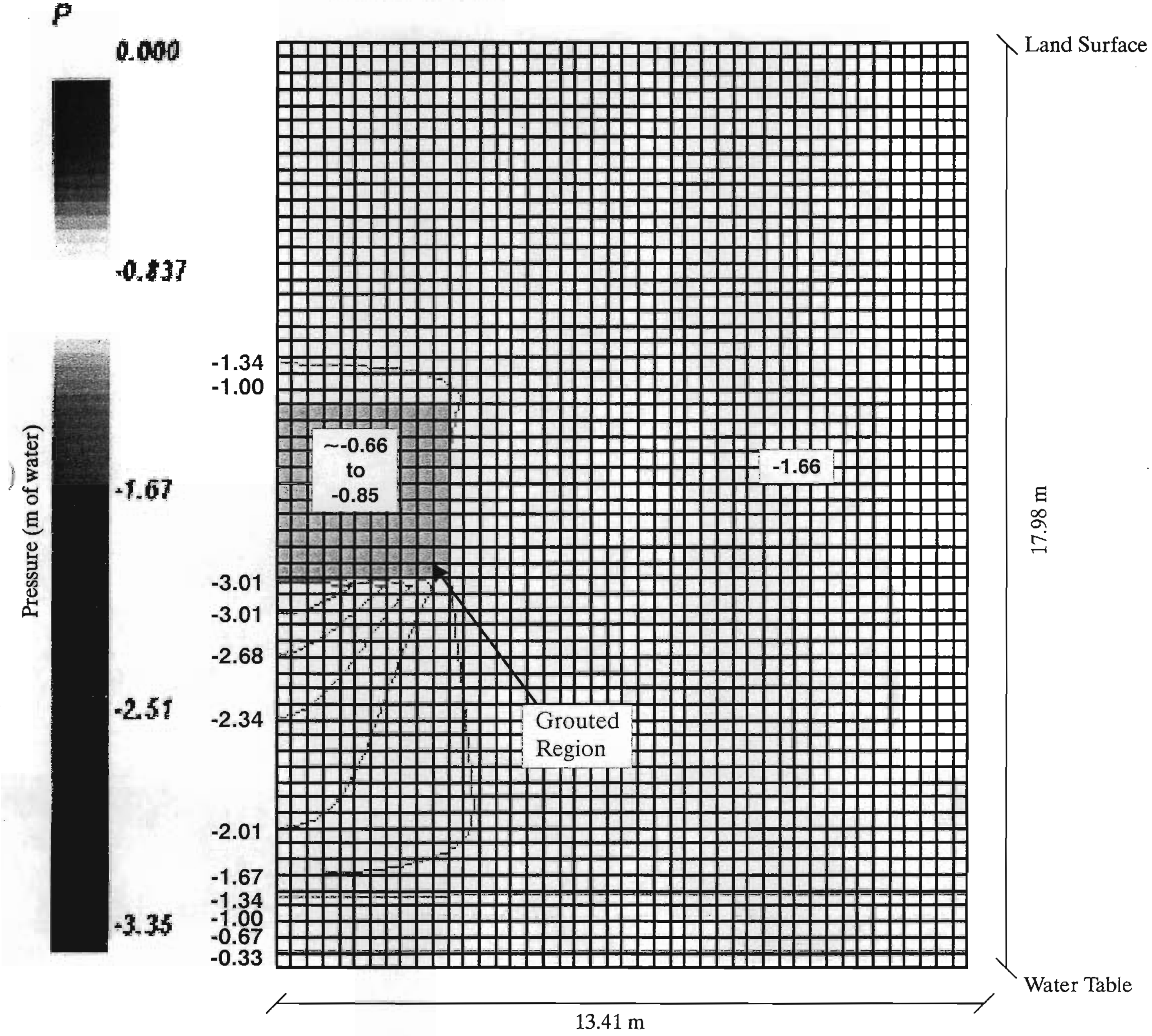
Water Saturation Distribution in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)



Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 5

Water Pressure Distribution in a 1-Radian Portion of the Cylindrical Modeled Domain (BNL-BLIP Site)



Result of POREFLOW™ Simulation
(see Table 1 for soil parameters used)

Figure 6

4.2 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 is called "matric potential" (in this document denoted as P), which is a function of the volumetric water content. This relationship, called the moisture retention curve or the soil moisture characteristic curve, is one of the entry parameters used for simulation of unsaturated flow. Such functions for native and solidified sands were determined as previously described in Section 2.

The modeling efforts for the BLIP site consisted of three steps:

- The moisture 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, as stated in Section 4.1. This step modeled the flow regime without a solidified region, hereafter referred to as the pre-injection model.
- The output file of the pre-injection flow regime was then read by the input file for the steady state simulation to predict post-injection flow regime at equilibrium.
- The output file of the pre-injection flow regime was also read by the input file for the transient simulation, to model changes of the post-injection flow regime in time.

4.3 Actual Simulations

All simulations were performed using consistent units (i.e., time in years, and spatial measurements and coordinates in meters).

Transient simulations were conducted using the following settings:

Total simulated time:	1 year and 30 years for pre- and post- injections, respectively.
Time step at start:	0.0001 years
Geometric multiplier for time step:	1.01
Maximum permissible time step:	0.001 years
Minimum permissible time step:	1.0 E-10 years
Geometric divider for the time step:	2 (Each successive step is decreased by this factor if the number of iterations to convergence is larger than prescribed)
Convergence (average residual) for flow:	0.0001
Maximum number of iterations for convergence:	500

Steady state flow simulation was conducted using 1000 and 500 for the maximum and minimum number of iterative steps performed on the matrix, respectively.

All final simulations achieved acceptable water balance for the modeled domain as indicated in Table 2.

Table 2. Water Balance of Simulations.

Simulation	Original Volume (Q_O) [m^3]	End Volume (Q_E) [m^3]	Total Inflow (Q_{IN}) [m^3]	Total Outflow (Q_{OUT}) [m^3]	Disparity Q_O-Q_E+ Q_{IN}-Q_{OUT} [m^3]	Ratio Disparity to End Volume	Ratio Disparity to Total Outflow
Pre-injection	172.612	130.377	35.319	77.560	-0.00593	-4.5 E-5	-7.6 E-5
Post injection (transient)	175.025	133.574	830.230	871.685	-0.00418	-3.1 E-5	-4.8E-6
Post injection (steady state)	175.025	133.607	NA	NA	NA	NA	NA

4.4 Modeling Results

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

4.4.1 Steady State Conditions

Results of the steady state flow simulation are depicted in Figures 1 through 6 and Table 3. They include values of:

- Flux [m/year],
- Vertical and horizontal components of flow vectors (flux) [m/year],
- Water saturation ratio, i.e., the ratio of volumetric moisture content to total porosity,
- Matric potential [m of water], and
- Flow [m^3/year or m^3/time of simulation]

The vertical components (U) of the flow vectors (fluxes) are depicted in Figures 1 and 3 . They are always positive, signifying that the flow in the domain is downward. They range from nearly zero, 0.0004 m/year, in elements 617 to 623 (Figure 3) 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/year. For most of modeled domain, to the right of the solidified Region2, the U value equals the rate of recharge, 0.3048 m/year.

The horizontal component (V) of the flow vectors are depicted in Figures 2 and 4. Within most of the modeled domain they are positive, i.e., this flow component is from left to right. The maximum V value, 1.18 m/year, appears in element 613 (Figure 4). 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. There, in element 35, the V value is -0.0008 m/yr.

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

Matric potential, P, ranges from -3.35m 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 -0.66m to -0.85m.

Although information regarding 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 3.

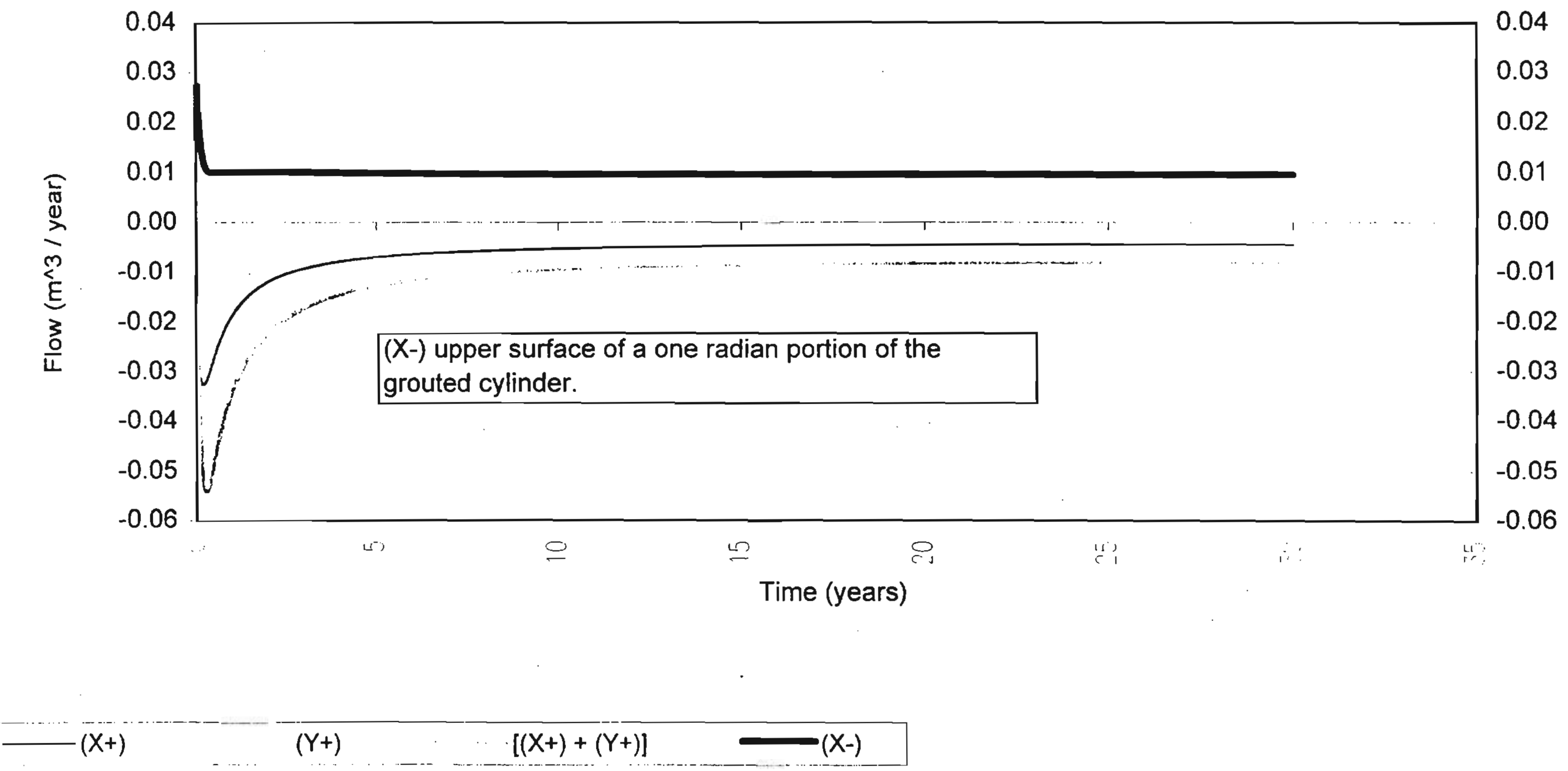
Table 3. Flow Balance of the Solidified Region.

Face	Steady State Flow		Flow after 30-year transient simulation		Comment
	Inflow rate [m^3/year]	Outflow rate [m^3/year]	Inflow rate [m^3/year]	Out-low rate [m^3/year]	
X-	0.00962		0.00962		
X+		-0.00576		-0.00447	Negative sign denotes flow leaving the region.
Y+		-0.00386		-0.00360	Negative sign denotes flow leaving the region.
Y-	0.00000	0.00000	0.00000	0.00000	Boundary conditions of flux = 0
Total	0.00962	-0.00962	0.00962	-0.00807	
Difference	0.00000		0.00155		

4.4.2 Transient Flow Conditions

The results of the transient flow simulation, depicted in Figures 7a and 7b (time is in logarithmic scale) and Table 3, indicate that the steady state conditions are yet to be obtained 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/year. By the end of the 30-year period, the difference is 23 fold. The smallest difference occurs after half a year of transient flow simulations, when the sum of the flows through face X+ and Y+ is approximately 0.052 m^3/year.

Figure 7a. Flow vs. Time for Solidified Region



ATTACHMENT B
Lab Data for 0.5 Pore Volume Column

0.5 Pore Volume Column

MSE: injected BNL sand ('0.5 Pore Volume Sample)

measured 9/99

apparatus weight includes funnel with saturated fritted glass and water in the base, but not the weight of the hose

sample weights other than apparatus weight also include parafilm covering

Sample Dia: 8.1 (cm)

****************Mass of apparatus plus sample (g)************************

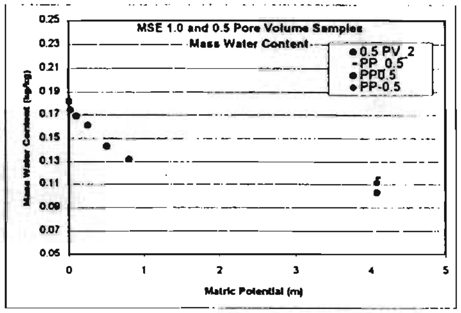
funnel	apparatus	saturated	2 cm	10 cm	25 cm	50 cm	80 cm	can #	can wt	an+wet so	wet soil	parafilm	an+dry so	oven dry so	ass wate	ThetaM	Sample Volume	Sample ulk Dens.	Sample Porosity
0 5_2	348.99	522.88	521.83	521.05	519.93	517.35	515.79	15	36.18	199.21	163.03	2.39	180.16	143.98	19.05	0.13231	79.01091	1.82228	0.312347

Sample Mass (g) (without apparatus or parafilm)

saturated	2 cm	10 cm	25 cm	50 cm	80 cm
171.5	170.45	169.67	168.55	165.97	164.41

Mass Water Content (kg/kg)

	funnel	saturated	2 cm	10 cm	25 cm	50 cm	80 cm		
HangCol:	0.5_2	0.181553	0.17426	0.168843	0.161064	0.143145	0.13231		
	h (m)	0	0.02	0.1	0.25	0.5	0.8	4.079135	27.53416
PressPlate:	0.5_1							0.116269	0.071904
	0.5_2							0.102998	0.075973
	0.5_3							0.112065	0.073171
							Mean:	0.110444	0.073683



Pressure Plate Results:

0.4 bar

4.079135 m H2O

Sample	Can Wt	n&Ring&W	h&Ring&D	Ring	Wet Soil	Dry Soil	Mass WC
0.5_1	34.82	99.73	94.27	12.49	52.42	46.96	0.116269
0.5_2	35.39	90.91	86.89	12.47	43.05	39.03	0.102998
0.5_3	35.86	100.09	94.87	12.43	51.8	46.58	0.112065

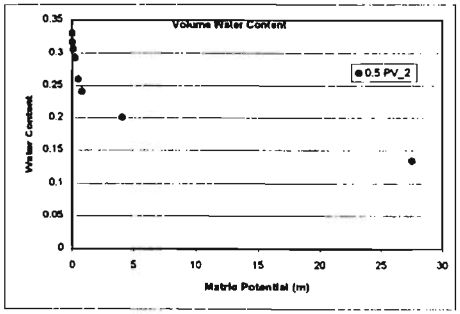
2.7 bar

27.53416 m H2O

0.5_1	35.57	96.31	94.85	11.16	51.56	48.12	0.071904
0.5_2	35.75	99.57	95.94	12.41	51.41	47.78	0.075973
0.5_3	35.44	99.29	95.69	11.05	52.8	49.2	0.073171

Calculated Volume Water Content

Bulk Density	ID	saturated	2 cm	10 cm	25 cm	50 cm	80 cm	0.4 bar	2.7 bar
1.822	0.5_2	0.33084	0.317551	0.307679	0.293504	0.26085	0.241106	0.20128	0.13427
	h (m)	0	0.02	0.1	0.25	0.5	0.8	4.08	27.5



Adjust Bulk Densities to Scale Porosity by - 5%, -10%:

	'Scaling' BulkDensity	New ThetaS
-5%	1.55	0.281407
-10%	1.27	0.230572

5% lower porosity: Volume Water Contents

h (m)	0	0.02	0.1	0.25	0.5	0.8	4.08	27.5
0.5_2	0.281407	0.270103	0.261706	0.249849	0.221875	0.205081	0.171188	0.114208

10% lower porosity: Volume Water Contents

h (m)	0	0.02	0.1	0.25	0.5	0.8	4.08	27.5
0.5_2	0.230572	0.221311	0.21443	0.204551	0.181794	0.168034	0.140264	0.093577

ATTACHMENT C
Retention Data for Unconsolidated Sand

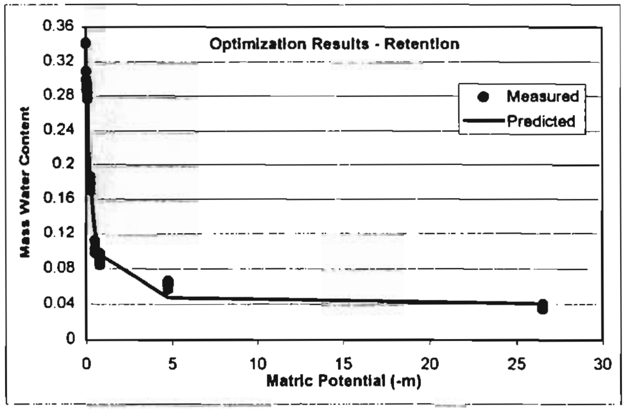
Retention Data Optimized to van Genuchten's (1980) Eq.

Using Volume Water Contents

ThetaS:	0.341351	fitted	**SSE:**	0.007744
ThetaR:	0.04	fitted	**Variance:**	0.012903
Alpha:	3.25684	fitted	**Count:**	24
n:	2.306492	fitted	**r^2:**	**0.975**
m:	0.566441	=1-1/n		

Unconsolidated Sand

h (m)	Measured WatCont	Predicted WatCont	Error^2
0	0.341164	0.341351	3.5E-08
0	0.341783	0.341351	1.86E-07
0	0.341108	0.341351	5.93E-08
0.02	0.287765	0.317503	0.000884
0.02	0.299557	0.317503	0.000322
0.02	0.309208	0.317503	6.88E-05
0.1	0.27664	0.2485	0.000792
0.1	0.284564	0.2485	0.001301
0.1	0.292896	0.2485	0.001971
0.25	0.186157	0.178388	6.04E-05
0.25	0.170432	0.178388	6.33E-05
0.25	0.179072	0.178388	4.68E-07
0.5	0.111991	0.12526	0.000176
0.5	0.098221	0.12526	0.000731
0.5	0.102949	0.12526	0.000498
0.8	0.097528	0.096417	1.24E-06
0.8	0.084757	0.096417	0.000136
0.8	0.089899	0.096417	4.25E-05
4.76	0.057158	0.047733	8.88E-05
4.76	0.066443	0.047733	0.00035
4.76	0.062292	0.047733	0.000212
26.5	0.034291	0.040877	4.34E-05
26.5	0.039668	0.040877	1.46E-06
26.5	0.040174	0.040877	4.95E-07

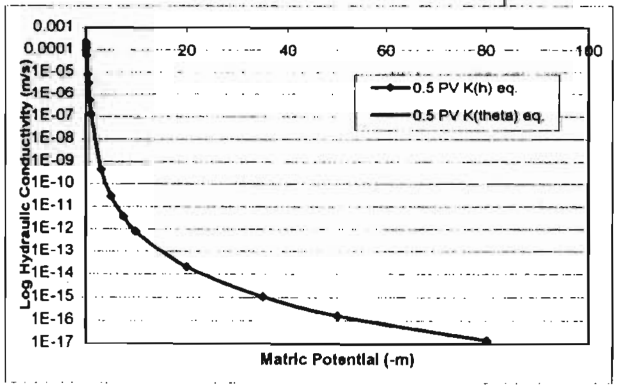


Resulting Hydraulic Conductivity, K(h), Relationships

Unconsolidated Sand Sample

ThetaS:	**0.341351**
ThetaR:	**0.04**
Alpha:	**3.25684**
n:	**2.306492**
m:	**0.566441**
θ(h) fit r^2:	**0.988**
Ks (m/s):	**0.000233**

h (m)	ThetaV	Se	K(h) (m/s)	K(theta) (m/s)
0	0.341351	1	0.000233	0.000233
0.02	0.341038	0.998961	0.00022	0.00022
0.05	0.338787	0.991489	0.000191	0.000191
0.1	0.329224	0.959757	0.000138	0.000138
0.2	0.29192	0.835968	5.8E-05	5.8E-05
0.4	0.206824	0.553587	8.22E-06	8.22E-06
0.5	0.1759	0.450968	3.39E-06	3.39E-06
0.75	0.127665	0.290906	5.41E-07	5.41E-07
1	0.102154	0.20625	1.32E-07	1.32E-07
3	0.055292	0.050746	4.52E-10	4.52E-10
5	0.047862	0.026088	3.09E-11	3.09E-11
7.5	0.044631	0.015368	3.66E-12	3.66E-12
10	0.043181	0.010555	8.05E-13	8.05E-13
20	0.041286	0.004268	2.09E-14	2.09E-14
35	0.040619	0.002055	1.1E-15	1.1E-15
50	0.040389	0.001289	1.68E-16	1.68E-16
80	0.04021	0.000698	1.41E-17	1.41E-17



ATTACHMENT D
Lab Data for Unconsolidated Sand

Sand Data.xls

MSE: unconsolidated BNL sand

measured 8/99

apparatus weight includes funnel with saturated fritted glass and water in the base, but not the weight of the tubing

sample weights other than apparatus weight also include parafilm covering

***************Mass of apparatus plus sample (g)***********************

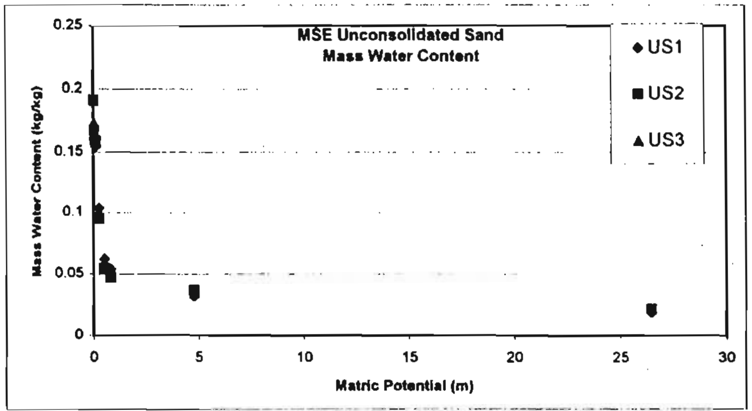
funnel	apparatus	saturated	2 cm	10 cm	25 cm	50 cm	80 cm	can #	can wt	can+wet soil	wet soil	parafilm	can+dry soil	oven dry soil	mass water	ThetaM
US1	360.66	421.14	419.7	419.4	416.96	414.96	414.57	11	47.81	98.71	50.9	2.44	96.08	48.27	2.63	0.054485
US2	351.6	424.47	423.09	422.6	418.87	416.51	416.07	34	46.9	108.17	61.27	2.44	105.4	58.5	2.77	0.04735
US3	364.14	425.93	425.05	424.6	421.46	419.36	419	3	47.81	99.67	51.86	2.41	97.19	49.38	2.48	0.050223

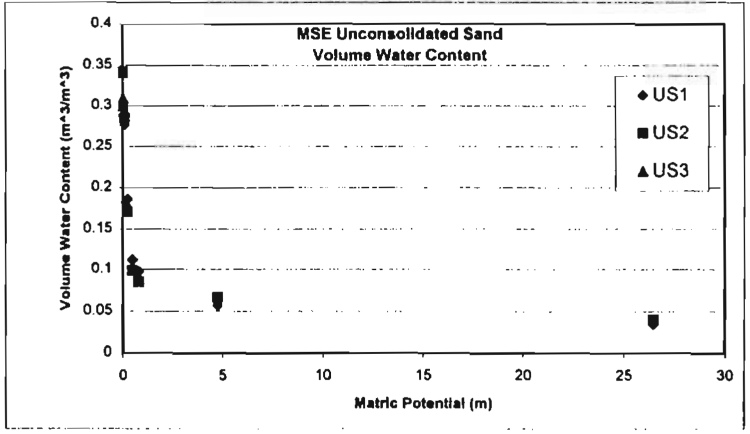
Sample Mass (g) (without apparatus or parafilm)

Init. saturate	2 cm	10 cm	25 cm	50 cm	80 cm
58.04	56.6	56.3	53.86	51.86	51.47
70.43	69.05	68.56	64.83	62.47	62.03
59.38	58.5	58.05	54.91	52.81	52.45

Mass Water Content (kg/kg)

	saturated	2 cm	10 cm	25 cm	50 cm	80 cm	(Pressure Plate)	
US1	0.190595	0.160762	0.154547	0.103998	0.062565	0.054485	0.031932	0.019157
US2	0.19094	0.16735	0.158974	0.095214	0.054872	0.04735	0.037119	0.022161
US3	0.190563	0.172742	0.163629	0.100041	0.057513	0.050223	0.0348	0.022443
h (m)	0	0.02	0.1	0.25	0.5	0.8	4.76	26.5





Pressure Plate Results:

35.0 cm Hg

4.76175 m H2O

Sample	Can Wt	n&Ring&Wn&Ring&D		Ring	Wet Soil	Dry Soil	Mass WC
US1	47.84	103.94	102.55	11.18	44.92	43.53	0.031932
US2	47.31	100.72	99.21	11.22	42.19	40.68	0.037119
US3	47.18	104.42	102.87	11.15	46.09	44.54	0.0348
2.6	bar						
26.51438	m H2O	97.1	94.5	12.31	37.48	34.88	0.074541
US1	47.84	102.8	102	12.4	42.56	41.76	0.019157
US2	47.54	100.57	99.69	12.44	40.59	39.71	0.022161
US3	47.18	103.62	102.65	12.25	44.19	43.22	0.022443

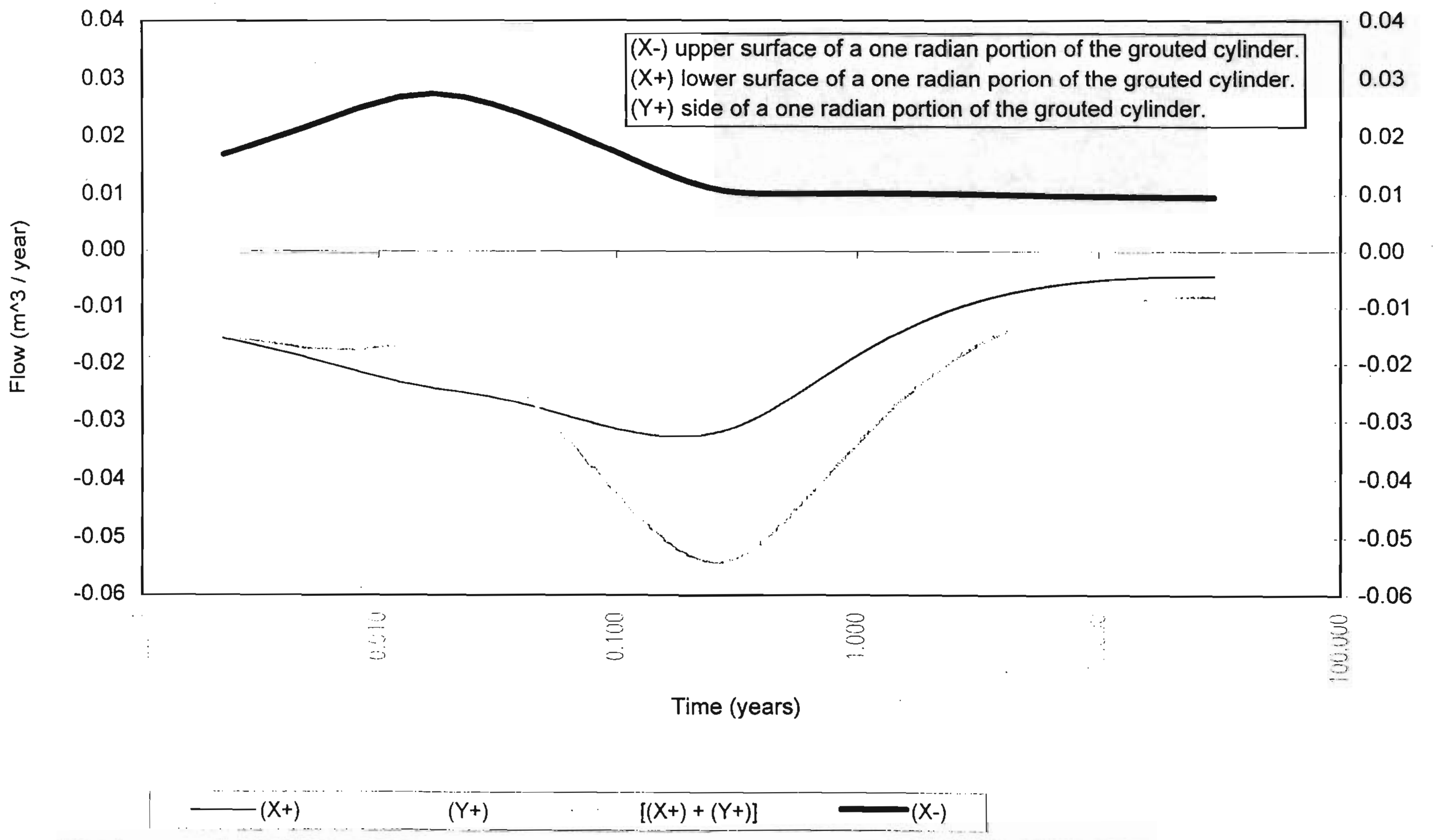
Sand Volume Water Content Calculations:

Bulk Density: **1.79**

US1	0.341164	0.287765	0.27664	0.186157	0.111991	0.097528	0.057158	0.034291
US2	0.341783	0.299557	0.284564	0.170432	0.098221	0.084757	0.066443	0.039668
US3	0.341108	0.309208	0.292896	0.179072	0.102949	0.089899	0.062292	0.040174
h (m)	0	0.02	0.1	0.25	0.5	0.8	4.76	26.5

Figure 7b

Figure 7b. Flow vs. Time for Solidified Region



5. LIMITATIONS

- The results reported describe only the flow pattern and flow rates that would be in effect some time after the gelation of CS takes place. The moisture conditions of the modeled domain are going through adjustment processes because the properties of the soil in the solidified region have been altered.

- The models described in this document neither simulate the effect of gelation of CS, nor do they simulate the effect of the "point source" while injecting CS.

6. CONCLUSIONS

- The results of the unsaturated flow simulation demonstrate that the performance goal of the barrier constructed using CS grout, variant to MSE-6, 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 $0.22\ m^3/year$.

- According to simulations of transient flow conditions, the minimal difference between the allowable flow rate and the out-flow from the solidified region occurs after half a year. At that time, the allowable flow ($0.22 m^3/yr$) is only 4 times greater than the outflow ($0.052 m^3/yr$) from the solidified region.

- The barrier performance goal has been exceeded despite the fact that the moisture retention curve used for the simulations was constructed based on laboratory testing of a grouted sample that was treated with only half a PV of CS.

7. REFERENCES

4. Klute, A. 1986. *Water retention: laboratory methods. p. 635-662.* In: A Klute (ed.) Methods of Soil Analysis. Physical and Mineralogical Methods. Part 2, 2nd Ed. American Society of Agronomy, Madison, WI.

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6. van Genuchten, M.Th. 1980. *A closed-form equation for predicting the hydraulic conductivity of unsaturated soils.* Soil Sci. Soc. Am. J. 44: 892-899.

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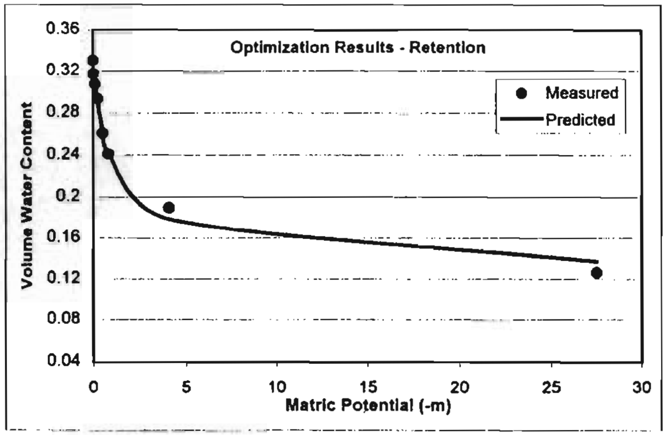
ATTACHMENT A
Retention Data of 0.5 Pore Volume Column

Retention Data Optimized to van Genuchten's (1980) Eq.
Using Volume Water Contents

ThetaS:	0.323497	fitted	**SSE:**	0.00035
ThetaR:	0.1021	fitted	**Variance:**	0.004981
Alpha:	3.215401	fitted	**Count:**	8
n:	1.409491	fitted	**r^2:**	**0.991**
m:	0.290524	=1-1/n		

0.5 Pore Volume Silica

h (m)	Measured WatCont	Predicted WatCont	Error^2
0	0.33084	0.323497	5.39E-05
0.02	0.317551	0.32217	2.13E-05
0.1	0.307679	0.311971	1.84E-05
0.25	0.293504	0.290744	7.62E-06
0.5	0.26085	0.263744	8.38E-06
0.8	0.241106	0.24257	2.14E-06
4.08	0.189534	0.178676	0.000118
27.5	0.126447	0.137405	0.00012



Resulting Hydraulic Conductivity, K(h), Relationships
0.5 Pore Volume Sample

ThetaS:	**0.323497**
ThetaR:	**0.1021**
Alpha:	**3.215401**
n:	**1.409491**
m:	**0.290524**
θ(h) fit r^2:	**0.988**
Ks (m/s):	**1.35E-08**

h (m)	ThetaV	Se	K(h) (m/s)	K(theta) (m/s)
0	0.323497	1	1.35E-08	1.35E-08
0.02	0.32217	0.994007	6.17E-09	6.17E-09
0.05	0.318832	0.978928	3.85E-09	3.85E-09
0.1	0.311971	0.94794	2.15E-09	2.15E-09
0.2	0.297516	0.882652	8.79E-10	8.79E-10
0.4	0.273245	0.773022	2.43E-10	2.43E-10
0.5	0.263744	0.73011	1.48E-10	1.48E-10
0.75	0.245509	0.647746	5.5E-11	5.5E-11
1	0.232483	0.588911	2.58E-11	2.58E-11
3	0.188601	0.390704	1.14E-12	1.14E-12
5	0.172691	0.318844	2.5E-13	2.5E-13
7.5	0.16204	0.270738	7.41E-14	7.41E-14
10	0.155437	0.240911	3.12E-14	3.12E-14
20	0.142311	0.181625	3.87E-15	3.87E-15
35	0.13409	0.144493	7.13E-16	7.13E-16
50	0.129747	0.124876	2.43E-16	2.43E-16
80	0.124909	0.103025	5.87E-17	5.87E-17