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# Field Evaluation of a Horizontal Well Recirculation System for Groundwater Treatment: Field Demonstration at X-701B Portsmouth Gaseous Diffusion Plant Piketon, Ohio

*Prepared by*


N. Korte
M. Muck
P. Kearl
R. Siegrist
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R. Schlosser
J. Zutman





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LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
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Environmental Sciences Publication No. 4720

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N. Korte[1]
M. Muck[1]
P. Kearl[1]
R. Siegrist[2]
T. Houk[3]
R. Schlosser[1]
J. Zutman[1]

*Managed by*

LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
for the
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[1] Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, Environmental Technology Section, Grand Junction, Colo., 81503
[2] Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, Tenn., 37830
[3] Lockheed Martin Energy Systems, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio, 45661

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## Abbreviations, Acronyms, and Initialisms

| | |
|---|---|
| amsl | above mean sea level |
| bgs | below ground surface |
| BH | borehole |
| CE | construction engineer |
| cm | centimeter |
| CMSs | corrective measures studies |
| CTS | Clean Test Site |
| d | day |
| DNAPL | dense nonaqueous-phase liquid |
| DOE | U.S. Department of Energy |
| DTD | Directed Technologies Drilling |
| EMEF | Environmental Management and Enrichment Facilities |
| ft | feet |
| g | grams |
| GAC | granular activated carbon |
| gal | gallon(s) |
| h | hour |
| HDPE | high-density polyethylene |
| ID | inside diameter |
| in. | inch |
| JMC | Johnson-Matthey Corporation |
| K | hydraulic conductivity |
| kg | kilograms |
| L | liter |
| lb | pound |
| m | meter |
| Mears | Mears Engineering, Inc. |
| $\mu$g | micrograms |
| mg | milligram |
| $\mu$m | micron |
| min | minute(s) |
| mL | milliliter |
| ng | nanogram |
| NTU | nephelometric turbidity unit |
| OD | outside diameter |
| O&M | operation and maintenance |
| ORNL | Oak Ridge National Laboratory |
| PCB | polychlorinated biphenyl |
| pCi | picocurie |

| | |
|---|---|
| Pd/Fe | palladized iron |
| PGDP | Paducah Gaseous Diffusion Plant |
| PORTS | Portsmouth Gaseous Diffusion Plant |
| ppb | parts per billion |
| ppm | parts per million |
| psi | pounds per square inch |
| PVC | polyvinyl chloride |
| QA | quality assurance |
| RCT | Research Corporation Technologies |
| s | second |
| TCE | trichloroethene |
| UofA | University of Arizona |
| U.S. | United States |
| vs | versus |
| VOCs | volatile organic compounds |
| yd | yard |

**Acknowledgment**

Identifying, testing, and implementing innovative technologies will be required in order to meet the expectations identified in the Ten Year Plan. The Portsmouth Gaseous Diffusion Plant (PORTS) has hosted and funded many technology demonstrations. The cooperative working relationship with the regulator community, a history of successfully moving from the demonstration stage to remediation of an existing unit, and the available technical support have combined to make PORTS an ideal site for field demonstrating new ideas.

Many individuals and organizations have contributed to the successful completion of this project. Without the financial support and management assistance of the U.S. Department of Energy (DOE) Office of Environmental Restoration and Lockheed Martin Energy Systems (LMES) at PORTS, this project could not have been accomplished. The project team is grateful to the following PORTS individuals for their support to the project:

| | | |
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## Executive Summary

This report describes the field-scale demonstration performed as part of the project, In Situ Treatment of Mixed Contaminants in Groundwater. This project was a 3 ½ year effort comprised of laboratory work performed at Oak Ridge National Laboratory and fieldwork performed at the U.S. Department of Energy (DOE) Portsmouth Gaseous Diffusion Plant (PORTS). The project was jointly funded by DOE-EM-50, Office of Science and Technology, Subsurface Contaminants Focus Area, and by DOE EM-40 through PORTS. The overall goal of the project was to evaluate in situ treatment of groundwater using horizontal recirculation coupled with treatment modules. Specifically, horizontal recirculation was tested because of its application to thin, interbedded aquifer zones. Mixed contaminants were targeted because of their prominence at DOE sites and because they cannot be treated with conventional methods. The project involved several research elements, including treatment process evaluation, hydrodynamic flow and transport modeling, pilot testing at an uncontaminated site, and full-scale testing at a contaminated site. This report presents the results of the work at the contaminated site, X-701B at PORTS. Groundwater contamination at X-701B consists of trichloroethene (TCE) (concentrations up to 1800 mg/L) and technetium-99 ($Tc^{99}$) (activities up to 926 pCi/L).

Two horizontal wells were installed at X-701B in May 1996. The wells, with horizontal sections 71 m (234 ft) in length, were installed at a depth of 10 m (32 ft) using directional drilling methods. The wells were placed along the bedrock surface in a 0.9 to 2 m (3 to 7 ft) thick zone of a moderately permeable, unconsolidated fluvial deposit. The horizontal sections of the wells were constructed with ductile, porous polyethylene, an innovative material originally developed in Germany by Schumacher Umwelt-und Trenntechnik GmbH and now distributed in the U.S. by Schumacher Filters America, Inc. This well filter has a pore size of 500 $\mu$m and is composed of sintered spheres of high density polyethylene. Drilling and installation of the wells was completed in ten days. A network of monitoring wells was installed to assess the influence of the horizontal flow field both on the subsurface hydraulics and the groundwater contaminants.

Field testing was performed for 74 days during which more than 580,000 gal of water were recirculated by extraction from one horizontal well and reinjection into the other. Pumping was performed at 6 gal/min, but testing demonstrated that a flow rate two to three times higher could have been used. No well screen or formation clogging or other hindrances to long-term performance were observed.

Hydraulic tests of well performance showed that a hydraulic gradient of 0.13 could be induced between the wells—an increase of two orders of magnitude over non-pumping conditions. The net effect is that horizontal recirculation is thirty times more efficient at flushing the contaminated zone as compared to no pumping. Furthermore, a bromide tracer test demonstrated that the entire flow field was affected by the

recirculation system. The tracer test did show, however, that preferential flow zones dominated the flow field.

A low flow zone is present in the heart of the plume where the highest $Tc^{99}$ concentrations are present. This is curious because geologic logs from drilling in this area indicate that the heart of the plume should be a preferential flow zone. It is believed that free-phase TCE blocks the pore spaces in the heart of the plume resulting in the low flow zone.

Locations where flow was preferential were rapidly cleaned of TCE and $Tc^{99}$ while low flow zones, with the highest concentrations of TCE, showed little treatment over the relatively short duration of the demonstration.

Treatment of the mixed contaminant stream was conducted with zero-valence iron for removal of $Tc^{99}$ and with activated carbon for removal of TCE and other halocarbons. Smaller scale testing of an innovative treatment process for TCE and palladized iron (Pd/Fe) was also performed. The treatment concept, to treat an aqueous-mixed waste without producing another mixed waste, was successfully demonstrated. The stream of $Tc^{99}$ and TCE contacted zero-valence iron initially. Reducing conditions caused by the reaction of iron with water caused the $Tc^{99}$ to precipitate rapidly. Indeed, all of the $Tc^{99}$ in the more than 580,000 gal of water was removed by approximately 12 in. of coarse iron particles. Because zero-valence iron also reduces TCE, albeit slowly, the remaining solid waste at the project's termination was not a mixed waste. After storage for a few days the residual TCE was degraded leaving only $Tc^{99}$ on the iron. During operation TCE was removed by the carbon following passage through the iron. Because the water no longer contained $Tc^{99}$, after flowing through the iron, the waste carbon could be handled as a hazardous waste with no concern for radioactivity.

The brief testing with Pd/Fe was also successful. Problems in the bulk manufacture which led to an initial failure were identified and corrected. Successful treatment was performed on a side-stream of the wastewater for approximately four days when an equipment malfunction terminated the test. Field preparation of bulk Pd/Fe was also demonstrated in this project.

A review of the test data demonstrates several advantages for horizontal recirculation, particularly at sites which are difficult to access and where aquifer zones are thin. Cost data showed that the system installed at PORTS is competitive with respect to conventional treatment. This cost comparison, however, does not take into account the higher efficiency of flushing the contaminated zone, the greater flexibility regarding overall operations, and the potential for use with enhancements (e.g, reactive fluids, surfactants) provided by the dual horizontal well system.

Consequently, the system demonstrated at PORTS is technically more effective and more cost-efficient than conventional facilities.

Recommendations have also been provided for additional testing and evaluation. Longer term testing would provide valuable information regarding operation and maintenance costs and would yield further delineation of the dense nonaqueous-phase liquid distribution at X-701B. Use of the horizontal wells with treatment agents or enhancing fluids such as chemical agents or surfactants should also be evaluated.

# 1. Introduction

This report is the third of three final reports for the project entitled "In Situ Treatment of Mixed Contaminants in Groundwater." This report presents the results from field tests of a horizontal well recirculation system at the X-701B site at the Portsmouth Gaseous Diffusion Plant (PORTS), Piketon, Ohio. The field work for this project included the following tasks: (1) characterization of the geology of the site, (2) installation of two horizontal wells and 11 monitoring wells, (3) hydrodynamic testing of the horizontal wells and monitoring wells, and (4) evaluation of the horizontal well recirculation system using pumping tests, a tracer test, and a treatment test. A report on the pilot testing of the horizontal recirculation system was the first report of the series (Muck et al. 1996). The second report described the innovative treatment aspects of the project (Korte et al. 1997).

This project was jointly funded by the U.S. Department of Energy (DOE) Office of Science and Technology and PORTS Environmental Management and Enrichment Facilities (EMEF). The overall purpose of this project was to study in situ treatment of mixed contaminants in groundwater using recirculation-well networks coupled with treatment modules. The 3½ year project began in October 1993 and involved several key research elements, including treatment-process evaluation and screening, hydrodynamic flow and transport modeling, bench- and pilot-scale experimentation, and full-scale field demonstration at a DOE site (ORNL 1994).

The overall goal of the project was to package one or more unit processes, as modular components in vertical and/or horizontal recirculation wells, for treatment of volatile organic compounds (VOCs) [e.g., trichloroethene (TCE)] and radionuclides [e.g., technetium $(Tc)^{99}$] in groundwater. The project was conceived, in part, because the coexistence of chlorinated hydrocarbons and radionuclides had been identified as the predominant groundwater contamination problem in the DOE complex (Riley et al. 1992). The project objectives included: (1) evaluation of horizontal wells for inducing groundwater recirculation, (2) development of treatment modules for simultaneous removal of VOCs and radionuclides, and (3) demonstration of a coupled system (treatment module with a recirculation well network) at a DOE field site where both VOCs and radionuclides are present in the groundwater.

The project was a direct extension of prior work with the DOE International Technology Exchange Program. Several European countries, notably Germany, have significant environmental restoration and waste management research and development programs. Confronted with contaminated land from the world wars and the postwar industrialization period, researchers have been actively developing and implementing technologies for effective environmental restoration. An investigation of German developments by Oak Ridge National Laboratory (ORNL) staff (Siegrist et al. 1993) determined that recirculation technologies had near-term potential for application at DOE sites. In addition, the investigation of German technologies also identified needs that would increase the applicability and utility of recirculation systems: (1) testing and demonstration of horizontal recirculation wells and (2) modular packaging of unit processes for treatment of multiple contaminant classes. Accordingly, this project was initiated with funding from DOE's Office of Science and Technology, Subsurface Contamination Focus Area (EM-50). Significant funding support was also provided by EM-40 through PORTS.

Horizontal wells have been used by the oil industry for years in an attempt to increase production from depleted or low permeability reservoirs (Gilman and Jargon 1992; PEI 1992). Enhanced recovery using horizontal wells has been reported in the literature with the highest degree of success observed in fractured systems. According to Gilman and Jargon (1992), horizontal wells provide both higher rates of recovery and significant incremental recovery in low permeability formations. In high permeability reservoirs horizontal wells provide accelerated recovery with marginal increases in ultimate recovery. Adapting horizontal wells to the environmental field for the recovery of groundwater contamination has been discussed by Kaback et al. (1989a), and Langseth (1990).

A pilot-scale test was performed at the Clean Test Site (CTS), an uncontaminated site at PORTS, to evaluate the hydrodynamics of the horizontal well recirculation system (Muck et al. 1996). The objectives of the pilot test at the CTS were to: (1) demonstrate innovative methods of installing horizontal wells, including the use of porous well filters; (2) determine the accuracy with which horizontal wells can be placed in a shallow, thin aquifer system; and (3) determine achievable pumping rates and aquifer hydrodynamics associated with a horizontal well recirculation system at the CTS. The CTS testing showed that a hydraulic gradient of 0.15 could be induced between the wells, an increase of two orders of magnitude over the preexisting gradient. A bromide tracer test showed that the entire flow field between the wells was affected by the recirculation system, with bromide transport dominated by advection in higher-permeability areas and by diffusion in lower-permeability areas. A follow-on elution test removed approximately 77% of the injected bromide mass during a period of 20 days. The tracer test and elution test results indicated that the horizontal well recirculation system showed great promise for application at a contaminated site.

One problem encountered with the pilot test was clogging of the extraction well during the tracer and elution tests. It was determined that the method of well development recommended by the filter manufacturer, low rate pumping, was inadequate. Thus, the horizontal wells were developed by a more aggressive method that included water jetting and overpumping. Hydraulic tests conducted immediately after well development showed markedly improved well performance. A subsequent

60-day recirculation test was performed with no evidence of clogging indicating that water jetting and overpumping are the proper methods for developing wells constructed with the ductile porous filter.

Based on the successful results of the field test performed at the CTS, a full-scale test was performed at X-701B to demonstrate the use of a horizontal well recirculation system for treatment of contaminated groundwater. A groundwater plume at X-701B contains TCE at concentrations up to 1,800 mg/L and $Tc^{99}$ at activities up to 926 pCi/L.

PORTS EMEF is performing corrective measures studies (CMSs) to evaluate clean-up technologies for groundwater contamination. This project supports those CMSs that address TCE and $Tc^{99}$ contamination by providing information on candidate treatment processes and by evaluating the feasibility of employing horizontal recirculation.

## 1.1 Previous Reports

Four reports have been issued previously for this project. They are as follows:

- ORNL. 1994. *In Situ Treatment of Mixed Contaminants in Groundwater: Project Description,* ORNL/FPO-94/53,

- Korte et al. 1994. *In Situ Treatment of Mixed Contaminants in Groundwater: Review of Candidate Processes,* ORNL/TM-12772,

- Muck et al. 1996. *Field Evaluation of a Horizontal Well Recirculation System for Groundwater Treatment: Pilot Test at the Clean Test Site,* ORNL/TM 13531,

- Korte et al. 1997. *In Situ Treatment of Mixed Contaminants in Groundwater: Application of Zero-Valence Iron and Palladized Iron for Treatment of Groundwater Contaminated with Trichloroethene and Technetium-99,* ORNL/TM 13530.

## 1.2 Objectives

Objectives for the evaluation of the horizontal well recirculation system at X-701B were as follows:

- Demonstrate innovative methods of installing horizontal wells at a site contaminated with a mixture of VOCs and radionuclides;

- Determine achievable pumping rates and hydrodynamics associated with a horizontal well recirculation system at X-701B;

- Determine the efficiency and capacity of the treatment system for removal of TCE and $Tc^{99}$ from contaminated groundwater at X-701B. The goal for treatment efficiency is removal of 90% of TCE and $Tc^{99}$ from the influent to the treatment system (ORNL 1994).

### 1.3 Organization

The remainder of this report is organized as follows:

- Section 2 describes the demonstration site and results of the site characterization.

- Section 3 describes the horizontal well installation and development.

- Section 4 describes the monitoring well installation and development.

- Section 5 describes the results of hydrodynamic tests of the horizontal wells and monitoring wells.

- Section 6 describes the results of a bromide tracer test of the recirculation flow field.

- Section 7 describes the design, construction, and the results of the treatment system test.

- Section 8 presents a cost comparison, a general discussion of the applicability of the technology, and recommendations for additional testing.

# 2. Background

## 2.1 Facility Description

PORTS is a federal facility owned by DOE. The plant is operated by Lockheed Martin Utility Services under a contract with the United States Enrichment Corporation, a government-owned corporation. Lockheed Martin Energy Systems performs EMEF activities as well as the site management required by DOE. The 15.75 $km^2$ (3,892 acre) federal reservation lies in Pike County, Ohio, between the cities of Chillicothe and Portsmouth and is approximately 113 km (70 miles) south of Columbus, Ohio (Fig. 2.1).

PORTS has been in operation since 1954 and is used to enrich uranium for commercial nuclear reactors. The PORTS process uses molecular diffusion techniques to separate the $^{235}U$ isotope from the $^{238}U$ isotope. PORTS consists of a complex cascade of compressors and convertors through which gaseous uranium hexafluoride feed is processed. The plant has an extensive support complex that consists of machine shops, laboratories, utilities, and decontamination facilities. As a result of plant operations, PORTS generates a wide variety of wastes, including low-level radioactive wastes, spent solvents, polychlorinated biphenyl (PCB)-contaminated oils, electroplating wastes, paint wastes, metal sludges, acids, and caustics.

## 2.2 Site Description

X-701B is located in the northeastern area of PORTS (Fig. 2.2). The site originally contained an unlined holding pond, 200-ft by 50-ft in area (U.S. DOE 1994a). The pond was used from 1954 to 1988 for neutralization and settling of metal-bearing waste water, solvent contaminated solutions, and acidic waste water. Most of the waste discharged to the pond originated at the X-700 Chemical Cleaning Facility and the X-705 Decontamination Building. Beginning in 1974 and continuing until 1988, slaked lime was added to the X-701B influent at the X-701E Neutralization Facility to neutralize the low pH and induce precipitation. This precipitation caused large amounts of sludge to accumulate in the pond and necessitated periodic dredging of the sludge. The holding pond has been drained, and the contaminated sludge and underlying silt and clay have been removed. A groundwater plume contaminated with TCE and $Tc^{99}$ emanates from this holding-pond and extends to the east (Fig. 2.3, U.S. DOE 1994b). [The horizontal well recirculation system was installed in the eastern portion of X-701B (Fig. 2.3).] PORTS EMEF personnel monitor the groundwater

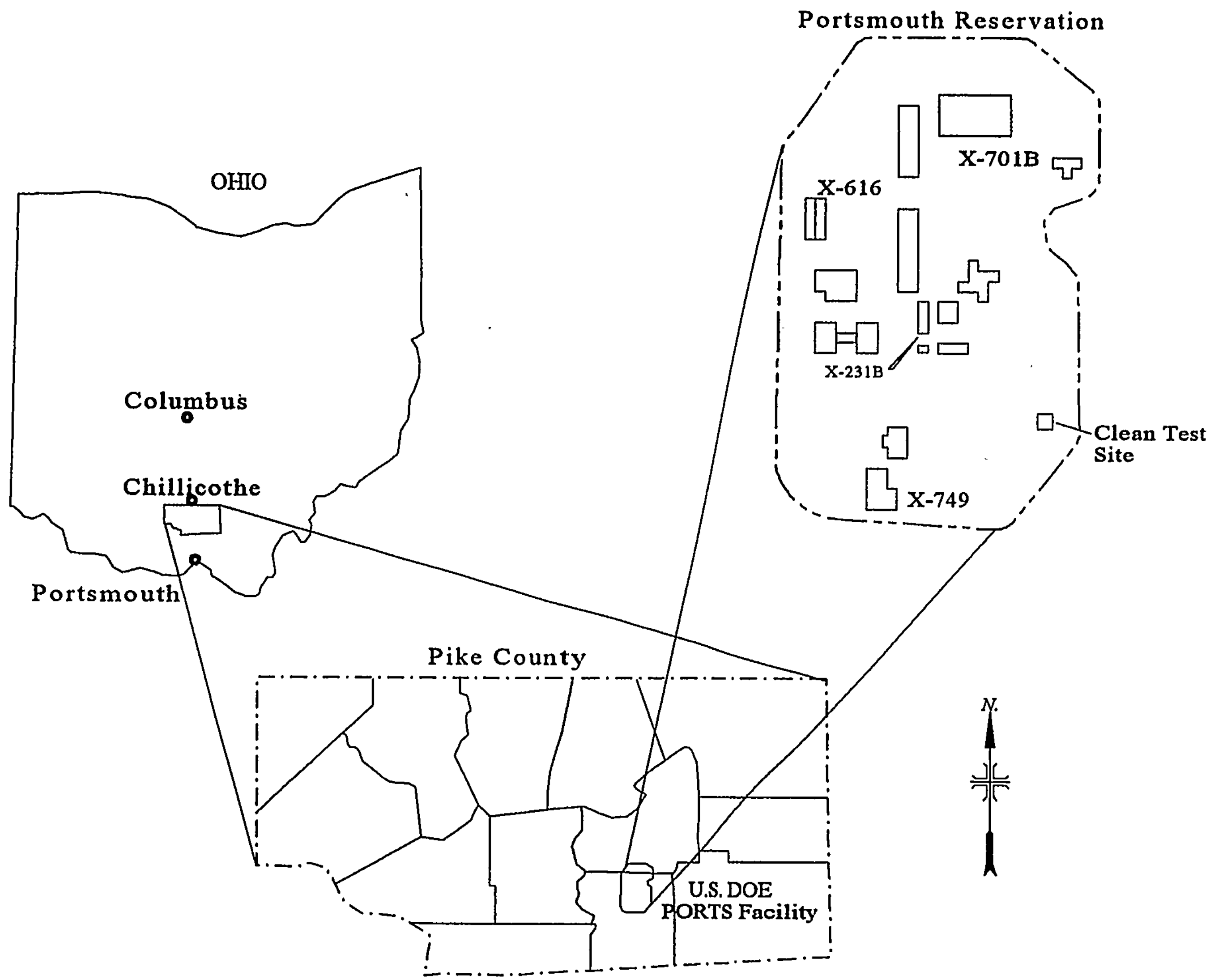



Fig. 2.1. Location of Portsmouth Gaseous Diffusion Plant.

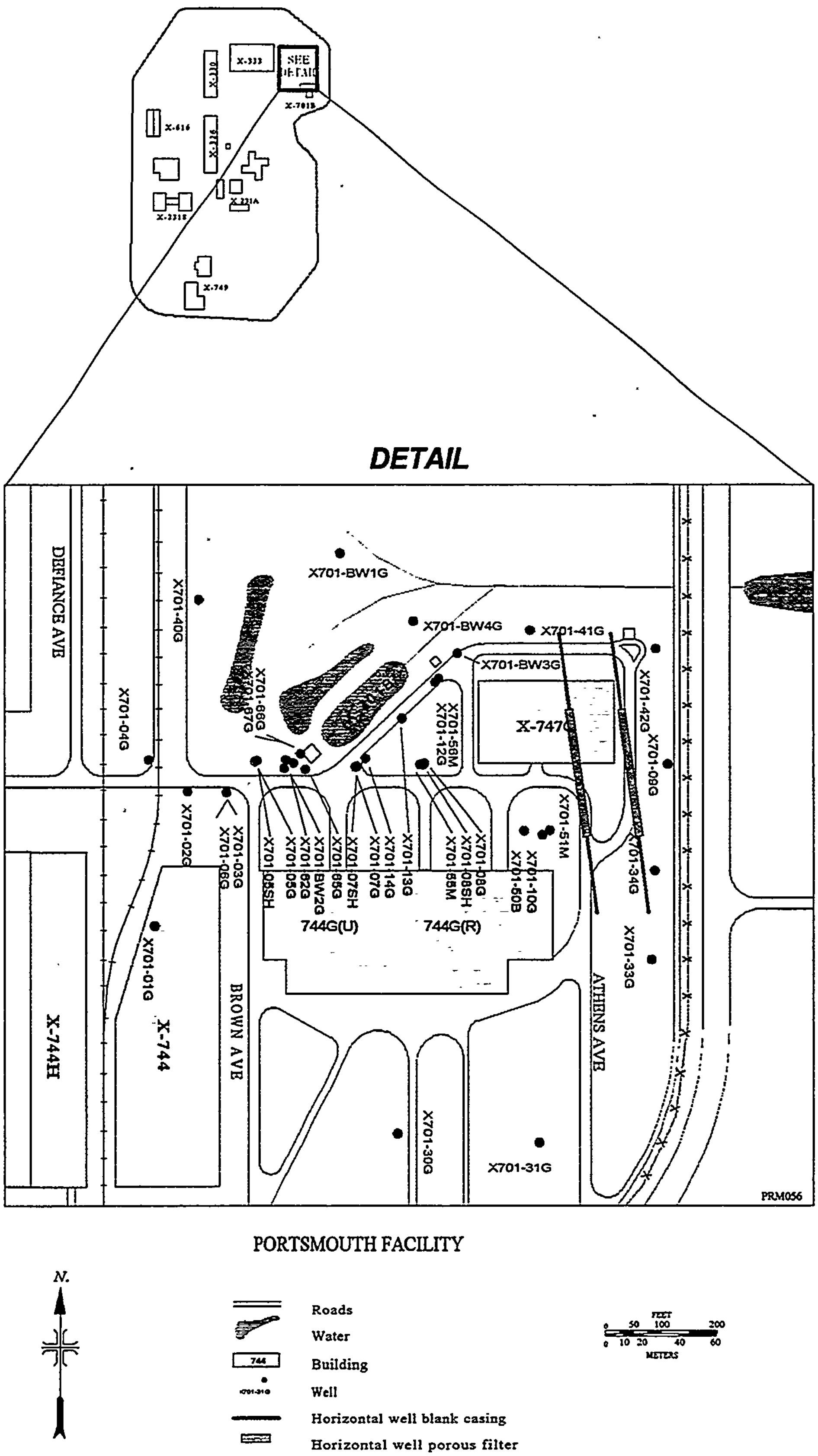



Fig. 2.2. Location of X-701B.

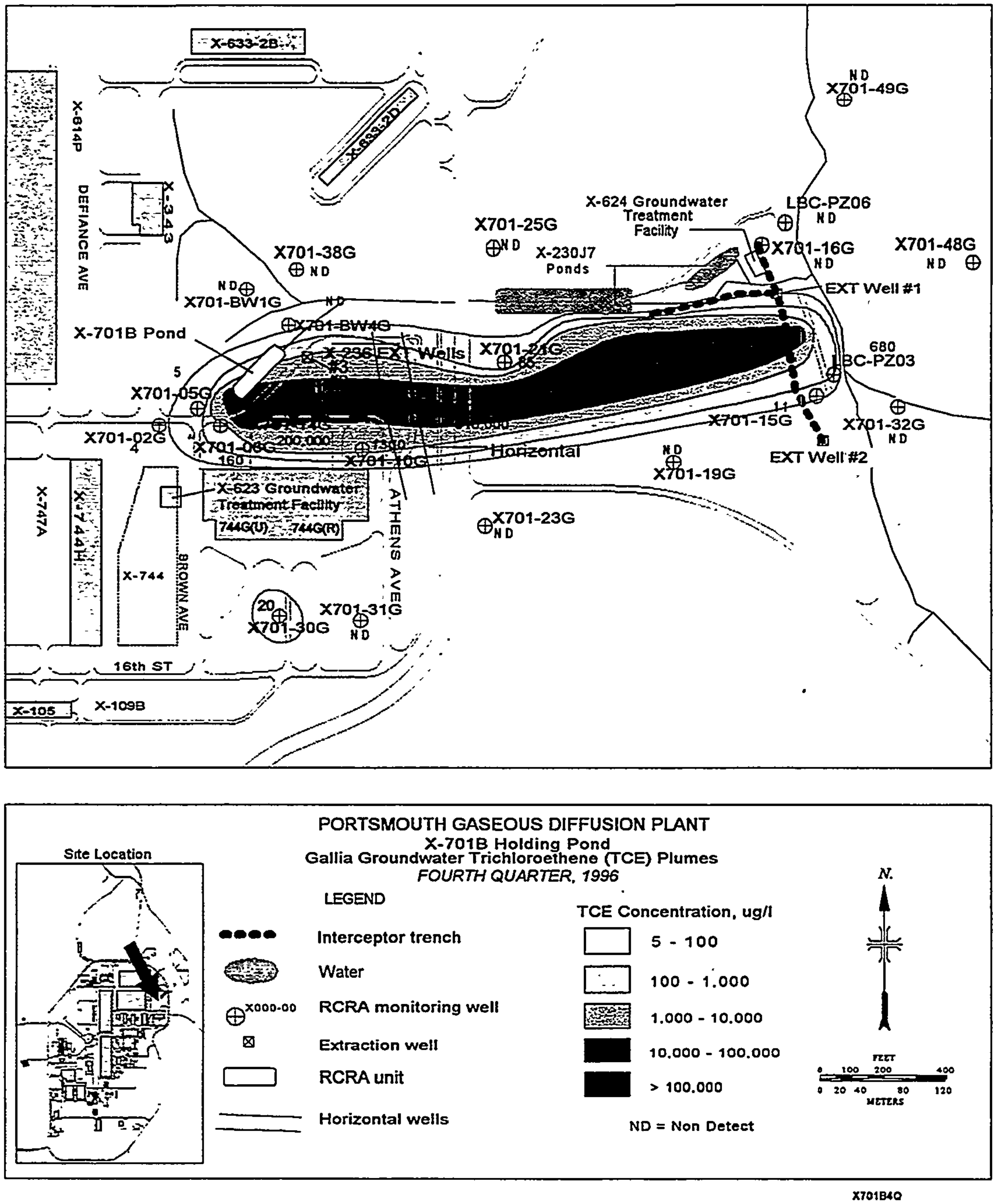



Fig. 2.3. TCE plume at X-701B and locations of the horizontal wells.

plume on a quarterly basis. Historically, the maximum TCE concentrations and $Tc^{99}$ activities have occurred in groundwater samples from monitoring well X701-09G, near the location of the horizontal well recirculation system. The maximum detections for this well have been 1,800 mg/L TCE (U.S. DOE 1997) and 926 pCi/L $Tc^{99}$ (Fig. 2.4) (U.S. DOE 1994a).

## 2.3 Site Characterization

The soil above bedrock at X-701B is composed of unconsolidated Quaternary fluvial deposits (U.S. DOE 1994a). These deposits consist of a 7.0 to 9.8 m (23 to 32 ft) thick unit of low-permeability clays and silts known as the Minford member. The Minford member is underlain by a moderately permeable sand unit known as the Gallia member. The Gallia consists of pebbles and gravel in a fine-grained silty-sand matrix and is approximately 0.9 to 2.1 m (3 to 7 ft) thick at X-701B. The bedrock underlying the Gallia at X-701B is a very low permeability, Mississippian-age shale unit known as the Sunbury shale.

Figure 2.5 is a bedrock contour map for X-701B, and Fig. 2.6 shows cross sections of the geology at the locations of the horizontal wells. Prior to installation of the horizontal wells, ORNL used a direct-push method to collect soil borings along the proposed locations of the well filters (X701-HW-BH01 through X701-HW-BH06 in Fig. 2.6) for the purpose of verifying the depth below ground surface (bgs) of the top and bottom of the Gallia member. This geologic information was used to guide the placement of the horizontal wells along the bedrock surface. Appendix A contains copies of the geologic logs from the six soil borings.

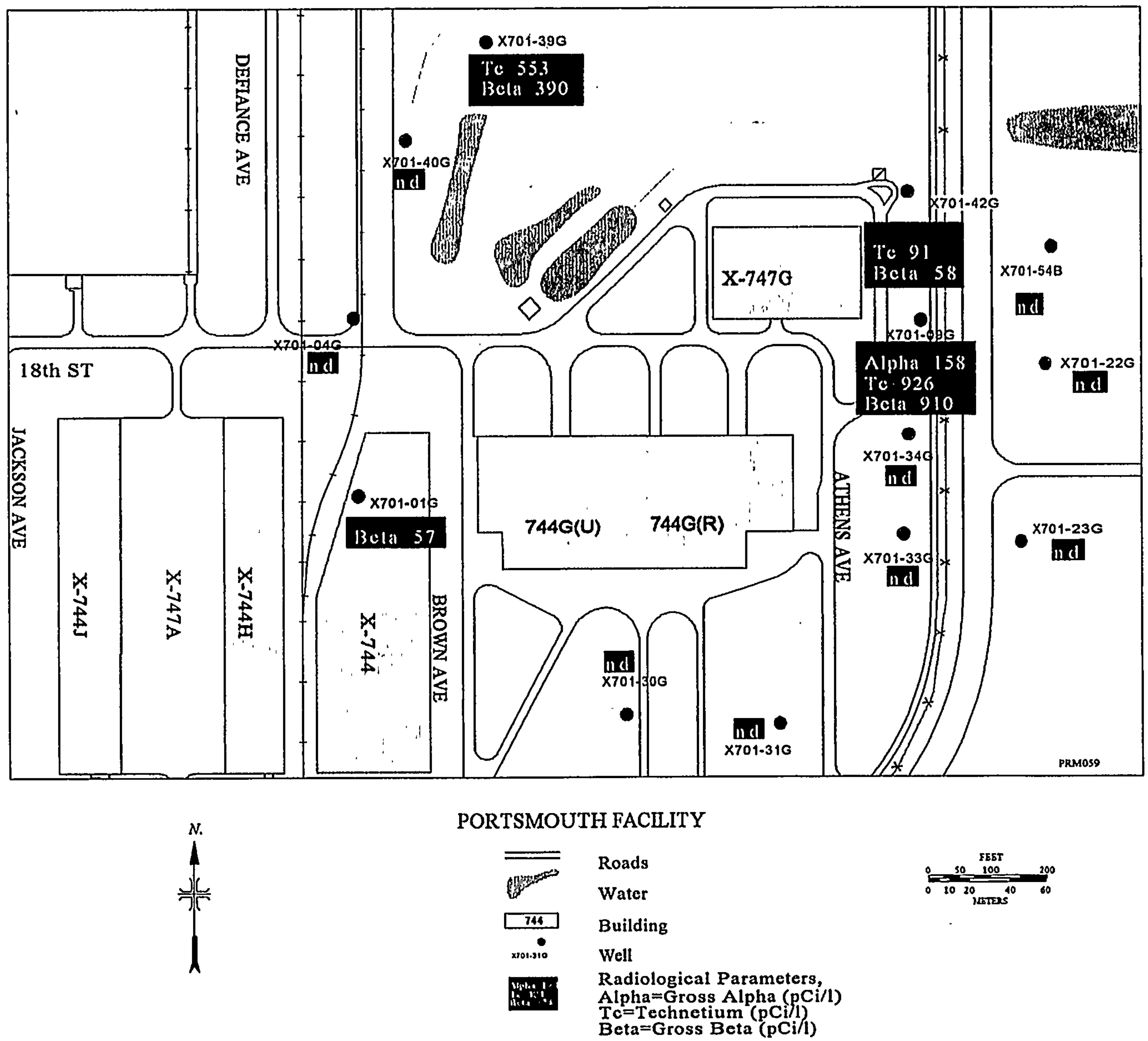



Fig. 2.4. Tc activities in groundwater samples from X-701B.

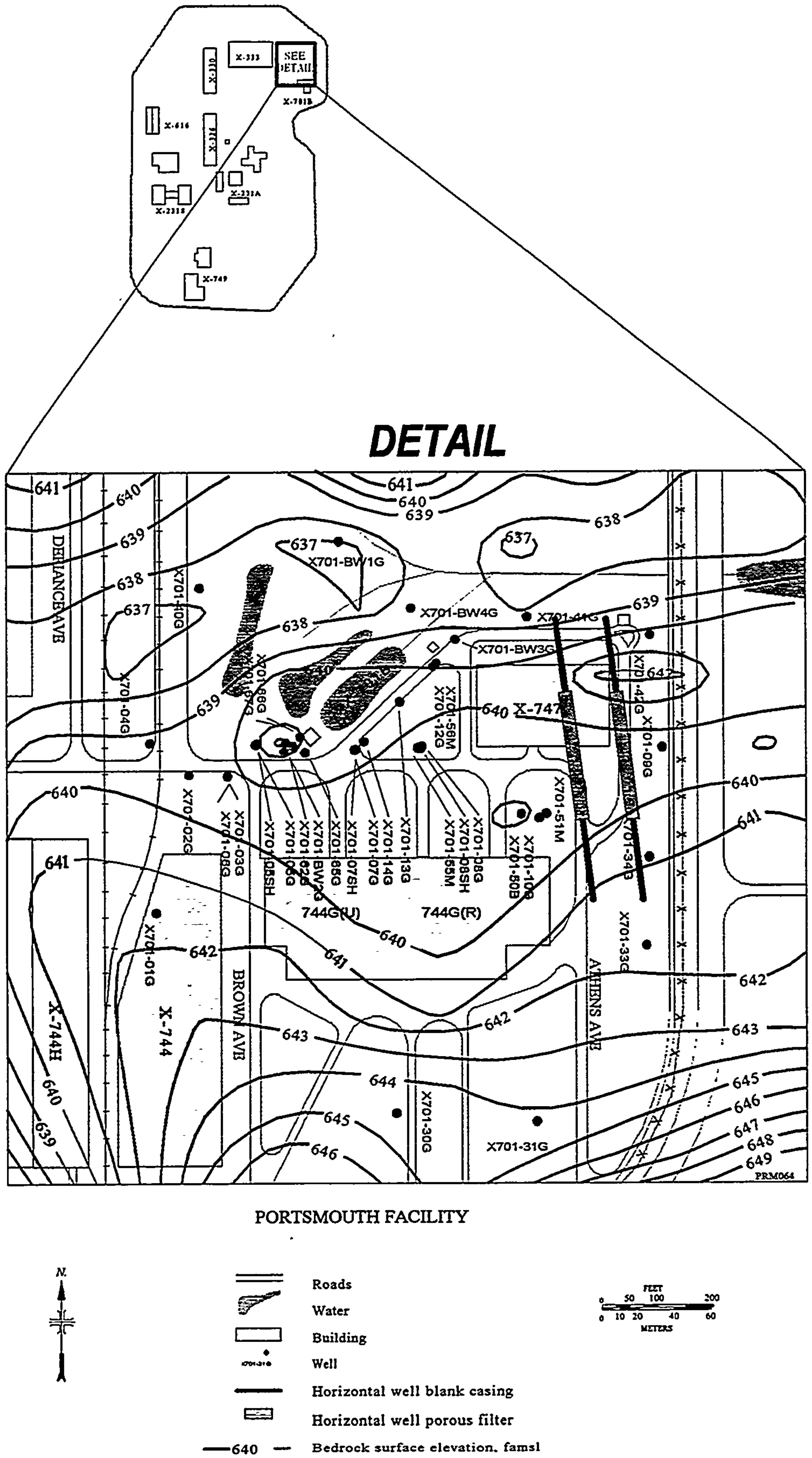



Fig. 2.5. Bedrock surface map for the X-701B area.

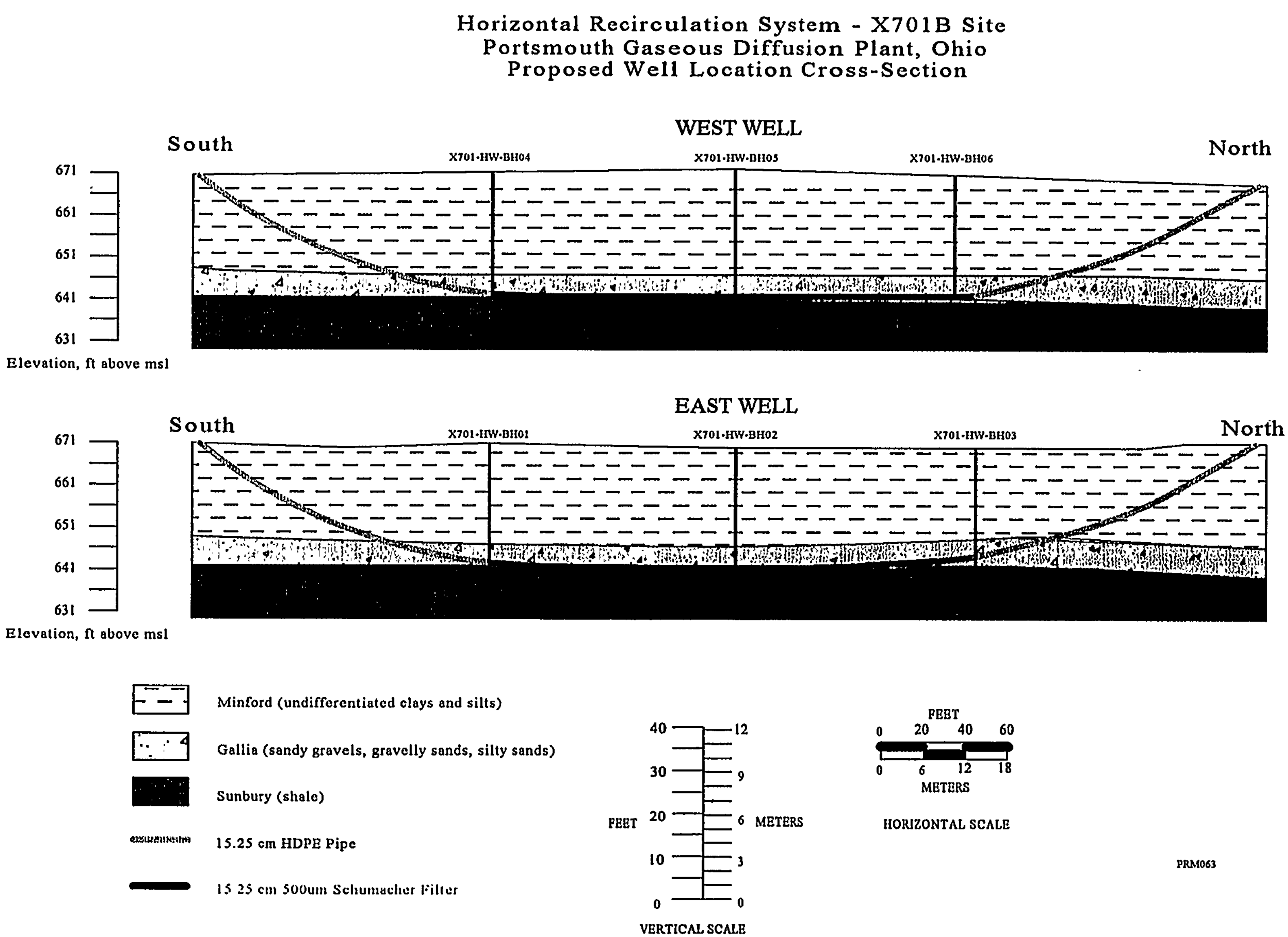



Fig. 2.6. Geologic cross sections at the locations of the horizontal wells.

# 3. Horizontal Well Installation and Development

## 3.1 Installation

There are three basic drilling technologies for horizontal wells: short-radius drilling, utility compactional drilling, and river crossing industry drilling. The merits of these three technologies were evaluated in detail during a field demonstration of horizontal well installations at the DOE Savannah River Site (Kaback et al. 1989b). The first technology, short-radius drilling, employs drilling equipment that is basically the same as for vertical wells. At the Savannah River Site, short-radius drilling was demonstrated with a mud-rotary rig that used a non-steerable drill bit with a whipstock to deflect the borehole direction. This drilling technology was not selected for the horizontal wells at X-701B because of the need for more accurate steering of the drill bit. Highly accurate steering was necessary to enable placement of the wells along the interface between the base of the unconsolidated sediments and the top of the bedrock surface.

The second technology for horizontal well installation, utility compactional drilling, employs drilling equipment that is basically the same as for the installation of utility lines or pipelines. The borehole is advanced from an inclined platform using hydraulic rams and a wedge-shaped bit, which allows the borehole to have multiple points of curvature. This technology generates minimal secondary waste and requires a minimal amount of drilling fluids. However, because this technology relies on compaction to advance the borehole, its use was not desired for the horizontal wells at X-701B. Compaction of the surrounding formation would lower the permeability of the soil surrounding the horizontal wells and limit their usefulness for extraction and reinjection of groundwater.

The third technology for horizontal well installation, river crossing industry drilling, employs an inclined platform and a steerable mud motor drilling assembly. A jet of mud from the bit cuts through unconsolidated sediments, and a downhole magnetic guidance system provides borehole location data. The drilling mud and cuttings are returned to the surface. This method was used for the installation of the horizontal wells at the CTS and at X-701B because this technology permits accurate placement of the wells without significant compaction of the surrounding sediments. The drilling contractor, Directed Technologies Drilling, Inc. (DTD), was selected through the use of a competitive bid process. DTD has extensive experience in horizontal well installations, having performed work at a variety of locations. DTD hired Mears Engineering, Inc., (Mears) to install the horizontal wells at X-701B. Mears had installed the horizontal wells at the CTS, so the drilling crew was familiar with the geologic setting at PORTS. Mears had also performed, to date, the only U.S. installations of horizontal wells constructed with the Schumacher porous filter.

Two horizontal wells were installed at X-701B during a 10-day period in May 1996. A geologist from ORNL worked in the field with the drilling crew to provide technical guidance during the well installation. The horizontal wells were installed using an American Directional Drill DD60 rig. Because the Gallia is a thin formation, accurate control of the depth and direction of the drilling bit was essential. Thus, a magnetic navigation and guidance system, the Sharewell TruTracker, was used to provide a vertical accuracy of ± 15 cm (± 0.5 ft) at a depth of 10 m (32 ft) bgs. Each screened well was completed to land surface at both ends (Figs. 3.1 and 2.6). The horizontal sections are approximately 71 m (234 ft) long, and the slanted riser sections, dependent on the turning radius of the drilling equipment, of pipe are approximately 43 m (140 ft) long. These sections were as short as practicle.

Each well was constructed with ductile high-density-polyethylene (HDPE) casing [15-cm (6-in.) inside diameter (ID)] and ductile HDPE porous filter [13-cm (5-in.) ID with a fitting at each end to connect to the 15-cm (6-in.) ID casing]. The porous filter, used to construct the horizontal sections of the wells, was produced by Schumacher Umwelt- und Trenntechnik GmbH (Schumacher) in Germany and was supplied in the U.S. by Schumacher Filters America. This innovative well filter material (Appendix B) was also used to construct the horizontal wells at the CTS (Muck et al. 1996). At the time this project was performed, no comparable product was known to be available from U.S. manufacturers, and there are no other distributors of the Schumacher filter in the U.S.

## 3.2 Porous Filter Pipe

The Schumacher filter was chosen for the horizontal well installations at X-701B because of its advantages over conventional well screen materials and its successful use at the CTS. The Schumacher filter doubles as a filter pack, so a smaller borehole may be used as compared to a traditional well screen plus sandpack installation. The use of a smaller borehole reduces the energy necessary to install the wells and reduces the volume of drilling wastes that are generated. Moreover, the surface of the HDPE filter material is hydrophobic which helps to prevent clogging. The Schumacher filter also has favorable hydraulic characteristics, producing a uniform headloss across the length of the filtered area. Development of the horizontal wells at the CTS and X-701B was performed successfully through the use of a water-jetting and over-pumping method. This method of well development allowed the clay-sized sediments adjacent to the well filter to be removed. The horizontal wells were then operated continuously for 74 days with no sign of clogging.

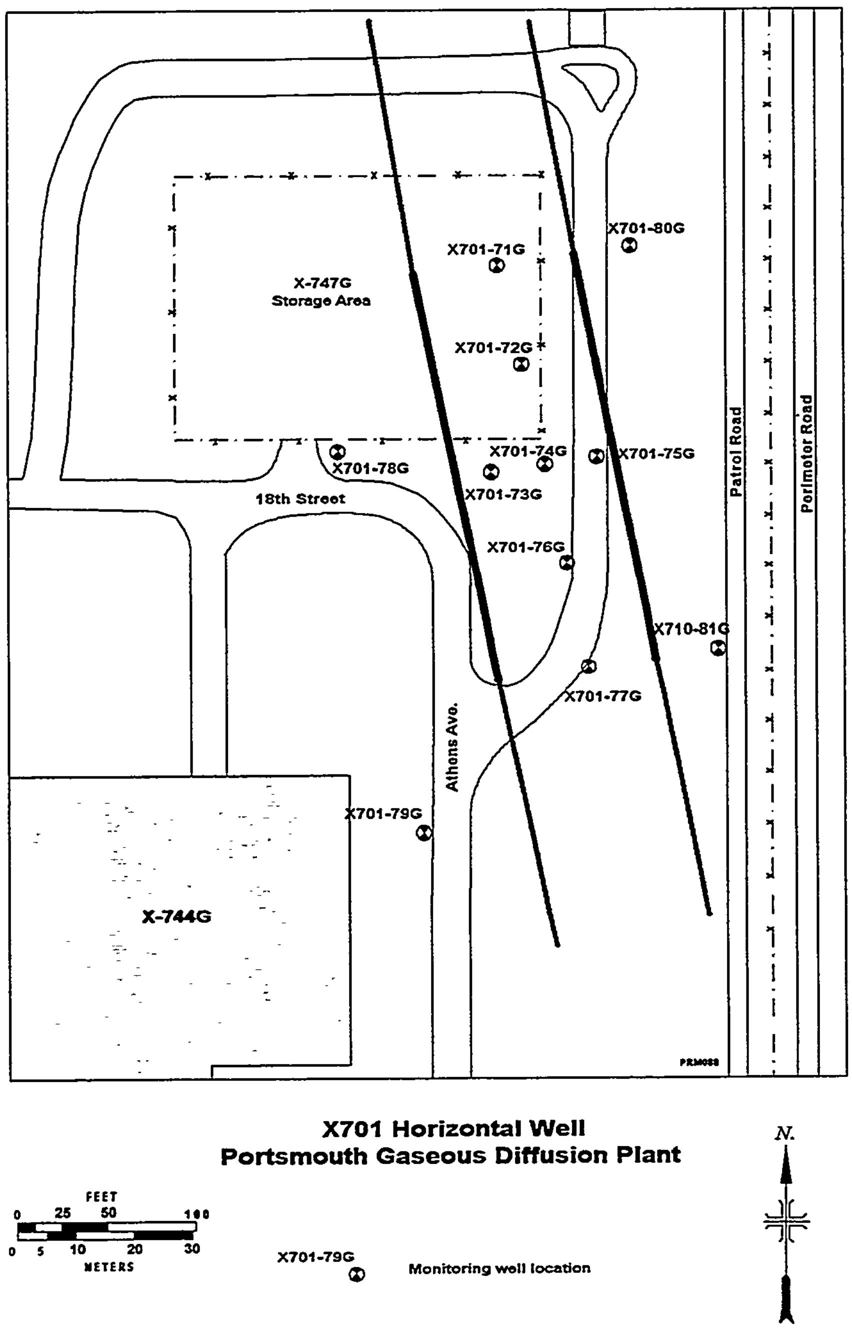



Fig. 3.1. Locations of horizontal wells and monitoring wells.

The casing materials came to the site in 12-m (40-ft) lengths and the filter materials in 3.7-m (12-ft) lengths. Prior to installation, the well materials were butt-fused together such that the porous filter was placed within the Gallia along the bedrock surface; the blank casing extended to ground surface from both ends of the filter. A filter with a pore size of 500 µm (Appendix B) was selected to provide optimum water clarity and well performance, based on the recommendations from Schumacher and the results of the pilot test conducted at the CTS.

The drilling method was as follows: (1) drilling a 17-cm (6.75-in.)-diameter guided pilot hole, (2) backreaming the pilot hole with a 42-cm (16.5-in.)-diameter back-reamer, and (3) picking up a 25-cm (10-in.)-diameter HDPE shelter casing at the exit hole and then pulling the shelter casing back into the hole with the backreamer (Fig. 3.2). The casing and filter materials for the horizontal well were housed inside the shelter casing during installation. After the shelter casing and well materials were in place, the shelter casing was pulled from the borehole, and the borehole was allowed to collapse around the well materials. Drilling fluid, a mixture of water and a biodegradable drilling polymer, was used to keep the borehole open during both drilling and installation of the shelter casing. Wastes that were generated during drilling were handled according to PORTS waste management protocol under the direction of the PORTS construction engineer (CE). A pressure-grouting system was used to seal the annular space at each of the well ends from 6 m (20 ft) from the ground surface to the ground surface.

The axes of the horizontal wells are approximately 24 m (80 ft) apart and have an orientation that is approximately north-south (Fig. 3.1). These well locations were chosen such that the horizontal well recirculation system would lie perpendicular to the groundwater plume (Fig. 2.3). The bedrock surface in this area slopes gently to the southeast (Fig. 2.5). It is emphasized that a geologist with extensive site experience is required to ensure proper placement of the wells and evaluation of the drilling progress. In this instance, the ORNL geologist who had performed the exploratory drilling to find the base of the Gallia was responsible for the supervision of the horizontal well installation.

### 3.3 Well Installation

Preparation for the drilling activities was conducted during the first three days of field work. The Mears crew of nine and DTD crew of two mobilized equipment to the site, attended health-and-safety training classes, laid out navigation lines for the

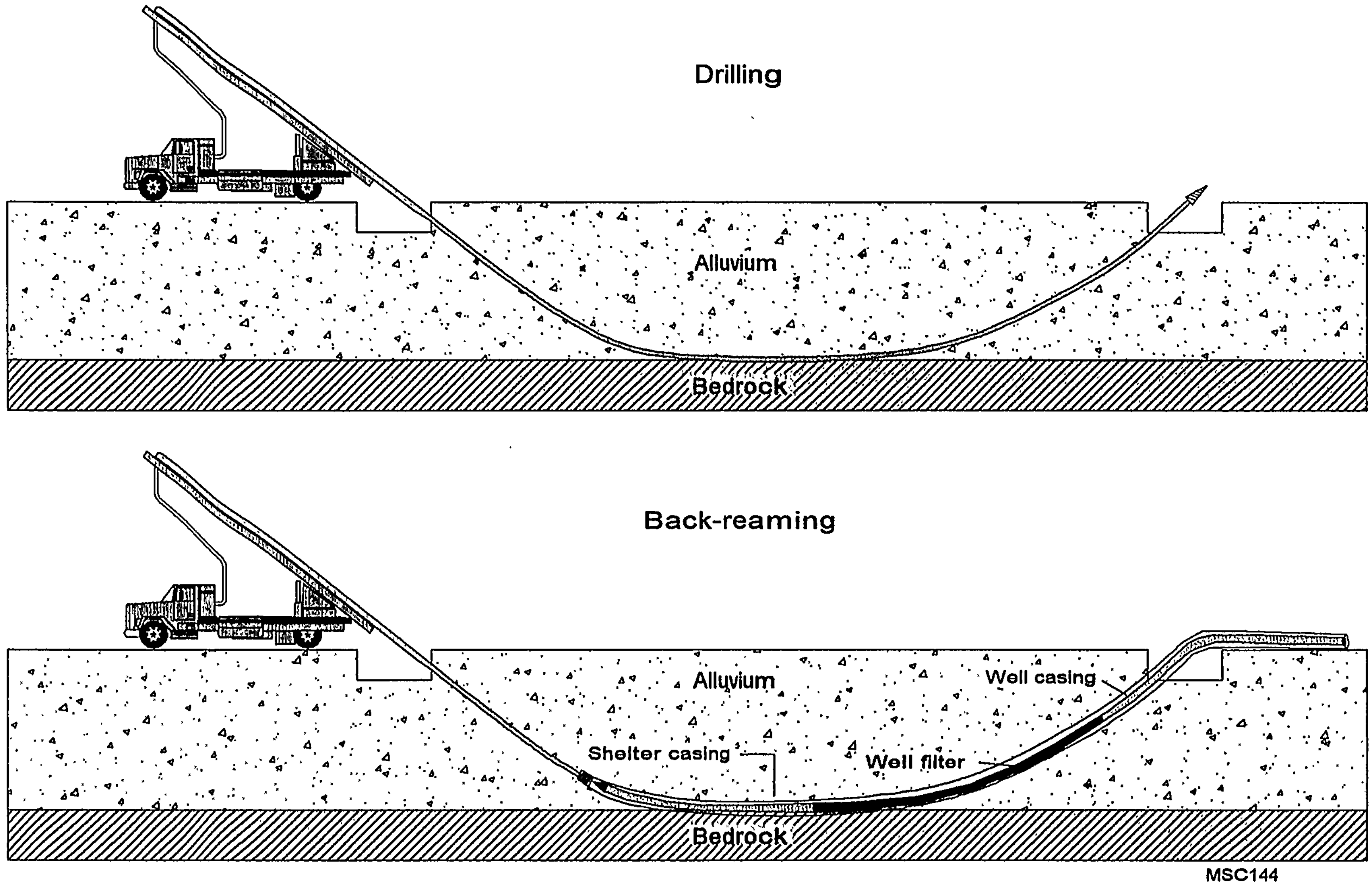



Fig. 3.2. Conceptual illustration of horizontal well drilling and installation.

horizontal injection well (east well), mixed the drilling mud, and began construction of the well materials. The drilling equipment was set up at the north end of the east well location.

Two of the Mears workers heat welded the blank sections of HDPE pipe. Four blank sections of 15-cm (6-in.)-diameter pipe were constructed for the horizontal wells, each approximately 46-m (150-ft) long, by welding together pieces of 12-m (40-ft)-long pipe. The blank sections were designed to stick up 3 ft above ground surface, and they were trimmed to the proper length after installation. One 535-ft long shelter casing was constructed by heat welding 25-cm (10-in.)-diameter pipe. The heat welding was performed by lining up the ends of two pieces of pipe, squaring them off with a cutting tool, touching the ends to a heating iron until soft, and pressing the ends together at about 80 pounds per square inch (psi) until cool. Each weld took approximately 30 min to complete. The bead that developed on the inside of each weld was removed with a cutting tool so that the inside surface of the finished casing was smooth.

Navigation personnel surveyed the ground surface along the drilling line for the east horizontal well and set up the navigation equipment for drilling. Navigation was conducted using a geomagnetic field induced by an electric cable that was laid in a loop around the length of the drilling line. The TruTracker downhole navigation assembly was attached behind the drill bit.

Drilling and installation of the east horizontal well occurred during the fourth through seventh days of field work. Seven of the Mears personnel worked at the drilling rig and support equipment: a driller, a navigator, and five helpers to assist with the drill pipe, drilling mud, and other tasks. The Mears drilling supervisor and two project managers from DTD coordinated the drilling effort. A backhoe operator working under contract to PORTS provided support to the drilling by digging the entrance hole and mud pits, removing excess mud from the pits, and maneuvering the well materials.

Two heat welders from Mears butt-fused together 20 lengths of 13-cm (6-in.)-ID by 3.7-m (12-ft)-long HDPE porous filter. Each weld took approximately 30 min to complete, and the entire job of welding together the 71-m (234-ft)-long filter took about 10 h to complete. The completed filter was allowed to cure overnight. The welders then butt-fused a section of 46-m (150-ft)-long, 15-cm (6-in.)-ID HDPE pipe onto each end of the porous filter, and a line of workers (all of the available drilling personnel) assisted by inserting the completed string of well materials into the shelter casing.

The pilot hole was drilled with a 17-cm (6.75-in.)-diameter tricone bit. The down-hole navigation assembly was attached behind the drill bit. The drilling fluid consisted of Barroid Bio-Bore drilling polymer mixed with water. Approximately 8 h of drilling was necessary to reach the base of the Gallia at 9.8 m (32 ft) vertical depth [directional drilling length of 44 m (146 ft)]. At this point, drilling proceeded horizontally along the base of the Gallia for 3.5 h. Return samples collected during horizontal drilling showed a combination of 95 to 97% Gallia sand and gravel and 3 to 5% Sunbury shale. This indicated that the drill bit was skimming across the surface of the Sunbury, as desired.

At a drilling length of 115 m (376 ft), the drill bit was angled back toward ground surface. Lateral navigation of the drilling bit was difficult while angling up through the Gallia because as the bit angled up, it tended to veer toward the east, following the dip of the Gallia. Approximately 3 h of drilling was necessary to reach ground surface. The exit hole was 14 ft east and 4 ft north of the intended target. The ORNL geologist determined that this exit location was satisfactory because the filtered portion of the well was located as desired, and the deviation in the location of the exit hole would not affect the well performance.

The drill bit and navigation tool were removed from the drill string and were replaced with a 42-cm (16.5-in.)-diameter backreamer. Cutting returns during back-reaming of the horizontal section consisted of approximately 90% Gallia sand and gravel and 10% Sunbury shale. Backreaming of the pilot hole was completed in 6 h. A small bulldozer dragged the shelter casing (with the housed well materials) into place behind the backreamer at the south end (exit hole) of the well. A swivel was attached to the backreamer, and the shelter casing and well materials were attached to the swivel. The backreamer was pulled back down the exit hole to the entrance hole while pulling the shelter casing into place. Installation of the 163-m (535-ft)-long shelter casing was completed in approximately 2 h.

The well was filled with a 1000 mg/L solution of calcium hypochlorite prior to removal of the shelter casing. The calcium hypochlorite solution was used to break down the drilling polymer prior to well development. The bulldozer then pulled the shelter casing back out of the borehole, leaving the well materials in place. The entire shelter casing was removed in one piece in 2 min. The shelter casing was set aside for reuse during installation of the western horizontal well.

Drilling and installation of the west horizontal well occurred during the eighth through tenth days of field work. The drilling equipment was moved to the north end of the west well location, the survey lines were laid out, and a new batch of drilling polymer was mixed. The pilot hole was drilled to the base of the Gallia during a 3 h period, the horizontal section was drilled in 4.5 h, and the exit section was drilled in 2 h. During drilling of the horizontal section, the cutting returns contained a low fraction of Sunbury, indicating that drilling was proceeding along the contact of the Gallia and Sunbury, as desired. Backreaming of the west well took 6.5 h to complete, and the final backreaming with installation of the shelter casing was completed in 2 h. As with the east horizontal well, the west horizontal well was filled with a 1000 mg/L solution of calcium hypochlorite prior to removal of the shelter casing.

Table 3.1 summarizes the production rates and total time requirements for drilling and installation of the horizontal wells.

A contractor working for PORTS provided the surface completions for the horizontal wells. The surface completions included grouting the well ends from 6 m (20 ft) from ground surface to ground surface, placing concrete pads and four bumper posts around each of the well ends, and placing protective caps over the well ends. The surface locations of the horizontal wells were surveyed with a horizontal accuracy of ± 15 cm (± 0.5 ft) and a vertical accuracy of ± 0.3 cm (± 0.01 ft). To ensure the required accuracy, the survey was looped and closed. Figure 2.6 shows surveyed cross sections of the wells based on navigation data collected during drilling.

### 3.4 Well Development

Phillips Engineering, working under contract to DTD, developed the horizontal wells by water jetting and overpumping. This method of horizontal well development was used successfully at the CTS (Muck et al. 1996). Driscoll (1979) presents data that indicate water jetting and overpumping are up to 40% more efficient than other well development methods such as surging. An ORNL geologist directed the well development and monitored physical parameters. A specially designed eight-nozzle jetting tool with a discharge velocity exceeding 30.5 m/s (100 ft/s) per nozzle was used to mechanically agitate the porous well filter and the adjacent formation. The jetting tool was inserted into the horizontal well to the distal end of the well filter and was pulled back along the length of the well filter while jetting at a rate of 26 to 30 L/min (7 to 8 gal/min). The pull-back of the jetting tool proceeded incrementally, with constant agitation of the tool along each increment. Each increment was approximately 5 ft in length, and the jetting tool was agitated in each increment for approximately 4 min (this gave an average time period of approximately 3 h to jet the entire 234 ft length of the horizontal well filter). The purpose of the agitation was to assure thorough coverage of the jets against the inside surface of the well filter by varying the nozzle orientations. Simultaneous with the water jetting, over-pumping was used to remove sediment from the well. The overpumping was performed by placing a submersible pump at the distal end of the horizontal well and pumping at a rate of 41 to 49 L/min (11 to 13 gal/min).

**Table 3.1 Task summary for drilling and installation of the horizontal wells**

| Activity | Average Production Rate | Total time |
|---|---|---|
| Casing and filter assembly | 0.5 h/weld | 8 h to construct four sections of blank casing (four welds/ section). Each section was 150 ft long.<br><br>20 h to construct two porous well filters (20 welds/filter). Each filter was 234 ft long.<br><br>7 h to construct the shelter casing (14 welds/casing). The shelter casing was 535 ft long. |
| Drilling (eastern well) | 36 ft/h | 14.5 h to drill 520 ft |
| Backreaming (eastern well) | 87 ft/h | 6 h to backream 520 ft |
| Installation of shelter casing and well materials (eastern well) | 260 ft/h | 2 h to pull shelter casing into place (520 ft) |
| Shelter casing removal | 260 ft/min | 2 min to extract 520 ft shelter casing (same for eastern and western wells) |
| Drilling (western well) | 56 ft/h | 9.5 h to drill 530 ft |
| Backreaming (western | 82 ft/h | 6.5 h to backream 530 ft |
| Installation of shelter casing and well materials (western well) | 265 ft/h | 2 h to pull shelter casing into place (530 ft) |

Table 3.2 summarizes the development results. Based on experience at the CTS, this method of well development produced satisfactory well performance even though, after several passes with the jetting tool, the development water remained cloudy (Muck et al. 1996). For this reason, the ORNL geologist directed that the horizontal wells at X-701B be developed using this method until no more sediment was removed from the wells (a final turbidity of 2 NTU) or until the full length of each well had been jetted eight times (approximately 24 h of jetting and over-pumping per well).

After jetting and overpumping, the horizontal wells were shock chlorinated to kill iron bacteria. Calcium hypochlorite was mixed with 1,890 L (500 gal) of water to yield a chlorine solution that exceeded 1,000 mg/L. The solution was injected using the jetting tool along the entire length of the well filter until all 1,890 L (500 gal) were injected. The process was repeated for the remaining horizontal well.

**Table 3.2. Task summary for development of the horizontal wells**

| Date | Horizontal well | Jetting rate, gal/min | Overpumping rate, gal/min | Development volume, gal | Development time, h | Turbidity, NTU | No. of passes |
|---|---|---|---|---|---|---|---|
| 6/3/96 | East well | 7.5 | 11.6 | 3,530 | 5.0 | 1,068 | 1 |
| | West well | 7.5 | 11.6 | 3,393 | 5.0 | 501 | 1 |
| 6/4/96 | East well | 7.5 | 12.6 | 6,810 | 9.0 | 750 | 3 |
| | West well | 7.5 | 12.5 | 6,835 | 9.1 | 131 | 3 |
| 6/5/96 | East well | 7.5 | 13.4 | 7,750 | 9.6 | 110 | 3 |
| | West well | 7.5 | 13.5 | 7,840 | 9.7 | 613 | 3 |
| 6/6/96 | East well | 7.5 | 12.8 | 2,490 | 3.3 | 21 | 1 |
| | West well | 7.5 | 12.9 | 2,510 | 3.3 | 121 | 1 |
| **Totals** | East well | 7.5 | 12.8 (average) | 20,580 | 26.9 | 21 (final) | 8 |
| | West well | 7.5 | 12.7 (average) | 20,578 | 27.1 | 121 (final) | 8 |

## 4. Monitoring Well Installation and Development

ORNL directed the installation of 11 monitoring wells at X-701B during June 1996. Figure 3.1 shows the monitoring well locations. The monitoring wells are screened in the Gallia and were constructed of 5-cm (2-in.)-ID polyvinyl chloride (PVC). The depths of the wells range from 8.5 to 9.8 m (28 to 32 ft) bgs (Table 4.1). The monitoring wells were used to assess the hydraulic influence of the horizontal wells on the surrounding groundwater flow system.

A CME-550 all-terrain drilling rig, utilizing 21-cm (8.25-in.)-outside diameter (OD) by 11-cm (4.25-in.)-ID augers, and standard well construction practices were used to install the monitoring wells. Wastes generated during drilling were handled in accordance with PORTS waste management protocol. A detailed geologic log of each borehole was prepared by collecting and logging soil samples with a 1.5-m (5-ft)-long continuous sampler. The sampler was run a few centimeters ahead of the lead auger to obtain undisturbed soil samples. Appendix C provides the geologic logs and monitoring well construction diagrams.

PVC riser casing extends from the top of the screened interval to approximately 76 cm (30 in.) above ground surface. All screen-to-casing and casing-to-casing couplings are flush-threaded. No glues or lubricants were used. The annular space was filled with a 10/20 grade silica sand pack. To minimize influence from the overlying Minford silt, the sand packs were extended a minimum distance above the screened interval. In most cases, the top of the sand pack was 46 cm (18 in.) above the top of the screened interval. A 2.0-m (6.5-ft) thick bentonite seal was placed on top of the sand pack using 1-cm (3/8-in.) bentonite chips. The annular space was then grouted from the top of the bentonite seal to within 0.9 m (3 ft) of ground surface. From 0.9 m (3 ft) bgs to the surface, concrete was used to install locking protective casings over the monitoring wells. Four bumper posts were then installed around each monitoring well.

Upon completion, the monitoring wells were developed by ORNL personnel. Due to the low flow rates encountered, the monitoring wells were developed with a water jetting tool. Development continued until the water removed from the monitoring wells was as clear as practical. Development times for each monitoring well ranged from 1 to 4 h. Development water was containerized and handled in accordance with PORTS waste management protocols.

A PORTS contractor surveyed the locations of the monitoring wells with a horizontal accuracy of ± 15 cm (± 0.5 ft), and ORNL surveyed the elevations of the monitoring wells with a vertical accuracy of ± 0.3 cm (± 0.01 ft). To ensure the required accuracy, the surveys were looped and closed. The monitoring wells are

**Table 4.1. Monitoring well survey data and screened intervals**

| Well number | Top of casing, ft amsl | Ground elevation, ft amsl | Total depth, ft bgs | Screen length, ft | Screened interval, ft bgs | Bedrock elevation, ft amsl |
|---|---|---|---|---|---|---|
| X701-71G | 673.88 | 671.33 | 31.0 | 5.0 | 26.5 to 31.5 | 640.53 |
| X701-72G | 673.83 | 671.39 | 30.6 | 5.0 | 25.5 to 30.5 | 641.89 |
| X701-73G | 674.85 | 672.30 | 30.6 | 5.0 | 25.6 to 30.6 | --- |
| X701-74G | 674.14 | 671.64 | 31.6 | 5.0 | 26.0 to 31.0 | 641.04 |
| X701-75G | 674.06 | 671.38 | 31.2 | 5.0 | 26.2 to 31.2 | 640.58 |
| X701-76G | 674.56 | 671.92 | 34.0 | 5.0 | 26.0 to 31.0 | 641.42 |
| X701-77G | 674.80 | 672.15 | 32.4 | 5.0 | 26.0 to 31.0 | 641.75 |
| X701-78G | 674.40 | 671.97 | 31.1 | 5.0 | 26.1 to 31.1 | 640.97 |
| X701-79G | 677.46 | 674.87 | 34.5 | 5.0 | 27.0 to 32.0 | 642.87 |
| X701-80G | 672.35 | 669.82 | 29.0 | 5.0 | 24.0 to 29.0 | 640.82 |
| X701-81G | 672.86 | 669.85 | 28.5 | 5.0 | 23.0 to 28.0 | 641.85 |

amsl = above mean sea level
bgs = below ground surface
Note - auger refusal at 30.6 ft bgs during drilling of well X701-73G.

locked and keyed alike with locks supplied by PORTS. Each monitoring well is identified by stamped numbers on the side of the protective casing. The monitoring wells are numbered as: X701-71G to X701-81G. Figure 4.1 presents a fence diagram based on the geologic logs from the monitoring wells.

After the network of monitoring wells was installed and developed, water levels in the monitoring wells were allowed to stabilize for at least 24 h. Figure 4.2 provides a baseline potentiometric map for the study area.

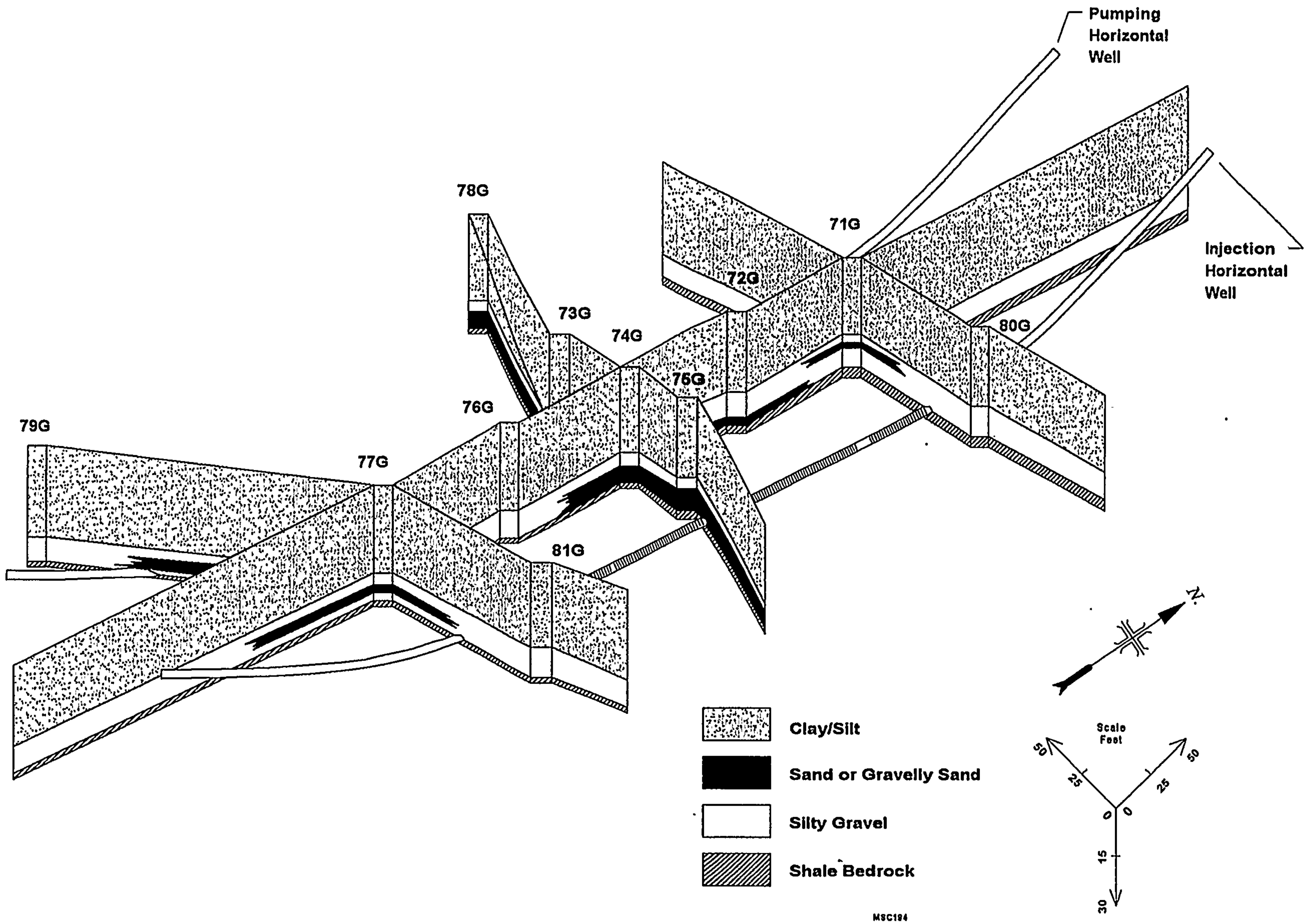



Fig. 4.1. Fence diagram of the horizontal well recirculation system.

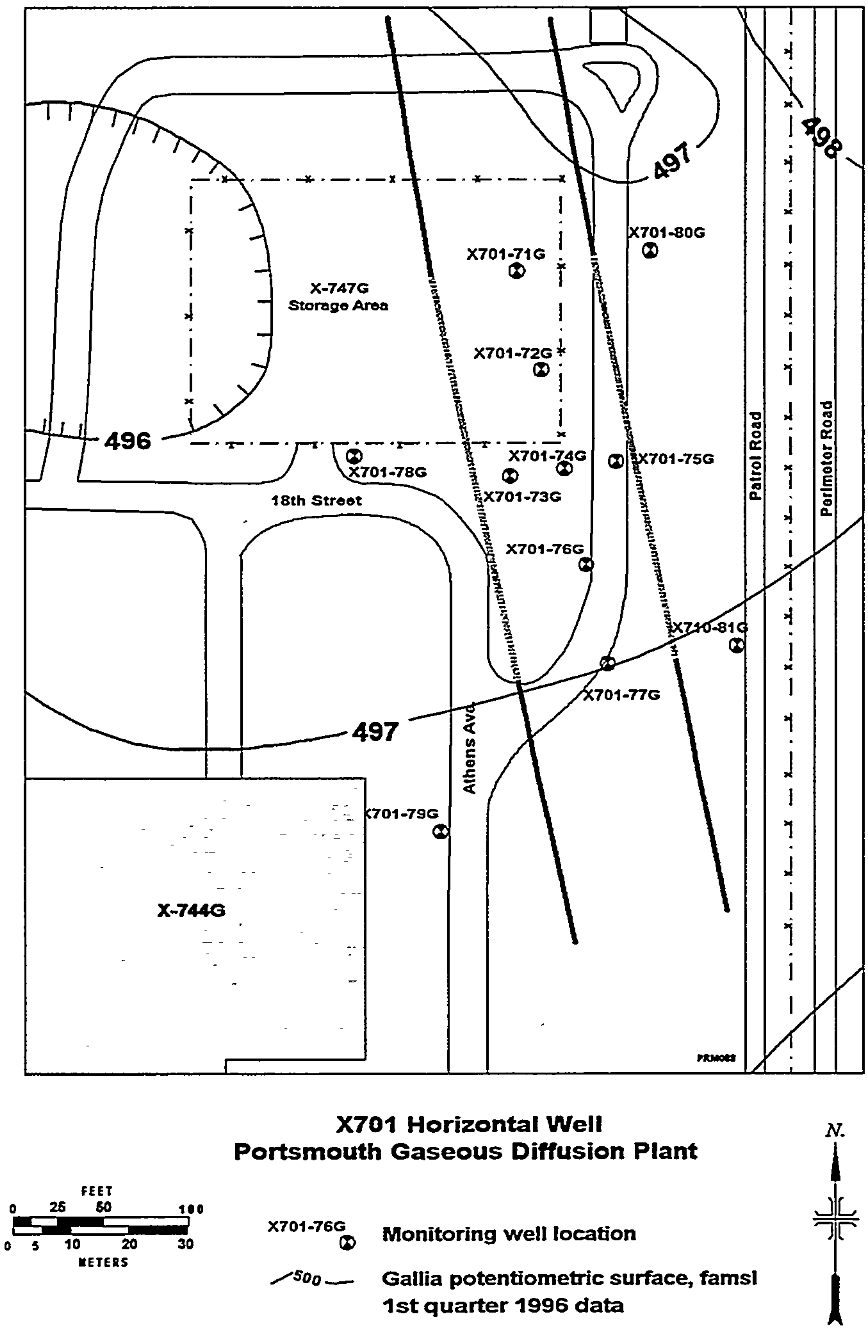



Fig. 4.2. Baseline potentiometric surface map.

# 5. Hydraulic Evaluation of The Horizontal Well Recirculation System

## 5.1 Introduction

This section discusses a series of field tests conducted at X-701B to evaluate aquifer characteristics and the hydraulic performance of the horizontal well recirculation system. The goals of these tests were to determine the horizontal well yields, area of influence, and the impact of subsurface heterogeneities.

Two pumping tests were conducted on the horizontal wells. The first test consisted of pumping the upgradient horizontal well to measure yield, area of influence, and hydraulic characteristics of the aquifer. The second test, referred to as the recirculation test, consisted of pumping one horizontal well, injecting into the other, and evaluating the influence on the surrounding groundwater flow system. In addition, a tracer test was performed to evaluate the effects of aquifer heterogeneity and the impact of dense nonaqueous-phase liquid (DNAPL) on the groundwater flow.

## 5.2 Site Hydrogeology

Prior to the installation of the horizontal wells, a series of boreholes were installed to delineate the unconsolidated deposits and the bedrock contact (see Sect. 3). In addition, 12 borings were drilled and completed as observation wells for the horizontal well hydraulic tests (see Sect. 4). The locations of the test borings are shown in Appendix A and the locations of the observation wells are shown on Fig. 3.1.

Based on the lithologic information for these borings and earlier borings drilled in the X-701B area, it is possible to construct a three-dimensional fence diagram of the site hydrogeology (Fig. 4.1). For presentation purposes, the hydrostratigraphy is divided into four hydrologically significant units. The upper unit at the site is comprised of undifferentiated fine-grained silts and clays of the Minford member. Because reported hydraulic conductivity values for the Minford are as low a $10^{-9}$ cm/s, the unit acts as a confining unit for the lower Gallia member (Law Engineering 1982).

The important water bearing unit at the site is the Gallia member. In the X-701B area, the Gallia has been subdivided into two separate units. The first is a sandy-gravel unit with a silty-clay matrix. This unit is more permeable than the overlying Minford; however, the silty-clay matrix significantly reduces the permeability. Also within the Gallia is a medium- to coarse-grain sand and gravel with relatively few fines. This sand and gravel unit exhibits a higher permeability than any of the other unconsolidated units or the underlying bedrock.

The Sunbury Shale is the uppermost bedrock unit at the site and consists of a weathered zone ranging in thickness from a few inches to less than 3 ft. Competent bedrock below the weathered zone is believed to be an effective barrier for the migration of water or contaminants and, consequently, forms the base of the unconsolidated aquifer at the site.

The most extensive sand and gravel unit in the Gallia at the X-701B site is located between the horizontal wells and is defined by wells X701-72G, -73G, -74G, -75G, and -78G. Although not visible in the fence diagram (Fig. 4.1), approximately 2 ft of this sand and gravel unit are present in well X701-73G. Unlike adjacent sand and gravel zones in the Gallia, this central unit is located near the base of the Gallia and contacts the underlying bedrock. Wells in this location exhibit the highest concentrations of TCE at X-701B. It is believed that through a combination of source area location and preferential flow along permeable zones, free-phase TCE migrated from the source and into this sand and gravel zone. Presently, free-phase TCE occupies a significant portion of the available pore space in this unit. This statement is based on the 1% rule that if groundwater concentrations of a selected organic compound exceeds 1% of the solubility limit for that particular compound then free-phase product is present (U.S. EPA 1992). All of these wells have groundwater concentrations exceeding 10 % of the solubility limit for TCE. With some of the wells exceeding 1000 mg/L, which is near saturation for TCE, it is certain that free-phase TCE exists between the horizontal wells.

Sand and gravel units were also found along the northern and southern extension of the horizontal wells. Two lines of evidence suggest that these units are hydraulically separate from the central sand and gravel unit. First, both the northern and southern sand and gravel units are stratigraphically located in the middle of the Gallia Formation unlike the central unit that is located at the base. Second, well X701-76G, which contains no sand and gravel, separates the southern from the central sand and gravel unit. While the southern sand and gravel unit is only evident in well X701-77G, its thickness and results of the tracer tests (discussed subsequently in Sect. 6) suggest that this unit has some areal extent. Well X701-72G, in which the sand and gravel is absent, indicates that the north and central units are not contiguous. Results of the tracer tests also suggest that the northern unit is of limited areal extent.

### 5.3 Single-Well Hydraulic Tests

Single-well tests were conducted on individual observation wells to evaluate the heterogeneity of the Gallia. Test results are presented in Table 5.1. Test curves from data obtained from the wells are found in Appendix D.

**Table 5.1. Hydraulic conductivity values based on single-well tests**

| Well No. | Hydraulic conductivity, ft/d |
|---|---|
| X701-73G | 39.6 |
| X701-74G | 182.8 |
| X701-75G | 99.0 |
| X701-76G | 24.2 |
| X701-77G | 411.1 |
| X701-78G | 65.5 |
| X701-79G | 142.6 |
| X701-80G | 31.7 |
| X701-81G | 60.2 |

The single well tests demonstrate that there is a wide range in the hydraulic conductivity values for the Gallia. The lowest hydraulic conductivity value, found in well X701-76G, corresponds with the site geology in that no permeable sand or sandy gravel zones were found in the Gallia at this location. In contrast, the highest hydraulic conductivity value was found in X701-77G which contains a permeable sand and gravel unit. During the tracer test, breakthrough of the tracer was detected in this well first thereby confirming the high relative hydraulic conductivity in the aquifer at this location.

Wells completed in the same central sandy gravel unit of the Gallia provide an interesting comparison. This sandy gravel unit is believed to contain significant quantities of free-phase TCE. Hydraulic conductivity values range from 39.6 to 182.8 ft/d. This range in hydraulic conductivities could be attributed to aquifer heterogeneity or a reduction in pore space and the subsequent reduction of permeability resulting from the presence of DNAPL (see Sect. 6).

### 5.4 Horizontal Well Pumping Tests

Pumping tests on the horizontal wells were conducted by placing a 3-in. submersible pump in one of the legs of the west (upgradient) horizontal well. The pump was placed at the base of the well next to the well filter. A flow totalizer was connected to the discharge line to monitor pumping rates. Water from the single horizontal well tests was routed to a 21,000 gal frac tank for temporary storage and by fire hoses to the X-701B groundwater treatment system. Steady pumping rates (variation <2%) were maintained during the individual pumping tests.

Water levels were monitored using pressure transducers and water-level indicators. Six wells were equipped with pressure transducers for continuous water-level measurements. Water levels in 17 observation wells were periodically measured by hand with a water-level indicator. In addition, water levels in each leg of the horizontal wells were periodically monitored during the tests.

A pumping or recirculation test of 48-hrs was conducted on each horizontal well. Conventional curve-matching analyses were performed in the field to ensure that the duration of the tests was sufficient to assess aquifer boundary conditions.

Based on the results of the pumping tests, it was possible to determine the yield of the individual horizontal wells, the recirculation rate, extent of drawdown, aquifer heterogeneities, and the extent of the Gallia channel deposits. Data from the pressure transducers are presented in Appendix E.

### 5.4.1 Single Horizontal-Well Pumping Test

#### 5.4.1.1 Well Yield

The west horizontal well was pumped at a rate of 10 gal/min for 48 hrs. At the end of the test the drawdown was approximately 7 ft. Using the concept of specific capacity for a horizontal well, the west horizontal well is capable of producing 1.4 gal/min/ft of drawdown. To maintain a safe yield, a common rule-of-thumb is to leave one-third of the aquifer saturated. With 15 ft of saturated thickness, therefore, the west horizontal well is capable of maintaining a maximum sustained yield of 11.4 gal/min.

In order to assess the effects of pumping on the aquifer, it is necessary to compare the post-pumping effects with the natural groundwater flow system. The pre-pumping potentiometric map for the Gallia Formation at X-701B is presented in Fig. 5.1. A large portion of the area is poorly defined due to the lack of wells. In the vicinity of the horizontal wells however, there is adequate definition. The pre-pumping potentiometric map in this area suggests that an east-west zone of higher permeability exists near the center of the horizontal flow field. Equipotential lines bend in an upgradient direction suggesting a preferential flow zone. Results of water samples collected for plume delineation purposes indicate that the heart of the plume is located in the same area further suggesting a zone of preferential flow.

It is evident from the potentiometric map in Fig. 5.1 that a single horizontal well has a large area of influence. Water levels are affected several hundreds of ft upgradient from the well, over 300 ft downgradient and 300 ft north and south of the end of the well filter. In order to capture a groundwater plume, therefore, it is not necessary to extend the ends of the horizontal well filter to the edge of the plume. The permeability effects of the sand and gravel zone associated with well X701-77G are not evident from the drawdown induced by pumping. This may be an indication of the limited aerial extent of this unit.

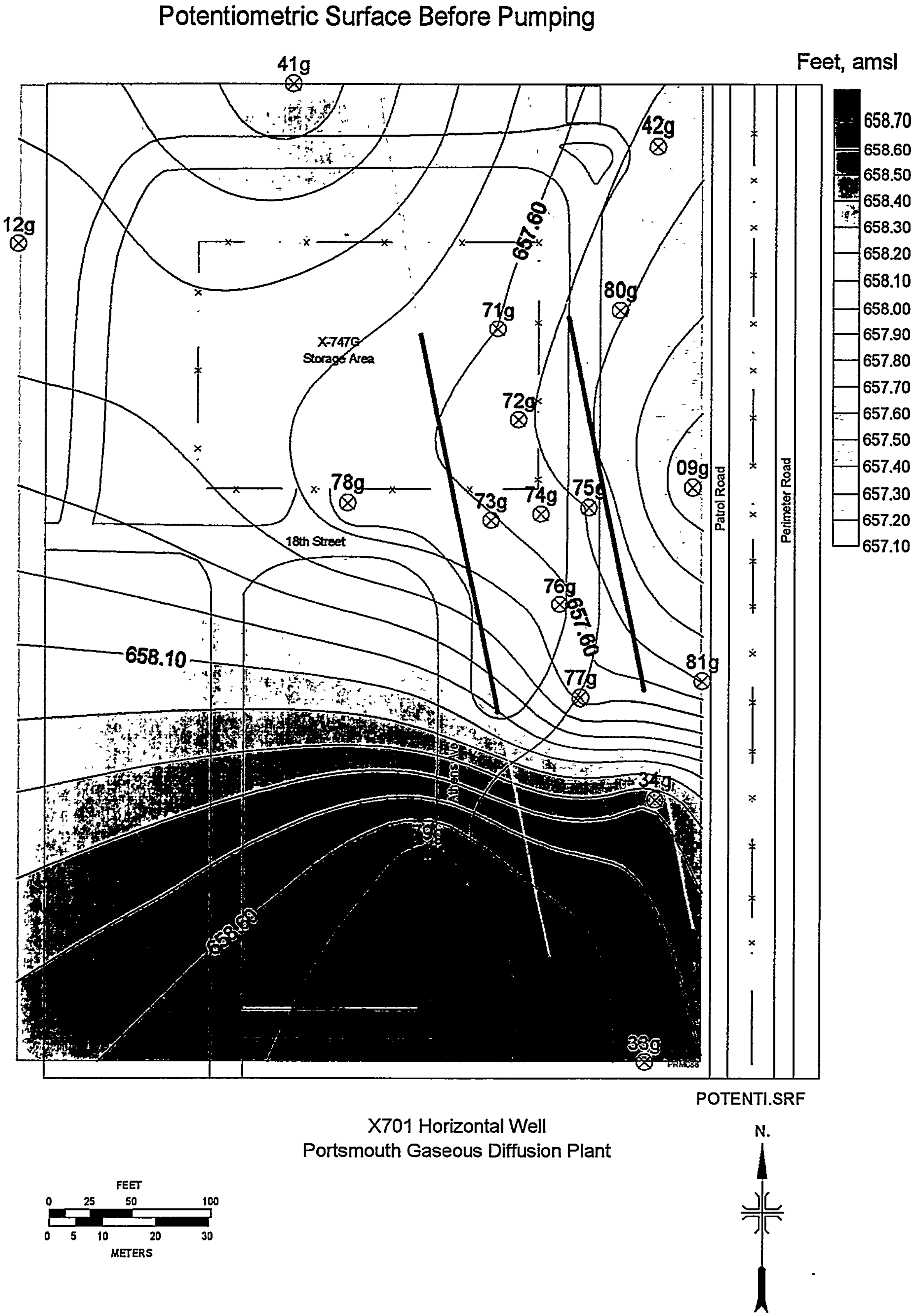



Fig. 5.1. Ambient potentiometric surface for the Gallia formation at the X-701B area.

## 5.4.2 Hydraulic Analysis of the Single Horizontal Well Aquifer Test

The upgradient (west) horizontal well pumping test was also used to assess the hydraulics of the aquifer. Figure 5.2 illustrates the response of the observation wells to pumping the west horizontal well.

Drawdown vs time plots for selected wells that were monitored using pressure transducers are presented in Appendix E. Conventional Theis curves analyses were conducted as part of the software plotting program. However, this analysis is based on a vertical well with radial horizontal flow conditions. Using the method for a line sink developed by Ferris (1950), transducer data collected during the west horizontal well pumping test is compared to a type curve presented in Lohman (1979). Logarithmic plots of D(u) versus $u^2$ with actual water level data obtained from wells during the west horizontal well pumping test show that there is not a reasonable match for this type curve. Similar results were obtained for curve matching analyses using data for other observation wells. The poor curve match, with the various methods indicate that the assumption that the aquifer is homogeneous, isotropic, and has a semi-infinite aerial extent (Lohman 1979) is not valid for the horizontal well in the Gallia aquifer at this location. This was not the case at the CTS where the Gallia aquifer behaved in a manner consistent with the assumptions inherent in this type of hydraulic analysis (Muck et al. 1996). It is also important to note that tracer tests indicated that the CTS was a relatively homogeneous aquifer as compared to X-701B. Consequently, it was necessary to use a different analytical method to estimate the hydraulic parameters at X-701B.

Schafer (1996) presented a method for determining the steady-state capture zones in three dimensions around a horizontal drain in homogeneous, anisotropic aquifers in a uniform flow field. Because the assumption of homogeneity is violated, the results will be an average of the hydraulic conductivity over the affected region and the accuracy of the solution will be limited. However, an estimate of the average hydraulic conductivity can be compared to the hydraulic test results from the single-well tests to estimate the aquifer heterogeneity. Equation (1) provides the Schafer solution for the expected drawdown values resulting from pumping a horizontal drain.

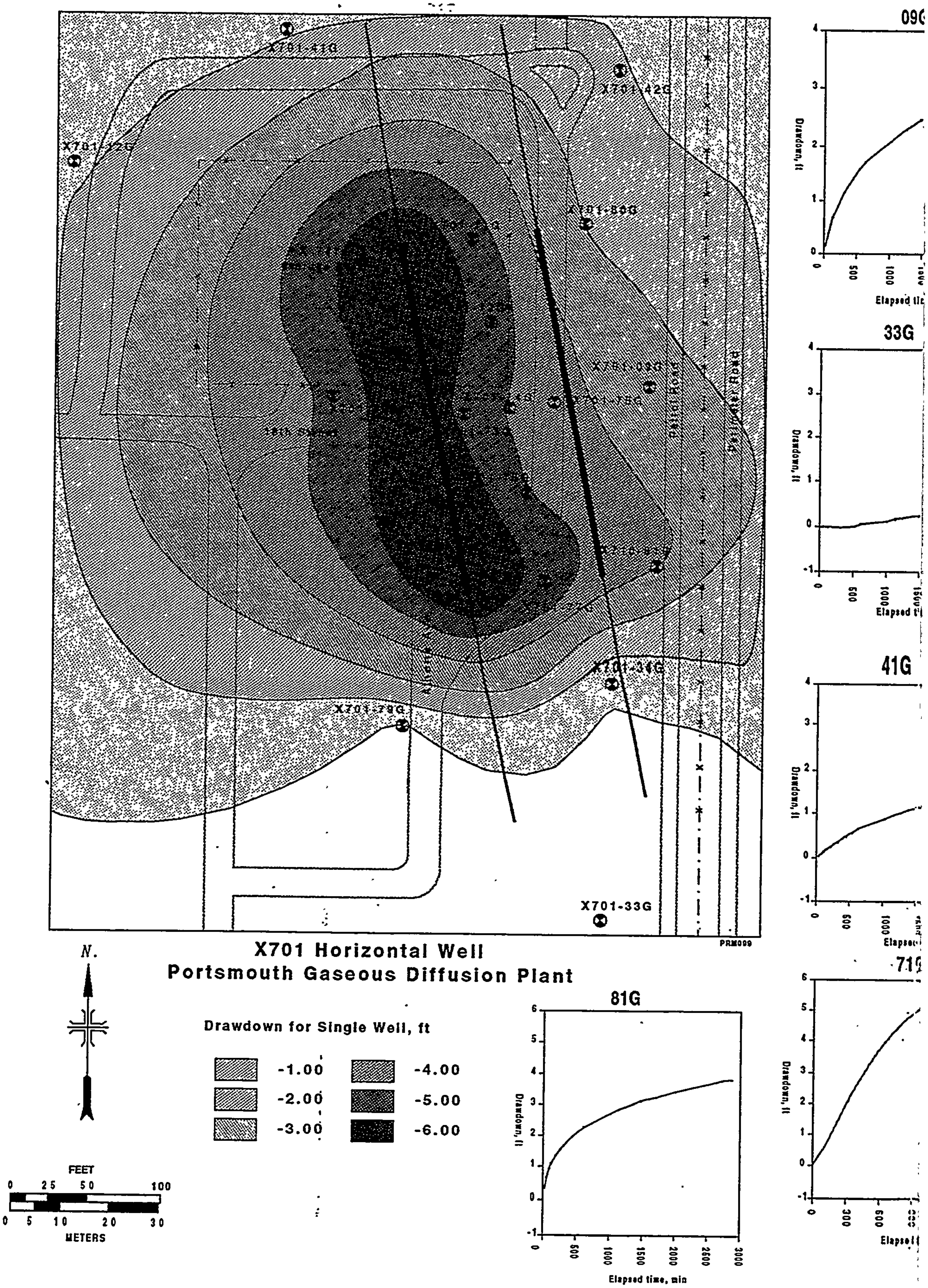
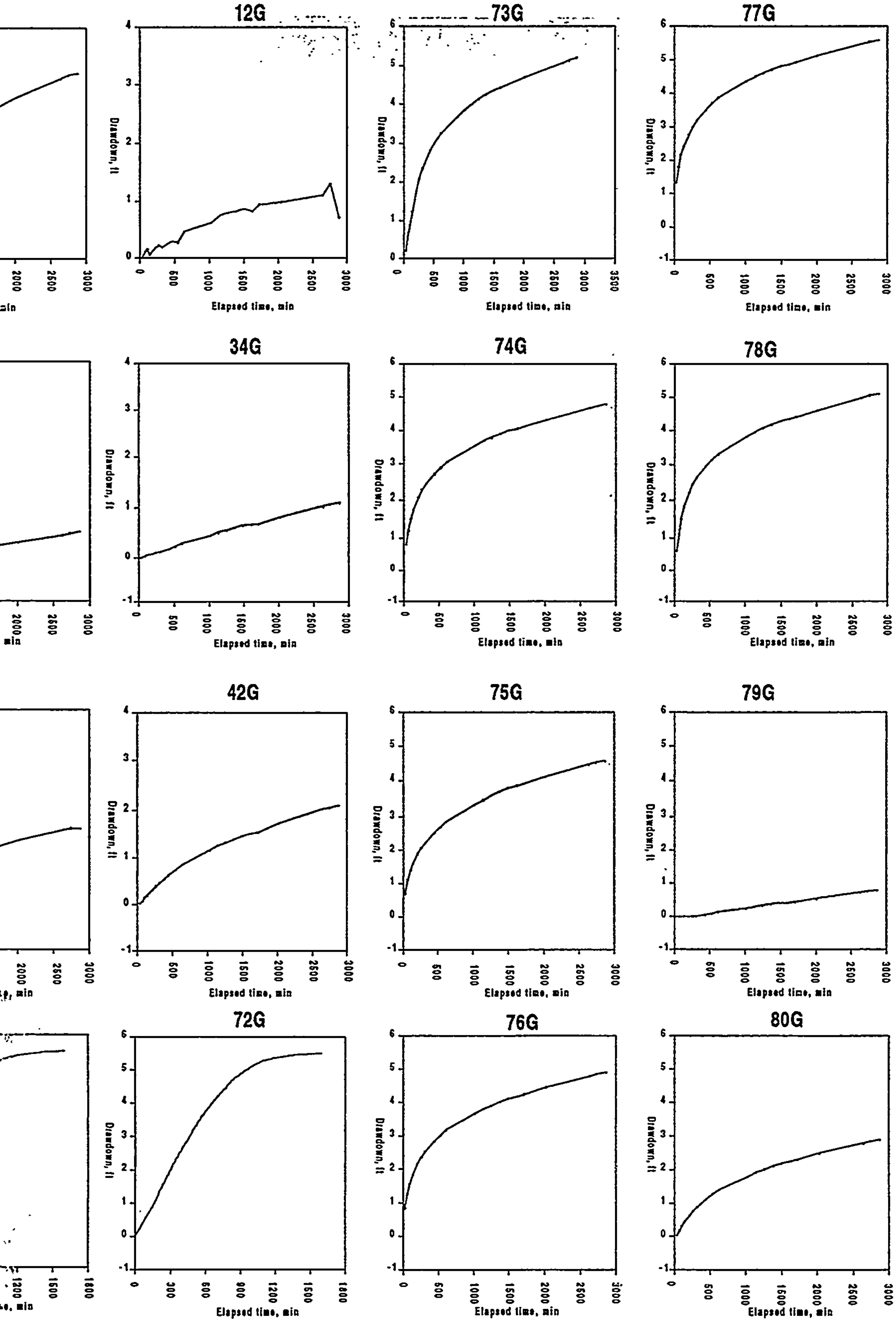



Fig. 5.2. Potentiometric surface and observation well at 10 gal/min.




well drawdowns in response to pumping the western horizontal

$$s = Ix\cos\theta + Iy\sin\theta + \frac{Q}{4\pi KL(A)^{1/2}} \sum_{n=-\infty}^{\infty} \left[ \ln \frac{\left[x^2 + \left(y + \frac{L}{2}\right)^2 + \frac{(z - 2nb - d)^2}{A}\right]^{1/2} + y + \frac{L}{2}}{\left[x^2 + \left(y - \frac{L}{2}\right)^2 + \frac{(z - 2nb - d)^2}{A}\right]^{1/2} + y - \frac{L}{2}} \right. \quad (1)$$

$$\left. + \ln \frac{\left[x^2 + \left(y + \frac{L}{2}\right)^2 + \frac{(z - 2nb + d)^2}{A}\right]^{1/2} + y + \frac{L}{2}}{\left[x^2 + \left(y - \frac{L}{2}\right)^2 + \frac{(z - 2nb - d)^2}{A}\right]^{1/2} + y - \frac{L}{2}} \right]$$

Summarizing the terms in equation (1), $s$ = distance of the water level at ($x$, $y$, $z$) below the static water level measured at the origin of the coordinate system; $I$ = regional gradient; $\theta$ = gradient direction, measured from the positive x axis; $Q$ = flow rate; K = horizontal hydraulic conductivity; $A$ = anisotropy ratio = $K_z/K$ ($K_z$ = vertical hydraulic conductivity); $L$ = length of drain; $x$, $y$, $z$ = coordinates of point where $s$ is computed; $b$ = aquifer thickness; and $d$ = depth below top of aquifer.

For calculating the hydraulic conductivity of the Gallia member, all of the variables were fixed, based on the geometry of the aquifer, with the exception of the hydraulic conductivity which was varied until the calculated drawdown matched the measured drawdown from the 48-hr single horizontal well pump test as shown in Fig. 5.3. Based on the reasonable match between the calculated and measured drawdown values, an average hydraulic conductivity of 20 ft/d is estimated for the Gallia. This value is similar to that measured at the CTS (Muck et al. 1996) and is consistent with the lowest values measured with single well tests (Table 5.1). Several of the hydraulic conductivity values from the single well tests were, however, more than an order of magnitude higher. Taken together, these data indicate that the aquifer is relatively heterogeneous.

### 5.4.3 Dual Recirculation Horizontal Well Pumping Test

A pumping test was also performed to evaluate the extraction and injection performance of the horizontal well pair.

#### 5.4.3.1 Well Yield

Groundwater was pumped from the west horizontal well at a rate of 10 gal/min and injected into the east horizontal well for 48 hrs. At the end of the test there was approximately 3 ft of drawdown in the extraction well and a 9 ft increase in the water level at the injection well. This discrepancy in water levels between the two

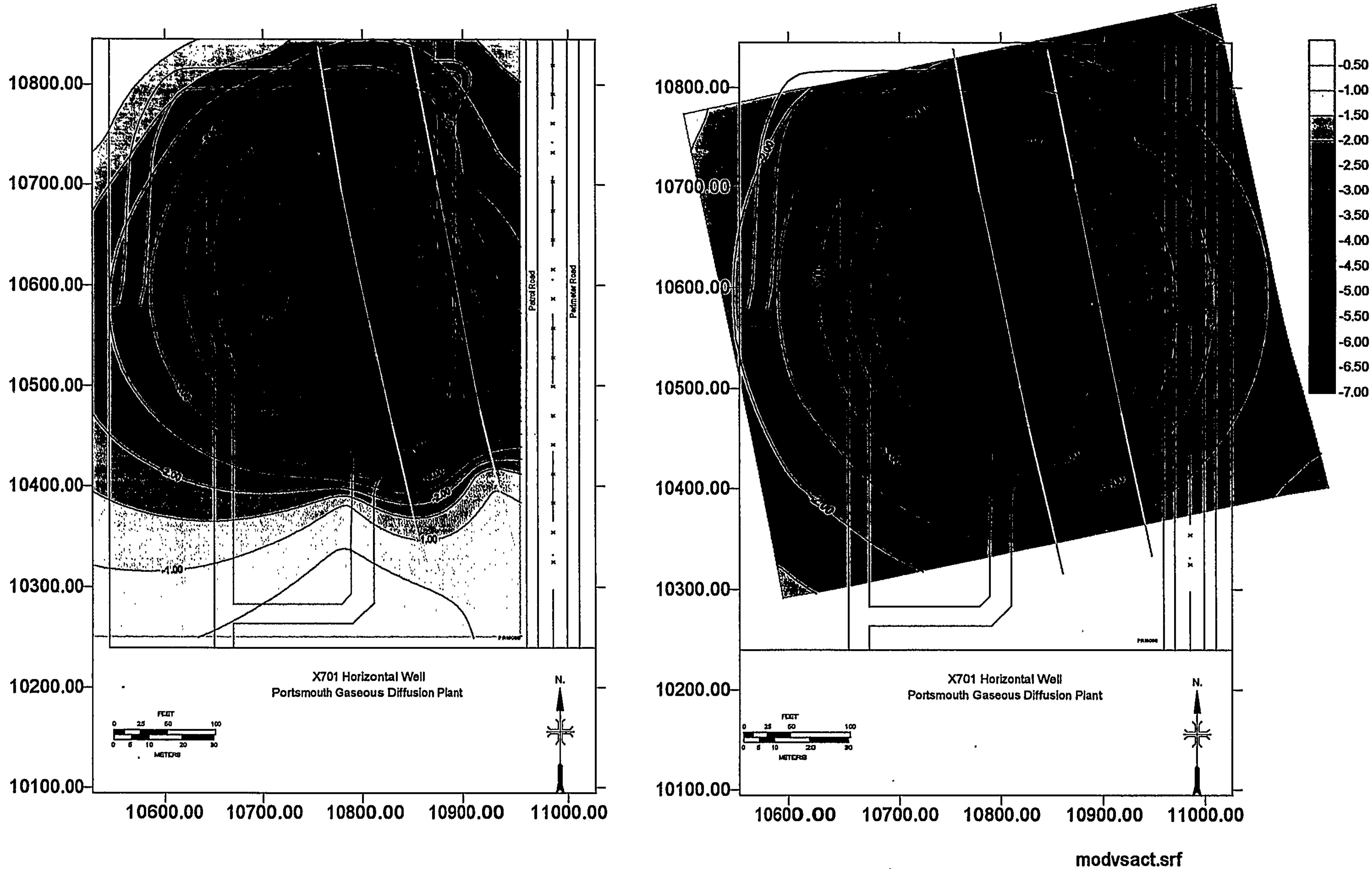



Fig. 5.3. Actual vs predicted potentiometric surfaces for the horizontal well pumping at 10 gal/min for an aquifer with a hydraulic conductivity of 20 ft/d.

horizontal wells indicates that the injection well is not as hydraulically efficient as the extraction well. The lower efficiency could be a consequence of different formation characteristics or an indication that the well development was not as complete in the injection well.

By injecting the extracted water in the nearby horizontal well, the specific capacity of the extraction well increases to 3.3 gal/min/ft of drawdown. By using, the rule-of-thumb that a safe yield requires maintenance of 5 ft of saturated thickness above the base of the extraction well, it is possible to recirculate 28 gal/min between the horizontal wells. This flow rate would require sealing the injection well to prevent surface leakage. The injection well would become pressurized but the surface leakage through the upper clays and silts should be minimal. It should be noted that the long-term testing was performed at only 6 gal/min, obviously well below the theoretical capability of the wells.

### 5.4.3.2 Aquifer Response to Pumping

Figure 5.4 shows the response of the aquifer to the horizontal well recirculation pumping tests. There is a significant decrease in the water levels resulting from the horizontal recirculation test compared with the single-horizontal well test. The area showing no influence due to pumping is much smaller indicating that the pressure resulting from reinjection is impacting the extraction well. During steady-state conditions, the reinjection well acts as a constant head boundary supplying water to the extraction well. The area of influence extends less than 300 ft upgradient and a few hundred ft beyond the ends of the well filter.

A high hydraulic gradient (13-ft water-level elevation difference) exists in the region between the two wells. This difference results in an average hydraulic gradient of 0.13 for the region between the wells. The increased gradient in this region will increase groundwater flow velocities by nearly two orders of magnitude. Using an average hydraulic conductivity of 20 ft/d, an enhanced hydraulic gradient of 0.13, and an assumed porosity of 0.3, the average groundwater velocity is 8.7 ft/d. Instead of the ambient condition that less than one pore volume of groundwater moves through the region each year, over thirty pore volumes would flow through the area.

## 5.5 Distribution of TCE

The distribution of TCE in the X-701B area groundwater is illustrated in Fig. 5.5. The heart of the TCE plume dissects the center of the horizontal recirculation wells. TCE concentrations in this area exceeded 500 mg/L. As noted previously, this location is almost certain to contain DNAPL.

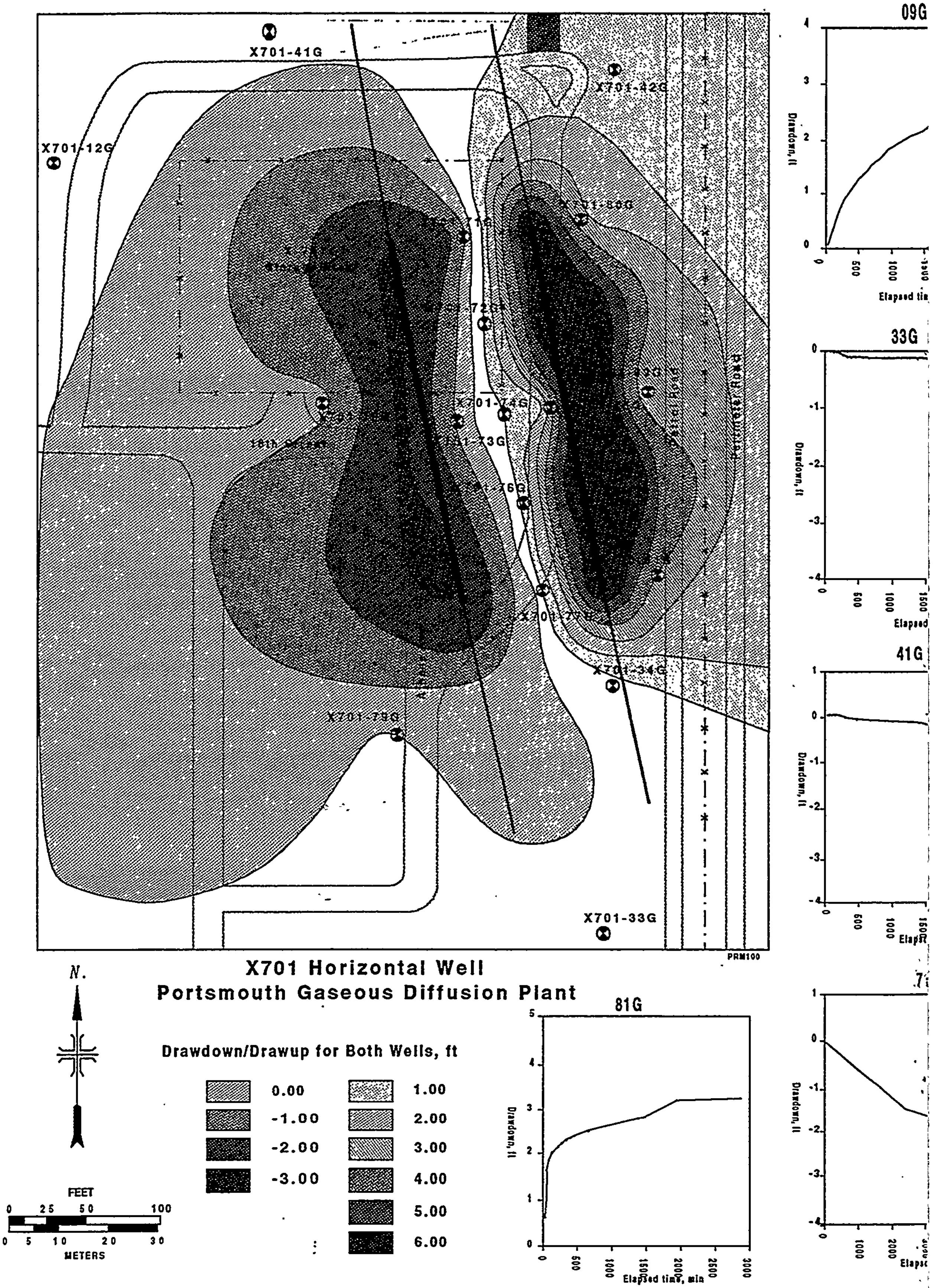



Fig. 5.4. Potentiometric surface and observatio
recirculation system pumping and injecting 10 gal/min

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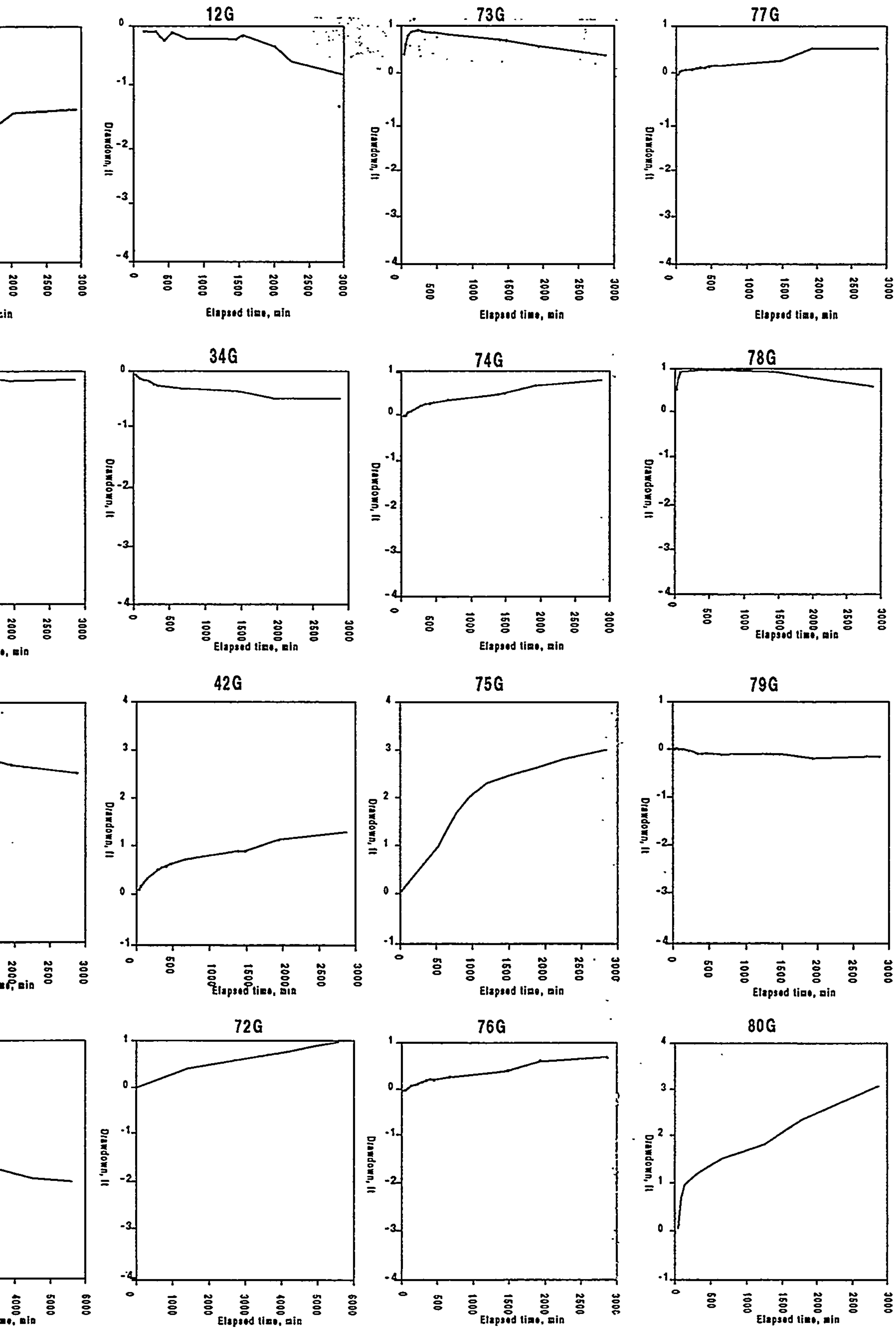



well drawdowns in response to the horizontal well
t steady-state conditions.

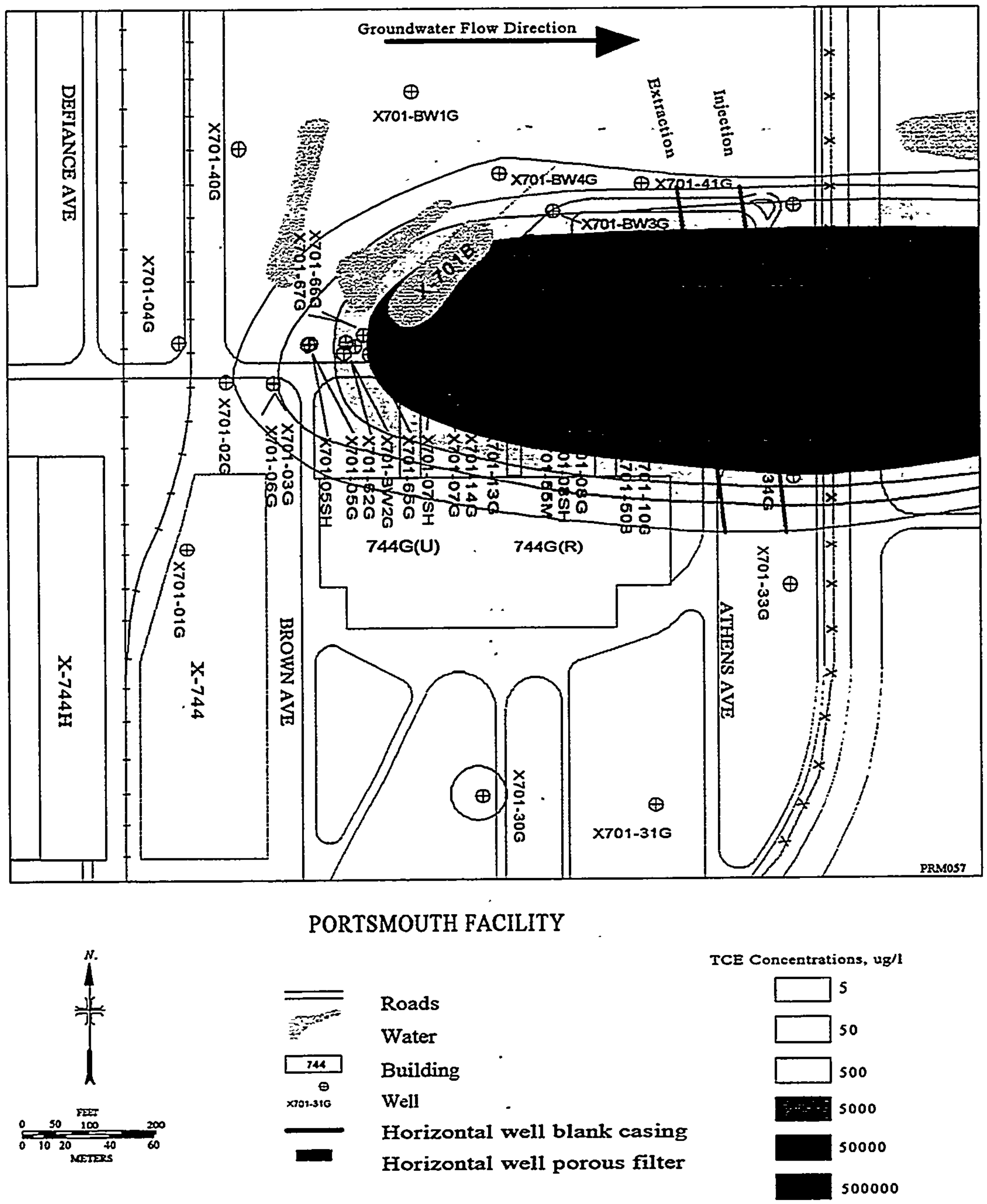



Fig. 5.5. Distribution of TCE in the groundwater at the X-701B site.

The location of this DNAPL coincides with a permeable sand unit discussed previously (Sect. 5.3). This evidence suggest that DNAPL moved from the upgradient source area preferentially in this sand unit. Because of the high groundwater concentrations exhibited by some wells (exceeding 1000 mg/L of TCE), the residual saturation in this sand unit is probably high. Cohen et al. (1993) report that DNAPL residual saturations for similar sands range from 15 to 40 % of the void volume. Using relative permeability curves presented by Schwille (1988), the effective water permeability of this sand zone would be reduced by an order of magnitude. If pools of DNAPL are present, then the water permeability may be reduced even more. The effect of DNAPL on permeability may have important implications for the tracer test as discussed in the next section.

# 6. Horizontal Well Recirculation Tracer Tests

## 6.1 Introduction

The performance testing of the treatment system provided an opportunity to conduct a tracer test using the horizontal well recirculation system. The purpose of this tracer test was to determine the hydrologic properties of the Gallia member and the characteristics of the TCE contamination. Contaminated water was withdrawn from the upgradient horizontal well, treated using zero-valence iron, palladized iron (Pd/Fe) or carbon, and then the clean water was injected into the downgradient horizontal well. This clean water acts as a tracer and an indicator of subsurface interactions with the TCE contamination. In addition to the clean water, a slug of bromide was injected into the downgradient horizontal well after quasi-steady state conditions were established in the groundwater flow field. Both the concentrations of TCE and bromide were monitored in the effluent from the horizontal extraction well, the effluent from the treatment system, and in selected monitoring wells located in the area.

The amount and the phase of the subsurface TCE, either dissolved or free product, will have an effect on the response of the aquifer to the injection of clean water. If the majority of TCE is in the dissolved phase and is located in preferential flow zones, then TCE concentrations will rapidly decline as the clean water displaces the contaminated water. Typically, a significant percentage of TCE will have diffused into adjacent low-permeability zones. Thus, as clean water moves through the system, the TCE concentration declines until a lower steady-state concentration, controlled by the rate of mass transfer occurs. If free-phase TCE is abundant in the groundwater flow paths, then TCE concentration levels observed in the monitoring wells may decline only slightly or perhaps not at all.

The bromide tracer test was performed to determine the locations of preferential flow paths in the Gallia, travel times for groundwater flow between the horizontal wells, and the efficiency of the recirculation system. A slug of 500 gals of bromide at a concentration of 500 mg/L was injected into the downgradient horizontal well. Water samples were analyzed in the field using a specific ion electrode.

### 6.2 Test Results

Results of the tracer tests for clean water and bromide are presented in Figs. 6.1 and 6.2, respectively. The graphs show TCE concentrations as a function of time with the injection of clean water being time equal to zero and bromide as a function of time since injection. The bromide was injected 48 hrs after the clean

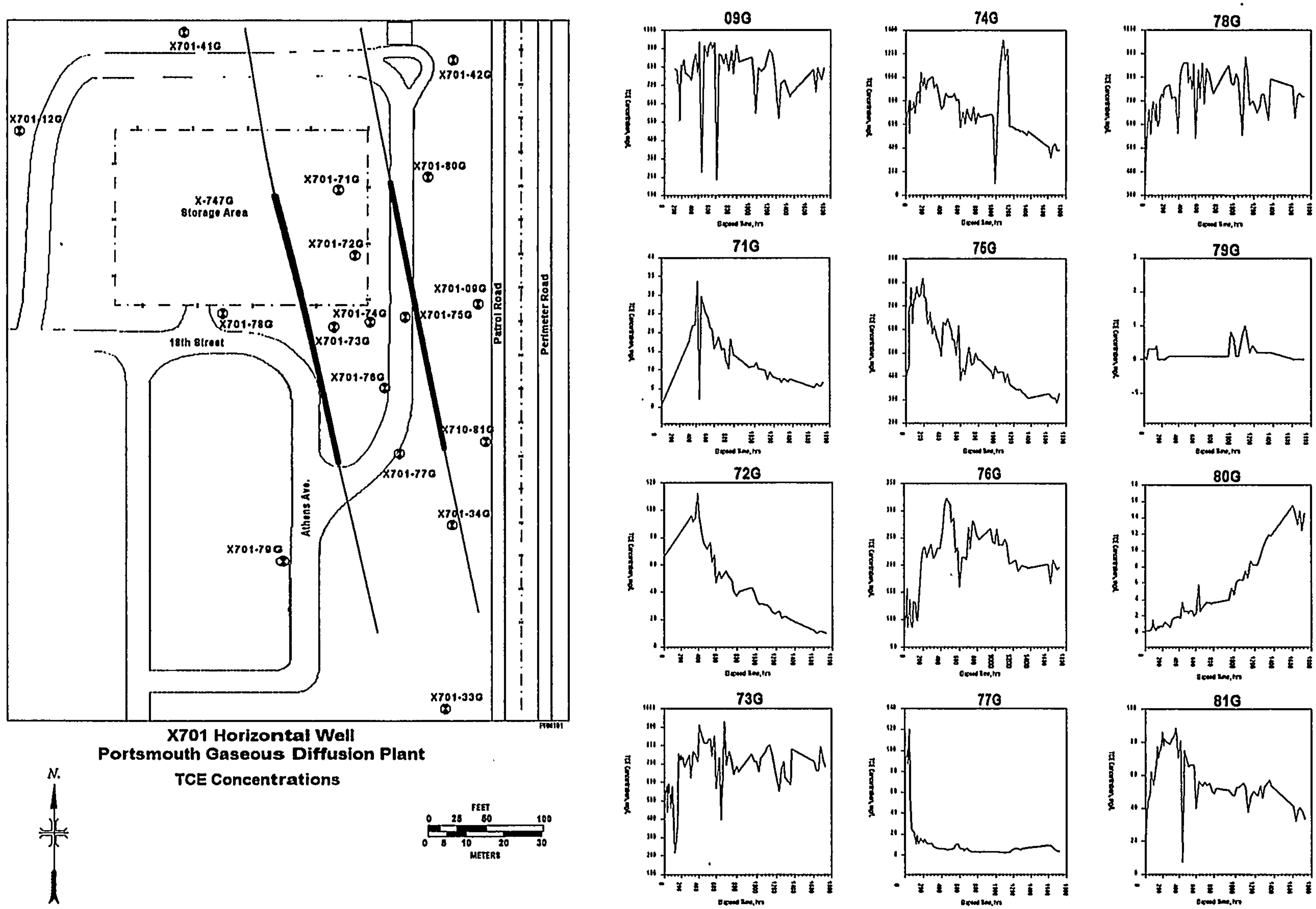



Fig. 6.1. TCE concentrations in the observation wells in response to injecting clean water.

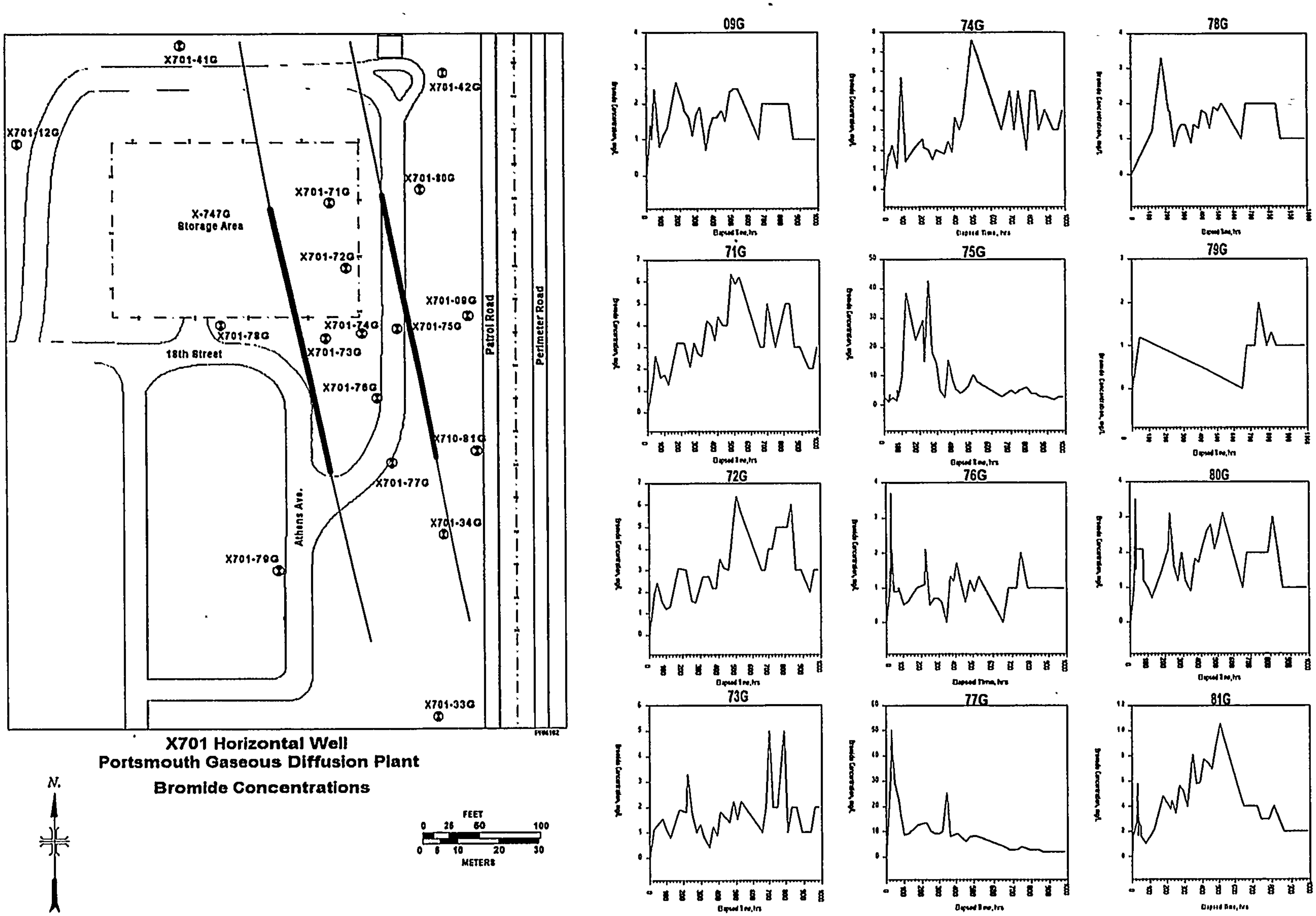



Fig. 6.2. Bromide concentrations in the observation wells for the tracer test.

water injection and when quasi-steady state hydraulic conditions in the aquifer had been established. There are several important observations apparent from the tracer tests. These include the following:

- Preferential flow zones dominate the movement of the tracers.
- Locations with the highest concentrations of TCE show limited movement of groundwater.
- Limited mobilization of DNAPL occurs in the region between the horizontal recirculation wells.

When interpreting the bromide tracer results, it should be noted that bromide concentrations below 1 to 2 parts per million (ppm) are not considered reliable.

The bromide tracer test indicates that a significant portion of groundwater flow in the horizontal well recirculation system occurs along the southern boundary. This is evident from the sharp peak in bromide concentration in well X701-77G at approximately 20 hrs after the initial bromide injection. Comparing the bromide peaks in the other wells clearly indicates that a preferential flow zone exists in the Gallia near the southern end of the horizontal wells. As noted previously, there is a permeable sand zone shown by well X701-77G. The tracer results indicate that the permeable sand unit associated with well X701-77G has a greater aerial extent than indicated by the drilling program (Sect. 5.3). For example, well X701-75G is completed in the central sand unit and is only 15 ft from the horizontal injection well. Well X701-77G is 45 ft away from the injection well. Yet it required approximately 200 hrs or 10 times as long for the bromide tracer to appear at X701-75G relative to -77G. In addition, the bromide peak in X701-75G is significantly broader due to a higher degree of dispersion. This evidence indicates that the flow path in the central region of the horizontal well pair is more heterogeneous or that the water permeability in the vicinity of well X701-75G has been reduced by a high residual DNAPL content.

The movement of water in the heart of the TCE plume can be evaluated by observing bromide concentrations in wells X701-75G, -74G, and -73G. As noted above, the breakthrough time for the bromide tracer occurred at approximately 200 hrs for well X701-75 G. At X701-74G, breakthrough time was approximately 500 hrs and at well -73G breakthrough occurred after 750 hrs. These data yield an approximate groundwater flow velocity of 0.1 ft/d. In contrast, well X701-77G yields a groundwater flow velocity of 60 ft/d or nearly two-orders of magnitude greater than velocities in the highly contaminated zone.

As noted previously, clean water injected into the aquifer also acts as a tracer and provides information on the contaminant cleanup rates. Most of the observation wells showed an initial increase in TCE concentrations. After this initial increase, TCE concentrations remained relatively steady or decreased. Wells that maintained a steady concentration were generally in the heart of the plume. For example, as shown in Fig. 6.1, TCE concentrations in wells X701-09G, -73G and -78G remain high suggesting that DNAPL is present, and the flow of clean water at these locations is not sufficient to lower TCE concentrations.

Wells such as X701-74G and -75G that are located in the heart of the TCE plume but are closer to the injection well show a gradual decrease in TCE concentrations. DNAPL is suspected to be present in these areas; nevertheless, clean water is flushing these zones and TCE concentrations are decreasing. The clean up process, however, is probably diffusion-limited.

Wells not located in the heart of the plume had an initial TCE concentration of less than 100 mg/L. These wells showed a rapid decline in TCE concentrations. Most notable is well X701-77G through which clean water moved rapidly. Well X701-72G showed similar effects. The lower initial concentrations and subsequent rapid decline suggests that DNAPL is not present in these wells.

Analyses of TCE and bromide of the effluent from the horizontal extraction well prior to the treatment system are shown in Fig. 6.3. The bromide data show breakthrough at approximately 340 hrs after injection. Based on this breakthrough time, the resulting average linear groundwater velocity between the recirculation wells is 6.7 ft/d compared with 8.7 ft/d based on the recirculation pumping test results. The good agreement between the two methods suggests that the pumping and tracer tests provided realistic estimates of the average aquifer hydraulic properties. TCE concentrations from the horizontal well effluent show an initial increase then a gradual decrease for the duration of the test (Fig. 6.4). Concentrations remain above 150 mg/L for most of the test. Considering these high concentrations and that water is being drawn by the horizontal well from a large area suggests that residual DNAPL exists over a large region of the X-701B site.

### 6.3 Colloidal Borescope Measurements

The colloidal borescope was placed in several monitoring wells to measure the impact of the horizontal well recirculation system on groundwater flow velocities. A detailed description of the colloidal borescope is presented by Kearl et al. (1994, 1997). Briefly, using the colloidal borescope, it is possible to obtain a direct measurement of groundwater velocity without relying on a Darcian solution.

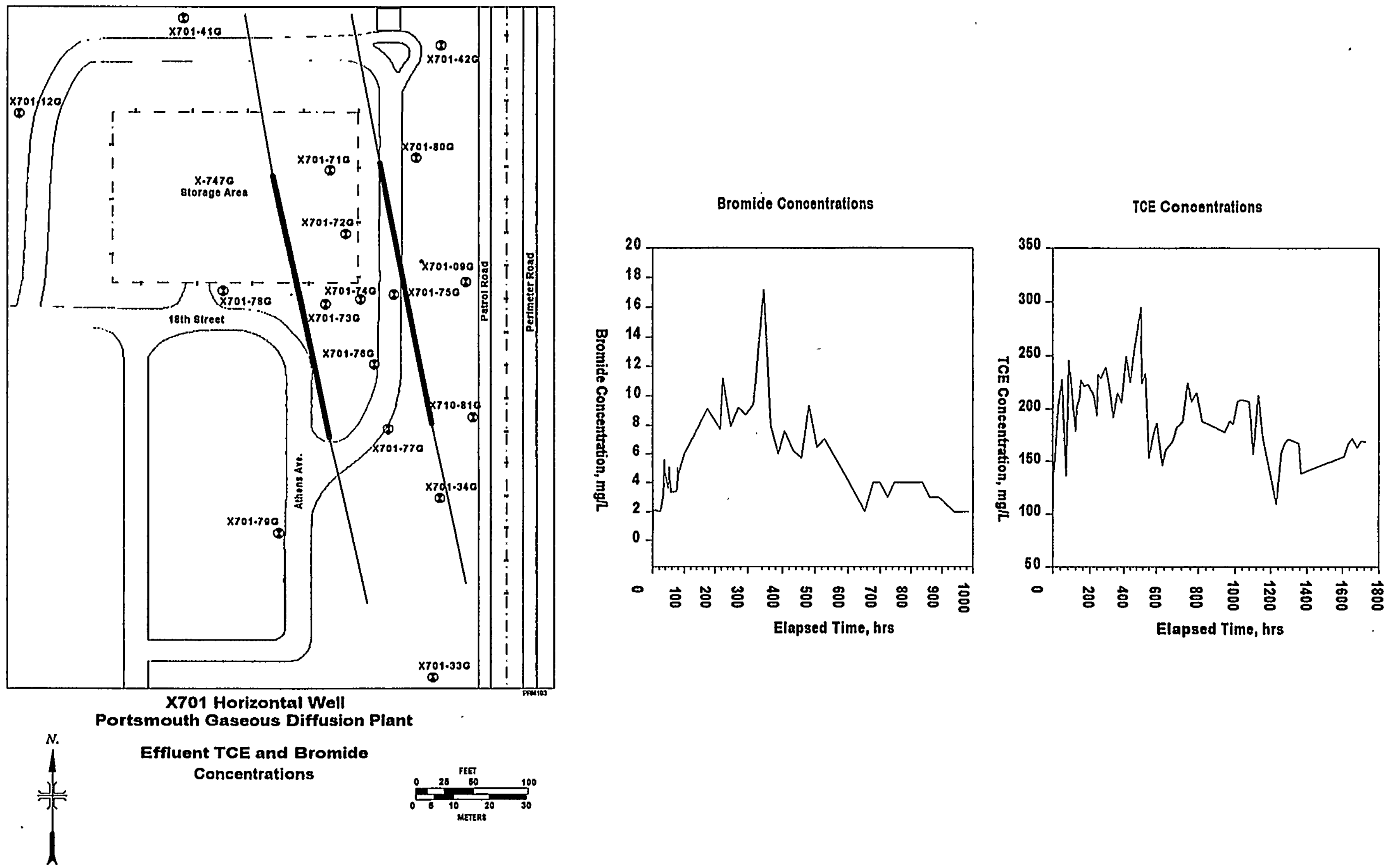



Fig. 6.3. Effluent concentrations of bromide and TCE from the horizontal extraction well during the recirculation tracer test.

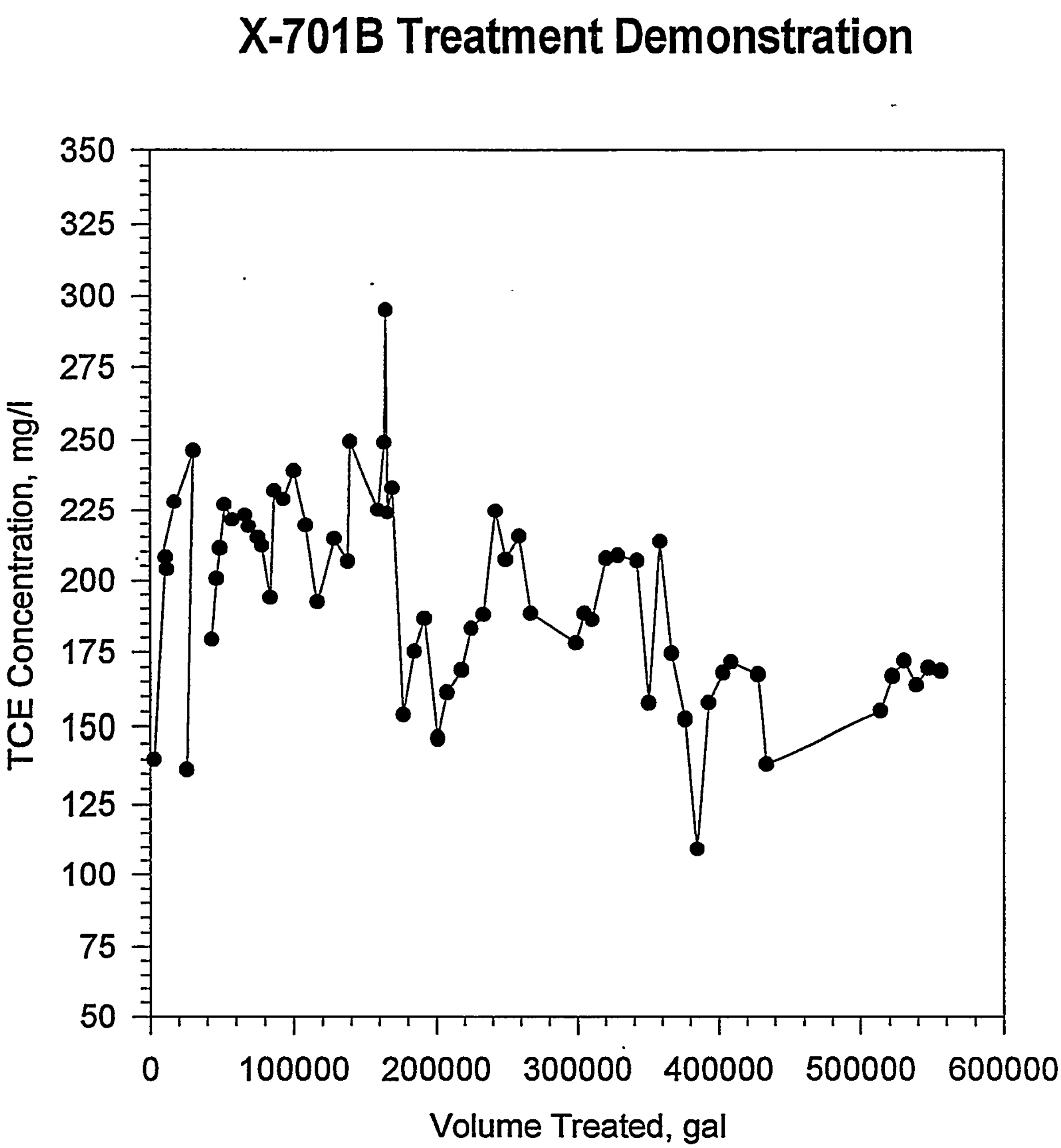



Fig. 6.4. Extraction well concentrations vs gallons pumped.

More detailed work with the borescope at the CTS demonstrated that the results were equivalent to the bromide tracer test (Muck et al. 1996).

The borescope was used to evaluate groundwater flow velocities during the tracer tests. The majority of the monitoring wells, including those in the heart of the plume (X701-73G and -75G), yielded swirling, nondirectional flow patterns typical of nonpreferential flow zones that have been observed at other field sites (U.S. DOE 1996). One exception was well X701-77G, described previously as being in a preferential flow zone. Well 77G had a distinct flow direction and relatively high velocity. The borescope measurements, therefore, support the results from the tracer and single-well tests..

## 6.4 Discussion

Results of the hydraulic testing have shown that the horizontal well recirculation system has an effective radius sufficient for capturing the entire plume of contaminated groundwater at X-701B. The recirculation system causes an increase in gradient of approximately two orders of magnitude between the wells, and has the capability to mobilize some of the DNAPL. Tracer tests showed the effects of heterogeneity in that the groundwater flow was predominantly at the southern end of the recirculation system. There also appears to be a reduction in permeability due to the presence of DNAPL in the central region of the recirculation system. Tracer tests estimated a groundwater velocity under pumping conditions for the central region of 0.1 ft/d although the lithology indicates that the central region contains a permeable sand and gravel unit. Moreover, the average linear groundwater velocity over the X-701B area is 8.7 ft/d. Consequently, a significant reduction in permeability apparently has occurred in the central sand and gravel zone.

The preferential flow paths evident with the tracer test are consistent with other recently published work. For example, a bromide tracer test with a vertical recirculation well yielded results that "show relatively uniform breakthrough at some locations and very nonuniform at other locations" (Blanford et al. 1997). In another study, bromide transport was studied under intermittent and continuous ponding conditions. Although this system was evaluating gravity-induced flow, "the magnitude of bypass flow was greater under intermittent conditions" (Ashraf et al. 1997). Whether or not the latter statement has implications for recirculation well operations is unknown, but the essential fact is that bypass or preferential flow was a critical aspect for describing solute transport.

Anderson et al. (1992) conducted a laboratory experiment concerning DNAPL removal from soil columns that is applicable to these field results. Two interesting results of the experiments were, 1) concentrations of DNAPL rose quickly to near-saturation values when water was forced through the soil columns and, 2) water flow through the residual DNAPL zones was not strongly affected by the presence of pure DNAPL. Similar rapid rises in TCE concentrations were observed in several monitoring wells during the recirculation test. For example, well X701-74G exhibited an initial TCE concentration of 500 mg/L but increased to over 1300 mg/L during recirculation. This TCE concentration in well X701-74G exceeds the solubility limit of TCE under ideal conditions which suggests that DNAPL has been mobilized by the increased hydraulic gradient between the horizontal wells.

In contrast to the X-701B results, Anderson et al. (1992) suggested that the presence of DNAPL did not affect the permeability of water flow through the sand column. However, it was estimated that the residual saturation of DNAPL in the sand column was 13 %. If the X-701B field test is consistent with these laboratory results and the assumption is correct that DNAPL between the horizontal wells is reducing the water permeability, then residual saturation in the field must be higher than 13 %. A higher value would be consistent with the work of Cohen et al. (1993) who reported that residual saturations up to 40 % could be assumed. In addition, for the laboratory experiment performed by Anderson et al. (1992), the initial dissolved concentration of chlorinated hydrocarbons was only 0.5 % of the saturation limit. At X-701B the concentration of chlorinated hydrocarbons was 75% of the saturation limit or more which further suggests that higher percentages of residual of DNAPL are present and are reducing water permeability.

# 7. Treatment System Operation

## 7.1 Introduction

This section provides an overview of treatment process considerations and results. A comprehensive report on the innovative treatment aspects of the project has been published previously (Korte et al. 1997a).

### 7.1.1 Technology Screening

The initial project activity was the screening and preliminary evaluation of candidate treatment processes for use in treating mixed contaminants (VOCs and radionuclides). Treating mixed contaminants presents unusual difficulties. Typically, VOCs are the most abundant contaminants, but the presence of radionuclides results in additional health concerns that must be addressed by a treatment approach vastly different from that used for VOCs. Furthermore, the presence of radionuclides may yield mixed-solid wastes if the VOCs are treated by conventional means (e.g., pump-and-treat with aboveground carbon adsorption). These issues were specifically addressed in the evaluation of candidate treatment processes for testing in this program. Because no research or development of a particular process was to be performed, the technology review focused on technologies that could be readily adapted and integrated for use with mixed contaminants. The objective was to couple emerging or available processes into treatment modules for use in situ.

This evaluation and screening effort led to selection of a set of promising treatment processes for initial study. These processes were selected from those that were commercially available or emerging, because they appeared compatible with an in situ treatment module system and offered a high probability of successful performance in that application.

This identification of treatment technologies was accomplished through a group effort that included meetings and contacts with technology experts, additional small-group meetings, and literature searches. Once technologies were selected, individual experts were requested to provide evaluations. The technology reviewers were provided with a specific reporting format and with ranges of contaminant concentrations and treatment-unit flow rates representative of the potential field sites (Korte et al. 1994). Based on the selection of the PORTS and Paducah Gaseous Diffusion Plant (PGDP) facilities as probable field-test sites, chlorinated hydrocarbons and $Tc^{99}$ were the target contaminants.

Table 7.1 lists the processes that were evaluated. These processes were identified by attendees at an initial scoping meeting. The candidate processes were selected based on known treatment rates and efficiencies and compatibility with in situ treatment of the target analytes. The planned approach was to package the technologies as modular components for use with horizontal or vertical recirculation wells. The modules were to be located in situ and to be used independently or in combination to treat the mixed contaminants.

**Table 7.1. Candidate processes for VOC and radionuclide removal or destruction**

| Candidate processes | Target |
|---|---|
| Stripping, with aboveground treatment of the gas stream | VOCs |
| Advanced oxidation processes, ultraviolet/peroxide | VOCs |
| Photocatalytic destruction ($TiO_2$), liquid-phase destruction | VOCs |
| Reductive dechlorination using zero-valence metal | VOCs |
| Radionuclide precipitation | Radionuclides |
| Reduction and sorption using zero-valence metal | Radionuclides |
| Selective ion exchange | Radionuclides |
| Selective sorption (ion exchange and adsorption) | Radionuclides |
| Organic sorbent mixtures | VOCs, radionuclides |
| Biodegradation in situ with injection of treatment agents | VOCs |
| Surfactant-enhanced bioremediation | VOCs, radionuclides |
| Reduction/sorption by Al and $Fe_2O_3$ | Radionuclides |
| Photocatalytic membrane | VOCs, radionuclides |

### 7.1.2 VOC Treatment Process Screening

The VOC candidate process screening resulted in the selection of air stripping as the process for use in the initial treatment program. Reductive dechlorination with zero-valence metals and organic sorbents were retained for further consideration because of ongoing research being conducted by this project's investigators. The other candidate processes were eliminated because they were deemed too cumbersome for downhole use or because treatment success was too uncertain (Korte et al. 1994).

### 7.1.3 Radionuclide Treatment Process Screening

The radionuclide candidate process screening resulted in the selection of selective ion exchange as the appropriate process for the initial treatment program. Sorption with zero-valence metals and sorption with organic sorbents were retained for further consideration as above. The other processes were eliminated again because they were too cumbersome or because success was too uncertain.

## 7.2 Treatment Process Selection

It was recognized at the outset of the project, that research into new treatment methods was very active. Indeed, other research being conducted by the principal investigators for this project resulted in the application of zero-valence metals in the treatment scheme rather than air stripping/ion exchange as initially selected with the screening process. (As explained in the following section, there were serious technical concerns about the use of air stripping as a component of the groundwater treatment system.) The other research being conducted included a series of DOE-EM-40 funded literature, laboratory, and field studies funded individually by the Pittsburgh Energy Technology Center, PGDP, PORTS, and the DOE Kansas City Plant. Each of these entities was interested in the potential application of zero-valence iron to chlorinated solvent degradation and/or metal or radionuclide removal. The work that was conducted was used to support CMSs for hazardous waste sites under the purview of the particular facility. The performance of this work led to the discovery that Pd/Fe degraded chlorinated hydrocarbons an order of magnitude or more faster than untreated zero-valence iron (Muftikian et al. 1995; Korte et al. 1997b). Moreover, Pd/Fe degraded PCBs and dichloromethane which are not degraded by zero-valence iron. This discovery was performed in conjunction with researchers at the University of Arizona (UofA). Research Corporation Technologies (RCT), a venture capital/technology transfer company filed a patent on the process, which was issued in March of 1997 (No. 5,611,936), on behalf of UofA and began a program to license the patent to the private sector. As part of that program, RCT offered to supply both the Pd/Fe and a treatment trailer if Pd/Fe were used in this project.

In the meantime, studies supporting CMS activities at PORTS and PGDP demonstrated that zero-valence iron was effective at removing $Tc^{99}$ (Clausen et al. 1995; Gu et al. 1996; Muck et al. 1995). Consequently, the decision was made to test zero-valence iron for $Tc^{99}$ removal and Pd/Fe for the destruction of chlorinated hydrocarbons.

### 7.2.1 Special Concerns of Recirculation and Coupled Treatment

Treating groundwater in a recirculation mode with coupled processes involves difficulties not encountered for conventional ex-situ treatment. The selection of treatment methods must address the effects the processes have on each other and on the aquifer. For example, air stripping does not couple very well with the use of iron to remove $Tc^{99}$. The primary mechanism for $Tc^{99}$ removal by iron is believed to be reductive precipitation (Gu et al. 1996). Thus, oxygen removal is necessary before $Tc^{99}$ can be reduced. Oxygen is also the principal clogging agent for iron columns or barriers (Mackenzie et al. 1997). Thus, to use air stripping with iron without risk of clogging the well or aquifer would require the use of nitrogen as the stripping fluid. Using nitrogen would have added significantly to the cost and complication of treatment.

Treated, recirculated, groundwater might also change the subsurface environment. For example, the Gallia aquifer at PORTS, which was being treated in this project, is relatively low in oxygen and contains dissolved iron in some locations. With air stripping, there was concern that oxygen injected during reinjection would both precipitate iron and stimulate growth of iron-oxidizing bacteria—a widely-recognized problem in southern Ohio. Iron precipitation and the growth of iron oxidizing bacteria could lead to clogging of the well and the aquifer. In addition, with ion exchange there is the problem that the resin would absorb a certain amount of VOC-containing water and, hence, would always have to be tested to determine if it were a mixed waste. Likewise, stripping is always accompanied by scaling from metal precipitation, sedimentation, and microbial growth. These solid phases would surely contain $Tc^{99}$ and require additional testing.

After reviewing these considerations, it was concluded that iron, Pd/Fe, ion exchange resin, and granular activated carbon (GAC) would provide combinations compatible with each other and with the Gallia aquifer. For example, in the iron-Pd/Fe system, any oxygen in the groundwater would initially be removed by the iron, which would simultaneously remove the $Tc^{99}$. Water entering the Pd/Fe, therefore, would be free of both oxygen and $Tc^{99}$. Thus, the Pd/Fe would be protected from clogging and could be regenerated because it was not a mixed waste. The iron also had the facility of slowly reducing chlorinated VOCs such that, after a few hrs or days of storage following removal from the system, it would contain only $Tc^{99}$ and would not be a mixed waste. The only effect on the aquifer would be the injection of soluble iron which was already present.

### 7.2.2 Backup Treatment Approaches

The laboratory and field tests had provided a high degree of certainty that elemental iron would be effective for removing $Tc^{99}$. Nevertheless, there was concern regarding clogging because of the formation of iron oxides, sulfates, and carbonates. Thus, a commercial ion exchange resin was considered the back-up for the treatment of $Tc^{99}$.

Field use of Pd/Fe for VOC destruction was considered much more uncertain than the use of iron to remove $Tc^{99}$. The material had never been prepared in bulk and Johnson-Matthey Corporation (JMC), the supplier hired by RCT, used proprietary preparation methods. Although the laboratory tests were promising, the technology had never been used in a full-scale field application. Thus, GAC was considered the backup for the removal of VOCs.

Some discussion is appropriate for the selection of carbon. Carbon is often considered an inferior approach for VOC cleanup because the contaminants are transferred from one media to another. However, carbon is particularly useful for using in situ in a horizontal well as this project was attempting to demonstrate. For example, carbon is light in weight and available in bulk. Thus, it could be easily deployed in canisters of various sizes including those which would fit in the arm of a horizontal well. In addition, carbon was also deemed the most useful surrogate for Pd/Fe in an operational sense. The iron would still remove the oxygen and $Tc^{99}$ and would dechlorinate residual VOCs when taken off line. The difference in the iron-carbon system as compared to the iron-Pd/Fe system, therefore, is that the VOC portion of the treatment relied on sorption and removal rather than on destruction. In other words, the carbon would have to be treated for removal of the sorbed VOCs. It should be noted that any of these configurations satisfied the initial intent of the project which was aimed at coupled, conventional treatment. Innovative treatment only became possible because of the additional work performed with funding from the additional sources mentioned in Sect. 7.2.

## 7.3 Treatment Trailer

A treatment system mounted in a mobile trailer (Fig. 7.1) was designed for the field tests. All parts for the trailer were provided by RCT at no cost to DOE and ORNL. Labor for the design and construction were funded by DOE-EM-50.

The trailer is 16 ft in length and 8 ft wide. Four large side doors and a double rear door provide convenient access to the treatment system inside the trailer. The system itself consists of six stainless steel columns supported on steel cradles and enclosed behind removable plexiglass windows. The column enclosures are mounted inside

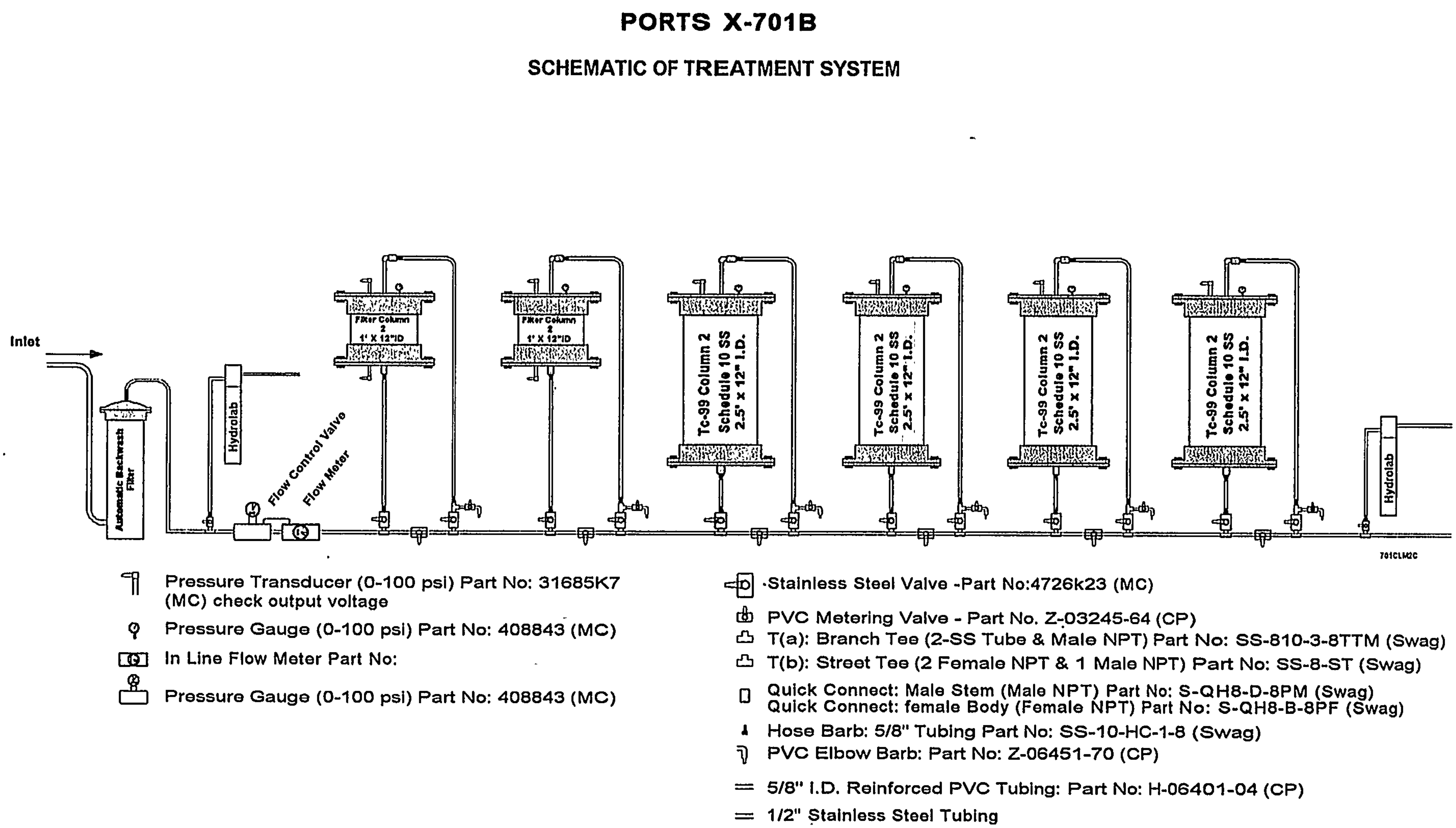



Fig. 7.1. Schematic of treatment trailer used for field tests.

spill containment liners equipped with leak detectors and an automatic pump shut-off. As secondary containment, the entire trailer floor is lined and equipped with leak detectors and automatic shut-off..

Two of the columns, used as pre-filters for removing particulates and dissolved oxygen (DO), are 12 in. long and 12 in. in diameter. The remaining four columns are 30 in. long and 12 in. in diameter. The column design is shown in Fig. 7.2. The lids on either end were packed with fine and coarse sands as a means of providing both additional filtration and to prevent loss of the reactive media, in this case iron or Pd/Fe.

The columns are connected by stainless steel tubing and valves and can be operated individually, in-series, or in-parallel (Fig. 7.3). Flexible metal tubing and quick disconnects enable rapid changes to be made without shutting off flow to the entire system. The columns are also easily rotated by means of the support cradles. Even with media as heavy as iron (approximately 500 lbs in this application), the columns could be rotated by a single person. Each column is also equipped with pressure transducers and analog pressure gauges. Flow meters are used to monitor total flow and flow through individual columns.

A data acquisition system was also designed and built to closely monitor treatment system parameters. Flow rates, pressures, treatment time, treated volume, and trailer alarm conditions can be logged at specified intervals. Thus, all of the aforementioned parameters can be compiled and evaluated in real-time. Analytical data derived from samples collected during operation can also be conveniently merged with the operational parameters such that treatment efficiency as a function of time, flow rate, and pressure can be easily viewed.

## 7.4 Treatment of $Tc^{99}$ with Zero-Valence Iron

Certain wells within the flow field contained more than 100 pCi/L of $Tc^{99}$ while no $Tc^{99}$ was detected in others. Table 7.2 presents the data for the individual wells. The highest concentrations (up to 369 pCi/L) were found in wells X701-09G, -73G, -74G, and -75G—the same wells with the highest VOC concentrations. As soon as the horizontal recirculation system was started, samples were collected for analysis of $Tc^{99}$. Influent concentrations remained low as shown by Table 7.3. The original plan had been to analyze frequently the effluent from the iron column to determine when $Tc^{99}$ breakthrough occurred. Those analyses were not performed because of the low influent concentrations and the high analytical cost. However, the columns were dismantled, segmented, and the segments analyzed for their $Tc^{99}$ content, following the cessation of the pumping and treatment.

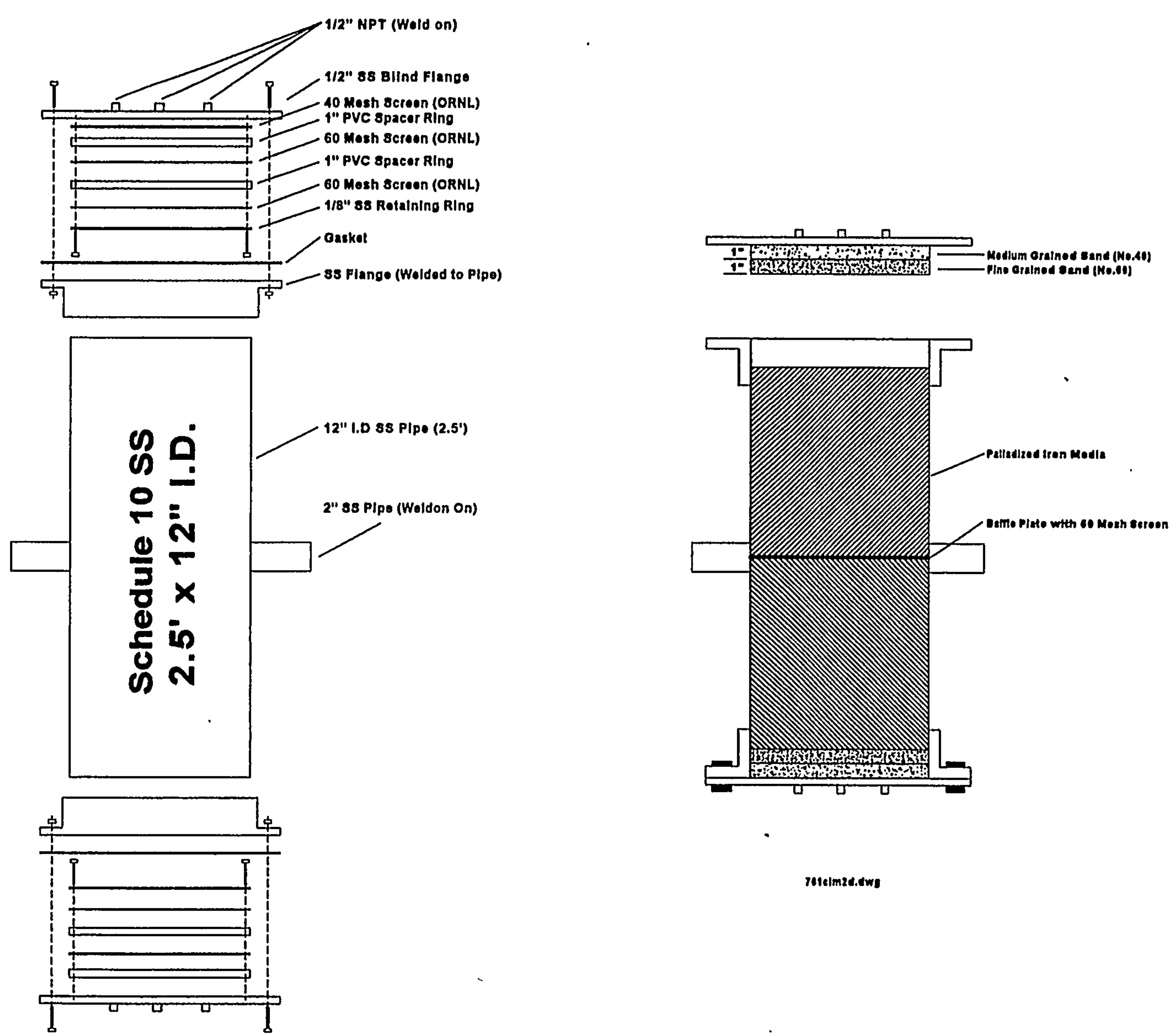



Fig. 7.2. Detailed view of columns used for field tests.

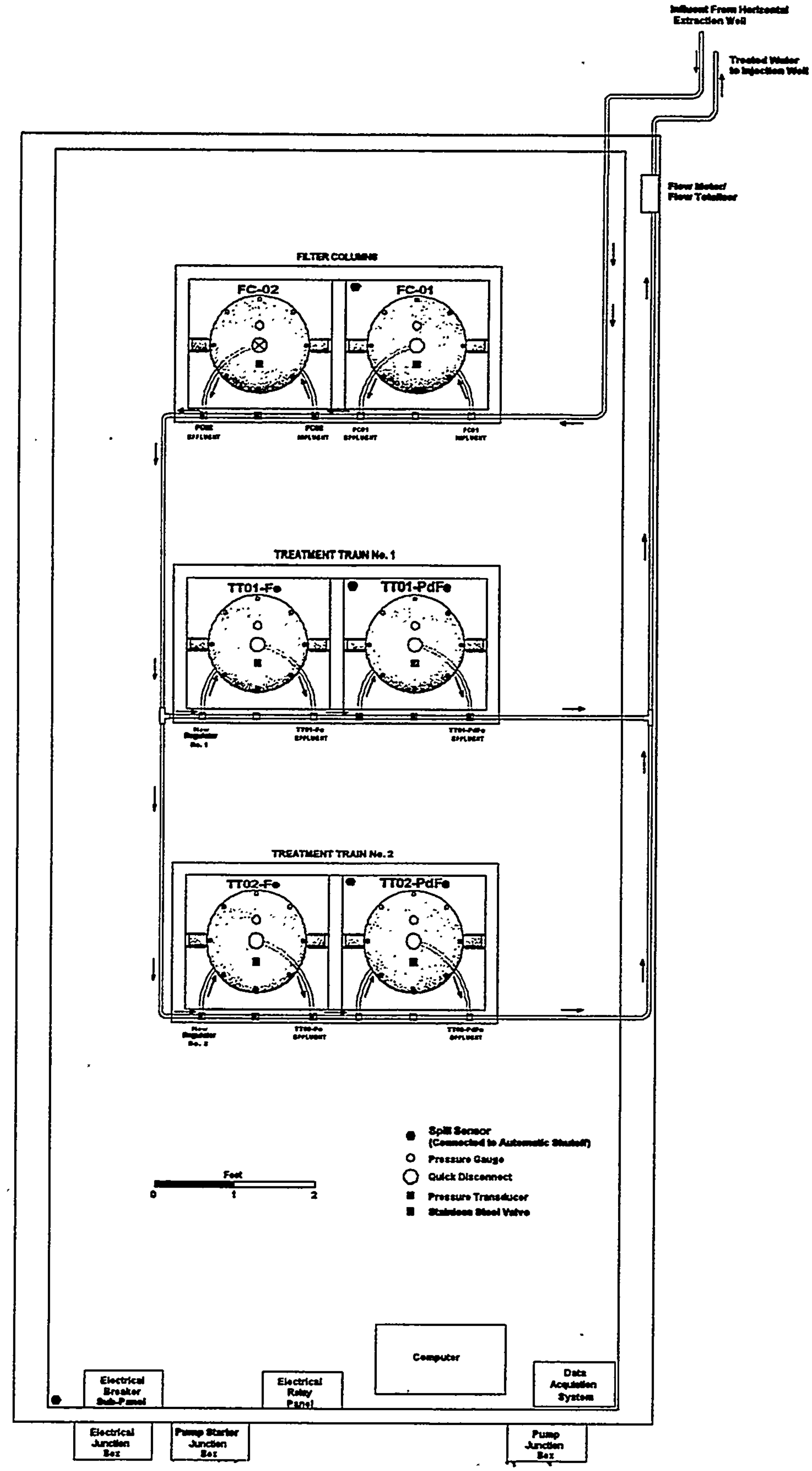



Fig. 7.3. Plan view of treatment trailer layout.

# Table 7.2. Monitoring well water sample data: technetium, pCi/L

| Begin @ 1000, 29-Sep-96 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End @ 1350, 12-Dec-96, Elapsed Time: 1781 hrs, Treated volume: 584,418 gal | | | | | | | | | | | | | | |
| **Sample date** | **Sample time** | **Sample numbers** | **Well 09G** | **Well 71G** | **Well 72G** | **Well 73G** | **Well 74G** | **Well 75G** | **Well 76G** | **Well 77G** | **Well 78G** | **Well 79G** | **Well 80G** | **Well 81G** |
| 5-Sep-96 | 1450 | W001 - W012 | NS | 139 | 91 | 250 | 352 | 299 | 69 | <27 | NS | <27 | <27 | <27 |
| 7-Sep-96 | 1030 | T001 - T006 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 11-Sep-96 | 805 | T034 - T037 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 30-Sep-96 | 1510 | W031 - W039 | NS | NS | NS | 271 | 315 | 212 | <21 | <21 | 152 | <21 | <21 | <21 |
| 10-Oct-96 | 1030 | T201, T204 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 28-Oct-96 | 1130 | T300, T301 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 16-Nov-96 | 1500 | TB246 - TB249 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 12-Dec-96 | 830 | TB476 - W759 | 239 | >21 | <21 | 369 | 40 | 154 | <21 | <21 | 210 | <21 | <21 | <21 |

NS = not sampled

**Table 7.3. Influent/effluent technetium, pCi/L**

| Sample date | Sample time | Sample numbers | System influent | Iron column effluent |
|---|---|---|---|---|
| 7-Sep-96 | 1030 | T001 - T006 | 52 | 30 |
| 11-Sep-96 | 805 | T034 - T037 | <21 | <21 |
| 30-Sep-96 | 1510 | W031 - W039 | <21 | NS |
| 10-Oct-96 | 1030 | T201, T204 | 29 | NS |
| 28-Oct-96 | 1130 | T300, T301 | 38 | <34 |
| 16-Nov-96 | 1500 | TB246 - TB249 | 45 | <21 |
| 12-Dec-96 | 830 | TB476 - W759 | 25 | <21 |

NS = not sampled

Figure 7.4 shows the results of the $Tc^{99}$ analyses of the iron segments. Approximately 600,000 gal of water had been pumped through the columns but all of the $Tc^{99}$ was confined to only 12 in. of iron. These data show that removal of $Tc^{99}$ from the mixed waste was successfully demonstrated. With higher concentrations of $Tc^{99}$, the iron columns would have been periodically changed. Laboratory data (Korte et al. 1997a) show that it is possible to select iron of varying capacity for $Tc^{99}$. Thus, the activity of the spent iron could be tailored to the particular treatment/storage option that is available.

## 7.5 Field Experiments with Pd/Fe

When the potential benefits of using Pd/Fe were identified, RCT contacted JMC who is one of the world's largest sources for precious metal preparations. JMC agreed to prepare Pd/Fe for laboratory testing. Several different preparations were provided to ORNL but JMC used a proprietary method of preparation and would not confirm whether they were using the published method (Muftikian et al. 1995). Laboratory kinetic data, however, were encouraging in that batch tests with the JMC material closely approximated what was obtained with Pd/Fe made in the ORNL and UofA laboratories. RCT desired a full-scale test and agreed to pay JMC to provide the Pd/Fe. Thus, the decision was made to use Pd/Fe for the full-scale horizontal recirculation program.

Pd/Fe was tested in three separate phases during the field program at PORTS. Initially, the test was to be full-scale with JMC-prepared Pd/Fe. As will be discussed, this experiment failed because of manufacturing problems at JMC's New Jersey facility. A smaller scale experiment, also using JMC-prepared Pd/Fe was attempted during a second phase of testing. This experiment met with some success but was prematurely terminated because of an operator error. Finally, a third phase, relying on field preparation of Pd/Fe was attempted. This third phase would have provided the most useful results but equipment malfunction and overall cessation of field activities prevented a complete test. Nevertheless, there were important lessons learned in each phase of activity as described below.

### 7.5.1 Pd/Fe Design Parameters

The treatment goal was to reduce the influent TCE concentration by at least 90% in one pass through the treatment system. Laboratory data had indicated that the influent TCE concentration would be reduced by ½ after approximately 23 s of contact with Pd/Fe. A 90% reduction, therefore, requires approximately four reductions by half (e.g., 100-50-25-12.5-6.25). Thus, residence time in the Pd/Fe would have to be approximately 2 min. In order to account for varying temperatures

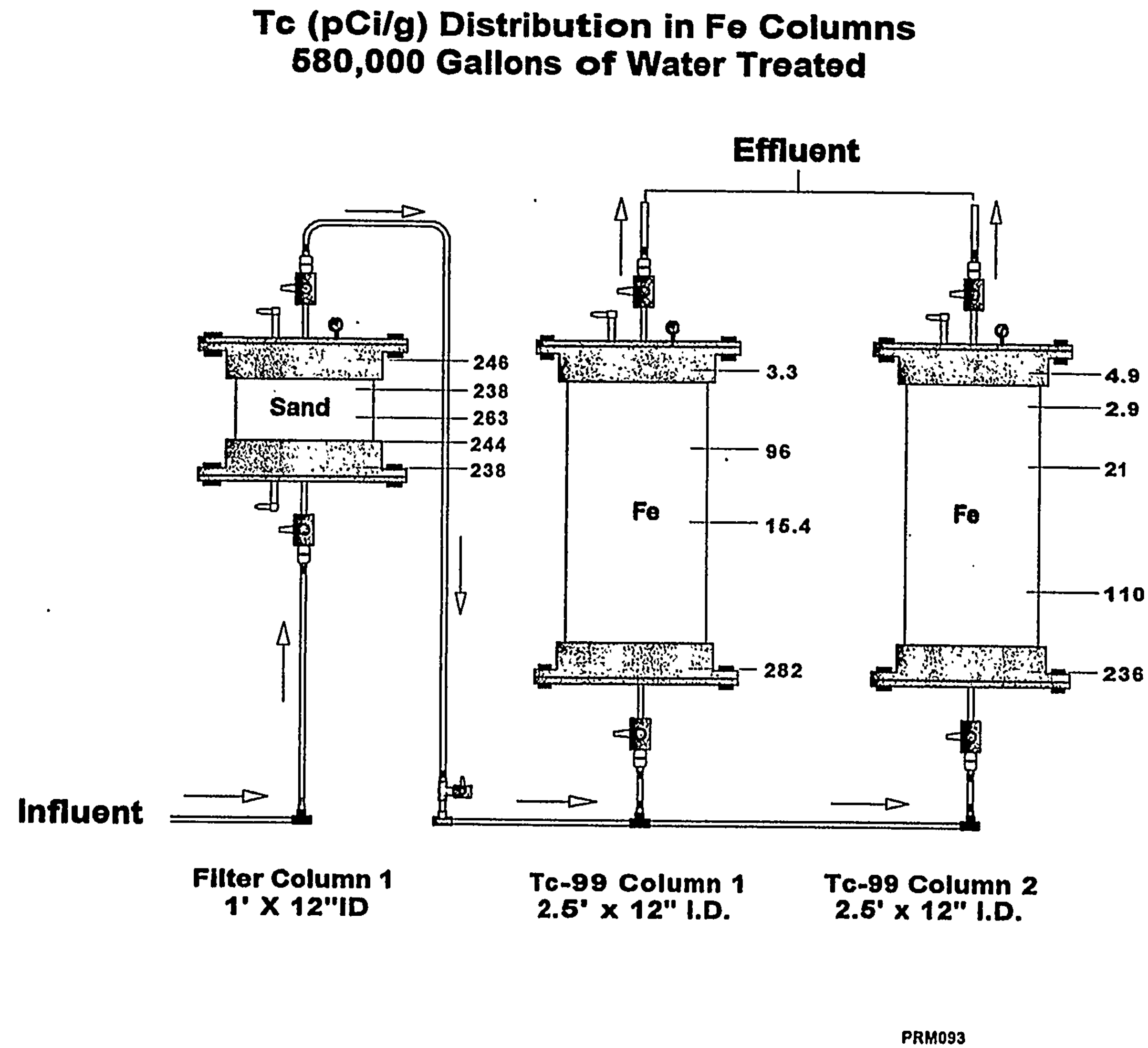



Fig. 7.4. $Tc^{99}$ (pCi/g) distribution in Fe columns 580,000 gal of water treated.

and an expected reduction in treatment efficiency with time, the system was designed with a 3 min (180 s) residence time. Hydrologic testing with the horizontal recirculation system had shown that the minimum flow rate needed for the hydraulic testing was approximately 5 gal/min although higher flow rates could be accommodated. Based on this information, 6 gal/min was chosen as the design flow. A higher flow rate was not selected because the amount of fine particles in the JMC prepared material was unknown and head loss/pressure build-up in the columns was a concern.

The system design parameters were calculated as follows:

Treatment canisters: 1 ft diameter, 2.5 ft long, 2 ft of Pd/Fe
$Q = 6$ gal/min $= 0.0134$ $ft^3/s$
$\theta = 0.6$ porosity
Pd/Fe density = 7.87 $gm/cm^3$ metal only
2.60 $gm/cm^3$ packed density

TCE ½ life = 23 s

Residence time: $$t_{res} = \frac{\theta A L}{Q} = \frac{(0.6)\ (0.5\ ft^2)\ \pi\ (2.0\ ft)}{0.0134\ ft/s} = 70\ s$$

Using two canisters, $t_{res} = 2\ (70\ s) = 140\ s$, $\frac{140}{23}$ = half-lives of TCE (98% removal efficiency)

Required packed volume of Fe/Pd: $$v = \frac{Q t_{res}}{\theta} = \frac{(0.0134\ ft^3/s)\ (140\ s)}{0.6} = 3.13\ ft^3$$

Mass of packed Pd/Fe:

$$3.13\ ft^3 \times \frac{m^3}{35.3\ ft^3} \times \frac{2600\ kg}{m^3} = 230\ kg\ Pd/Fe \approx 510\ lb \text{ for two canisters}$$

or,

$$(0.5\ ft)^2\ \pi\ (2.0\ ft)\ (0.40) = 0.628\ ft^3 \text{ Pd/Fe per canister (metal only)}$$

The system was designed, therefore, for 6 gal/min to flow through two canisters connected in series. Once in the field, in order to limit head loss, it was decided to split the input flow of 6 gal/min such that 3 gal/min were conducted through each Pd/Fe canister after which the flows were combined for reinjection.

### 7.5.2 Phase 1 - Full-Scale Experiment with JMC-Prepared Pd/Fe

The JMC-prepared Pd/Fe was packed in plastic bags and shipped in 5 gal plastic buckets. This Pd/Fe shipment was accepted based on a subsample, supposedly representative of the bulk material, that had been supplied to the ORNL laboratory. That subsample did not demonstrate the reactivity expected, being approximately ½ as reactive. It was decided that the lower reactivity would be compensated for by the somewhat conservative design of the field system. A backup system (GAC) for the Pd/Fe had already been selected. Moreover, schedule and funding considerations would not accommodate delays in starting the recirculation test. Consequently, the material was accepted and the field trial was initiated.

Knowing that excessive air contact was deleterious to the Pd/Fe, the field technicians were instructed to pack the Pd/Fe with minimal air contact and to immediately begin flow of deoxygenated water through the columns. Water was deoxygenated by being pumped through columns of iron prior to the Pd/Fe. Deoxygenation was verified with field measurements of DO. A flow of deoxygenated water, using the horizontal well recirculation system at the PORTS CTS, was continued for three weeks to determine whether clogging of the columns would be a problem. When no clogging occurred, the treatment trailer was moved to X-701B and the contaminated water was directed through the columns at a rate of approximately 6 gal/min. Effluent samples collected after 1½ hrs and again at 8 hrs showed essentially no treatment of VOCs. At this point, the flow rate was decreased by a factor of 10 such that column residence time was approximately
30 min.

Once the poor treatment results were observed, the drums of unused Pd/Fe obtained from JMC were inspected and the personnel who had packed the Pd/Fe columns were questioned. It was noted that from drum-to-drum the Pd/Fe was highly variable in appearance and moisture content. Some of the Pd/Fe was orange in color. All of it was distinctly brown as opposed to appearing black and metallic as expected. The moisture content was also highly variable. Some of the drums were wet, with water droplets visible within the material. Other drums were quite dry. It was also observed that hardened clumps were interspersed with the finer material. The Pd/Fe was supposed to be 40 mesh and JMC had been requested to remove as many finer particles as possible.

To test the reactivity of the material, a series of batch experiments were quickly performed in the field. Ten grams of the unused Pd/Fe were added to vials that were then filled with 40 mL of water from the groundwater extraction system. The vials were gently shaken for 5, 10, 15, 20, and 30 min at which point aliquots were taken for analysis. The results showed neither the reactivity nor the internal consistency expected. In other words, the 10 min sample did not dechlorinate twice as much TCE as the 5 min sample and so on. Indeed, there was little pattern to the data. Subsamples were then collected and shipped to ORNL for additional testing. Testing at ORNL showed similar results.

Unused Pd/Fe prepared by JMC and left over from a previous experiment (Liang et al. 1996) was also obtained from storage at PORTS. Batch tests showed that it was at least twice as reactive as the new material. A sieve analysis was then performed on the two preparations. The new material was 5-10% > than 40 mesh as compared to previously received Pd/Fe which was 22% > 40 mesh. Moreover, the new material had more than twice as much mass in the <60 mesh fraction even though JMC had been requested to remove a greater percentage of fine particles.

In the meantime, additional data from the treatment system became available. With a flow of 0.6 gal/min, a 67 ppm TCE influent was reduced to 17 ppm. While such data demonstrated that some treatment was occurring, the horizontal recirculation test could not be conducted at such a low flow rate. Consequently, the decision was made to switch to carbon for VOC removal. The iron columns were retained for removal of $Tc^{99}$.

Additional measurements were made on the various JMC-prepared materials including a total analysis for Pd. The previously-used sample (Liang et al. 1996) reportedly contained 0.36-0.52% Pd. Two separate drums of the new material showed 0.0325-0.047% Pd and 0.0098-0.012% Pd respectively. These data indicate that the desired coverage (0.05%) was obtained for the previously-received preparation but that the Pd content was both low and highly variable in the new material. JMC personnel stated that the only real difference in the two preparations was that the batch size was quite a bit larger for the new material.

### 7.5.3 Effects on Other Chemical Constituents

The purpose of this section is to convey additional data related to the use of Pd/Fe during the 1st phase of field testing. Only a minor amount of data were collected regarding the effect of the iron - Pd/Fe treatment system on other groundwater constituents. The following results, however, may be useful for predicting long-term effects. Samples were collected from 12 monitoring wells that were located in and near the horizontal recirculation flow-field and from the influent and effluent of each treatment column.

The data discussed in this section are all from field measurements performed within a few minutes to a few hrs of sample collection. The analyses were all performed with kits available from Hach Inc. (Loveland, Colorado).

**Chloride** - Chloride in the monitoring wells ranged from approximately 20 to 60 mg/L. The influent to the treatment system was approximately 35 mg/L. Effluent from the iron columns showed a slight increase (to 40 to 50 mg/L). Effluent from one of the Pd/Fe columns ranged to 82 mg/L suggesting that the rinse of the HCl wash performed by JMC during manufacture of the Pd/Fe was inadequate. If the Pd/Fe had been stored at low pH, significant corrosion might have occurred during storage. There was no increase in chloride through the other Pd/Fe column which may be explained by the varying conditions of the Pd/Fe as described previously.

**Sulfate** - Sulfate in the monitoring wells ranged from approximately 130 to 300 mg/L. Influent to the treatment system was approximately 215 mg/L. There was no evidence of sulfate removal in the iron columns but concentrations decreased to approximately 165 mg/L after passage through the Pd/Fe. Precipitation of ferrous sulfate in the iron columns was expected but obviously had not occurred to any significant extent over the length of this experiment. Time and funding did not permit an evaluation of the removal mechanism in the Pd/Fe.

Others (Mackenzie et al. 1997) have reported a grey-to-white precipitate attributed to ferrous sulfates and carbonates. In this experiment, neither the iron nor the Pd/Fe showed any evidence of this grey color unless there was exposure to air, even after three months of field use in a high sulfate environment.

**Alkalinity** - Alkalinity in mg/L as $CaCO_3$ in the monitoring wells ranged from 71 (well X701-80G) to 665 (well X701-75G). The influent to the treatment system was approximately 100 to 150 mg/L which increased to approximately 250 mg/L through the iron columns but did not change as it passed through the Pd/Fe. This increase in alkalinity may be an indication of microbial activity. More study, however, is needed to evaluate this speculation.

**Ferrous iron** - The detection limit for the ferrous iron analysis was approximately 0.1 mg/L. Ferrous iron in the monitoring wells was either not detected or found in trace concentrations with the exception of well X701-77G which contained approximately 8 mg/L. The ferrous iron influent concentration to the treatment system was unexpectedly high, 15 to 20 mg/L. As expected, ferrous iron increased throughout the treatment system, increasing to 110 to 125 mg/L as it passed through the iron columns and to 200 to 210 mg/L after passage through the Pd/Fe.

### 7.5.4 Phase 2 - Small-Scale Experiment with JMC-Prepared Pd/Fe

Once the data obtained in Sect. 7.5.2 were provided to JMC, they agreed to permit project personnel to witness the preparation of the Pd/Fe. JMC and RCT agreed to provide the funding and a smaller-scale field test was designed. The goal of the smaller-scale test was to obtain some long-term field data with Pd/Fe without jeopardizing the data collection or operation of the full-scale horizontal recirculation test which was successfully operating with iron and carbon treatment of the mixed waste influent.

Accordingly, a dilution system was built in a trailer adjacent to the treatment system. Treated water was taken from the carbon system and used to dilute incoming untreated water. This was done so that lower concentrations and lower volumes of TCE would be treated. The horizontal recirculation system was yielding water with 200 ppm TCE which was somewhat higher than expected. None of the laboratory work associated with Pd/Fe had been performed at such high concentrations. Hence, a lower concentration was desired so that a direct comparison could be made to the laboratory results. The smaller-scale test was designed such that the treated effluent went back through the carbon to eliminate any concerns about reinjecting partially treated water.

The preparation of the Pd/Fe at JMC's facility was witnessed by personnel from ORNL, RCT, and UofA. Instead of using 40-mesh iron, as used previously, 40-60 mesh, spherical, electrolytic iron (Alfa-Aesar, Ward Hill, MA) was used. Alfa-Aesar iron was selected because of excellent batch study results obtained at UofA. Discussions revealed that JMC had departed from the published procedure in several ways. They had used a sodium salt rather than a potassium salt and had not thoroughly washed the iron with acid prior to palladization (personal communication Kevin Donnegan and Bob McNair, JMC, to Nic Korte, ORNL, October 22, 1996). Use of the Na salt was not likely to pose a problem but an inadequate acid rinse probably was. At this time, JMC agreed to use a 1N HCl rinse as opposed to the 6N HCl that had been published (Muftikian et al. 1995). This acid rinse was to be followed by a thorough water rinse.

The on-site observations revealed that there were a number of shortcomings with respect to the preparation method at JMC. The following is an unprioritized list of the potential problems that were observed:

- The stirrer blade in the reactor did not agitate the bottom. Thus, only the top layer of iron was well-mixed.

- Deionized water was not readily available and there were several long periods of waiting while it was obtained. In the meantime, the iron corroded with air, water or acid.

- The reactor was not bottom-draining, meaning that a pipe had to be inserted to remove the excess water. The pipe could not remove the bottom 1 to 3 in. of solution. Thus, the acid rinse was very inefficient and the quality of the preparation of the iron surface was questionable. Moreover, the water rinse to remove the acid had to be conducted several times to raise the pH above that (2.54) of the palladizing solution. Thus, instead of a simple acid rinse and drain, acid was added and then drained as much as possible followed by several more rinses with water. Two hrs passed from the time the iron was added to the acid until the palladizing step could be performed. In addition, the rinse water was not deoxygenated so the iron would have been subject to much more corrosion than at the laboratory.

An obvious result of this preparation process was that a clear solution was not obtained following the palladization step. Instead, the solution was yellow-green which was indicative of a high concentration of dissolved ferrous iron. Chief among the concerns regarding the high concentration of ferrous iron is that it could reduce the $Pd^{+4}$ to Pd metal without the metal plating on the iron surface.

The packaging of the Pd/Fe was not observed but discussions with plant personnel indicated that previous batches had been subjected to significant air contact. It was requested, therefore, that this material be packaged wet and immediately shipped to PORTS. Samples were taken to ORNL and to UofA for batch testing. The batch testing again showed approximately half of the reactivity as the laboratory-prepared Pd/Fe.

The Pd/Fe preparation that was observed accounted for half of what was to be used in this test. A second batch was prepared the next day in which JMC personnel stated that air contact and time delays were much shorter. Because the batches were to be used in different columns, one item of interest was to determine if there was a performance difference.

The columns, as shown in Fig. 7.2, were cleaned and prepared for the Pd/Fe. Sand in the lids and all screens were removed and replaced with fresh materials. Less than half of each column was to be used. The procedure for packing the columns was to connect them to the treatment system and begin the flow of water until it just began to appear in the half of the column to which the Pd/Fe was to be added. At that point, the containers (sealed, plastic jars) sent by JMC were opened and the Pd/Fe added to the column. Once the Pd/Fe was added, the lid was put on the column, the column was rotated so that the Pd/Fe was now at the bottom and immersed in the deoxygenated water. Water flow through the system was started immediately. The entire packing process required less than 10 min. Visual inspection of the Pd/Fe indicated no obvious deterioration from the samples that were collected during manufacture. There was also no obvious difference in the batches from the two preparation periods. There was approximately 10% less material in batch 2. Thus, column TT01-Pd contained approximately 12 in. of Pd/Fe and column TT02-Pd contained approximately 10 in.

Data from this test are presented in Table 7.4. The system flow rate was approximately 0.5 gal/min and the influent concentration was nominally 1 ppm [1000 parts per billion (ppb)]. Based on the reactivity measured in the laboratory, the expectation was that the concentration reduction would be approximately 5 half-times. In other words, a concentration of 1000 ppb would be reduced to approximately 30 ppb (e.g., 1000-500-250-125-62.5-31.75). It is evident from the table that the amount of reduction approximated that expected from the laboratory measurements. The other primary feature of interest was that column TTO2-Pd generally outperformed TTO1-Pd. In 17 of the 20 measurement periods, there was greater reduction with TT02-Pd. The last nine measurements, constituting almost 46 hrs of operation all showed TT02-Pd with a lower effluent concentration. It is noted that the influent to TTO1-Pd was slightly higher than for TTO2-Pd, but the differences were 5 to 10% not factors of 5 to 10 as observed in the effluent. Also, recall that there was approximately 10% less Pd/Fe in TT02-Pd. The number of half-time reductions is plotted in Fig. 7.5. The differences seem especially striking in the last nine measurements where the data suggest successively poorer treatment with TTO1-Pd. It should be noted that in the final 24-hr period, there was a significant drop in air temperature (from 55° to 20°) and the dechlorination reaction is temperature sensitive (West et al. 1996) . Thus, the improved performance of TT02-Pd suggests, but certainly does not prove, that Pd/Fe performs better when prepared under more controlled conditions (principally less air contact).

Encouraged by this success, the decision was made to decrease the dilution and increase the influent concentration. Unfortunately, an error was made with the valving in the dilution system. The columns drained and air was pumped through them overnight. Upon resaturation with water, treatment was very poor and the experiment was terminated.

The columns were then taken apart and inspected. The Pd/Fe had solidified. When the column was drained and then the flow slowly resumed, it was evident that water was passing through only a small part of the bulk mass. Indeed, the Pd/Fe was now so hard that it had to be chipped out. Some of this Pd/Fe was removed, ground, and shipped to the laboratory. The half-life was now reduced by another factor of two. However, this was still approximately twice as reactive as was being observed in the field indicating that poor contact between the contaminated groundwater and the solidified mass of Pd/Fe was primarily responsible for the deteriorated performance.

The phase 2 test was considered to be a very positive development. The data demonstrated that laboratory kinetic data could be related to field reactivity and that Pd/Fe from a commercial manufacturing environment could be shipped and packaged without apparent loss of performance. In addition, the differences observed between the two production batches suggested that the observations at JMC regarding air

**Table 7.4. Phase 2 results, ppb - low concentration influent, 0.5 gal/min**

| Time, h | Influent to TT01 | Influent to TT02 | Effluent from TT01-Pd | Effluent from TT-02-Pd | Total gal |
|---|---|---|---|---|---|
| 0.25 | 938 | 874 | 46 | 59 | 15 |
| 1.25 | 1050 | 873 | 32 | 22 | 47 |
| 2.5 | ----- | ----- | 105 | 36 | 125 |
| 4.7 | 1224 | 1217 | 63 | 13 | 271 |
| 7.8 | 1037 | 990 | 33 | 7 | 457 |
| 23.7 | 1039 | 986 | 93 | 69 | 1411 |
| 27.3 | 1420 | 1441 | 66 | 32 | 1599 |
| 31.5 | 1537 | 1496 | 50 | 16 | 1856 |
| 34.7 | 1504 | 1450 | 67 | 43 | 2049 |
| 47 | 1478 | 1338 | 44 | 66 | 2780 |
| 51 | 1282 | 1264 | 44 | 57 | 3020 |
| 55 | 1279 | 1202 | 53 | 6 | 3255 |
| 57 | 1210 | 1067 | 63 | 26 | 3374 |
| 70 | 1040 | 1053 | 74 | 10 | 4092 |
| 74 | 928 | 873 | 74 | 23 | 4334 |
| 78 | 1092 | 984 | 92 | 16 | 4581 |
| 80.5 | 987 | 960 | 108 | 81 | 4733 |
| 93 | 919 | 760 | 128 | 17 | 5438 |
| 98 | 848 | 815 | 183 | 10 | 5744 |
| 101 | 726 | 698 | 161 | 49 | 5929 |

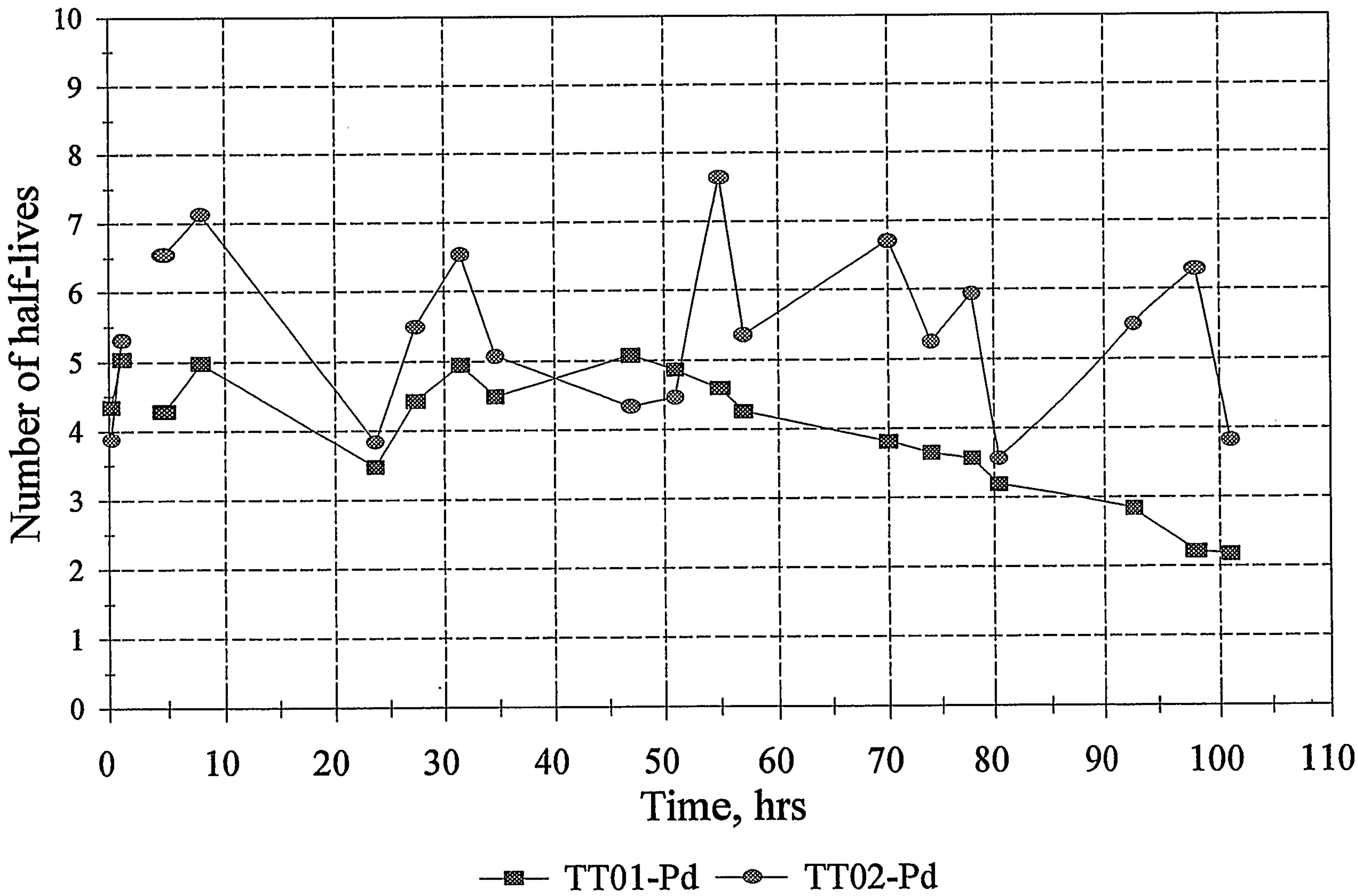



Fig. 7.5. Number of times influent TCE concentration was reduced by ½ as it passed through the Pd/Fe treatment columns.

contact during manufacture might account for the difference between the performance of laboratory and bulk-production.

### 7.5.5 Phase 3 - Small-Scale Experiment with Pd/Fe Prepared On Site

A decision was made to produce some Pd/Fe in the field without any air contact so that the best laboratory-measured reactivity might be duplicated in the field columns. The overall project was nearing its scheduled termination, however, and only 10 to 12 days were available for the test. Nevertheless, JMC agreed to provide the base iron and the Pd salt. Accordingly, a small reactor was built as shown in Fig. 7.6. The reactor was approximately 30 in. long and 8 in. in diameter with eight baffles arranged in a criss-cross fashion. The reactor was mounted in a cradle so that it would rotate about its center. During rotation, the baffles would assist in breaking up and mixing the Pd/Fe. Each side of the reactor had a gauge and pressure relief valve such that any buildup of hydrogen could be released. There was also an inlet for bathing the material in nitrogen.

The process used was as follows:

- The reaction vessel was purged with nitrogen and 30 kg of Alfa-Aesar iron was added. A positive nitrogen pressure was then maintained throughout the remainder of the procedure.

- Deionized water was deoxygenated by vigorous bubbling with nitrogen. A nitrogen pressure was maintained over three vessels of water. One of these was used for the acid rinse solution, another for the water rinse, and the third for the palladization solution.

- Three gal of deoxygenated 10% HCl were added. The cylinder was then rotated repeatedly for 20 min to perform the acid wash.

- The acid was drained from the bottom with a positive pressure of nitrogen maintained at all times. Draining required approximately 5 min.

- A single water rinse, with two gal of deionized, deoxygenated water was performed. The column was rotated for approximately 5 min and drained as with the acid rinse.

- 163 g of 18.44% Pd (sodium chloropalladate, a hydrated salt, assay provided by JMC), was added to three gal of deionized, deoxygenated water. This vessel was stirred with a magnetic stirrer for approximately 5 min and the entire contents were added to the iron in the reactor vessel.

# Pd Fe Production Chamber

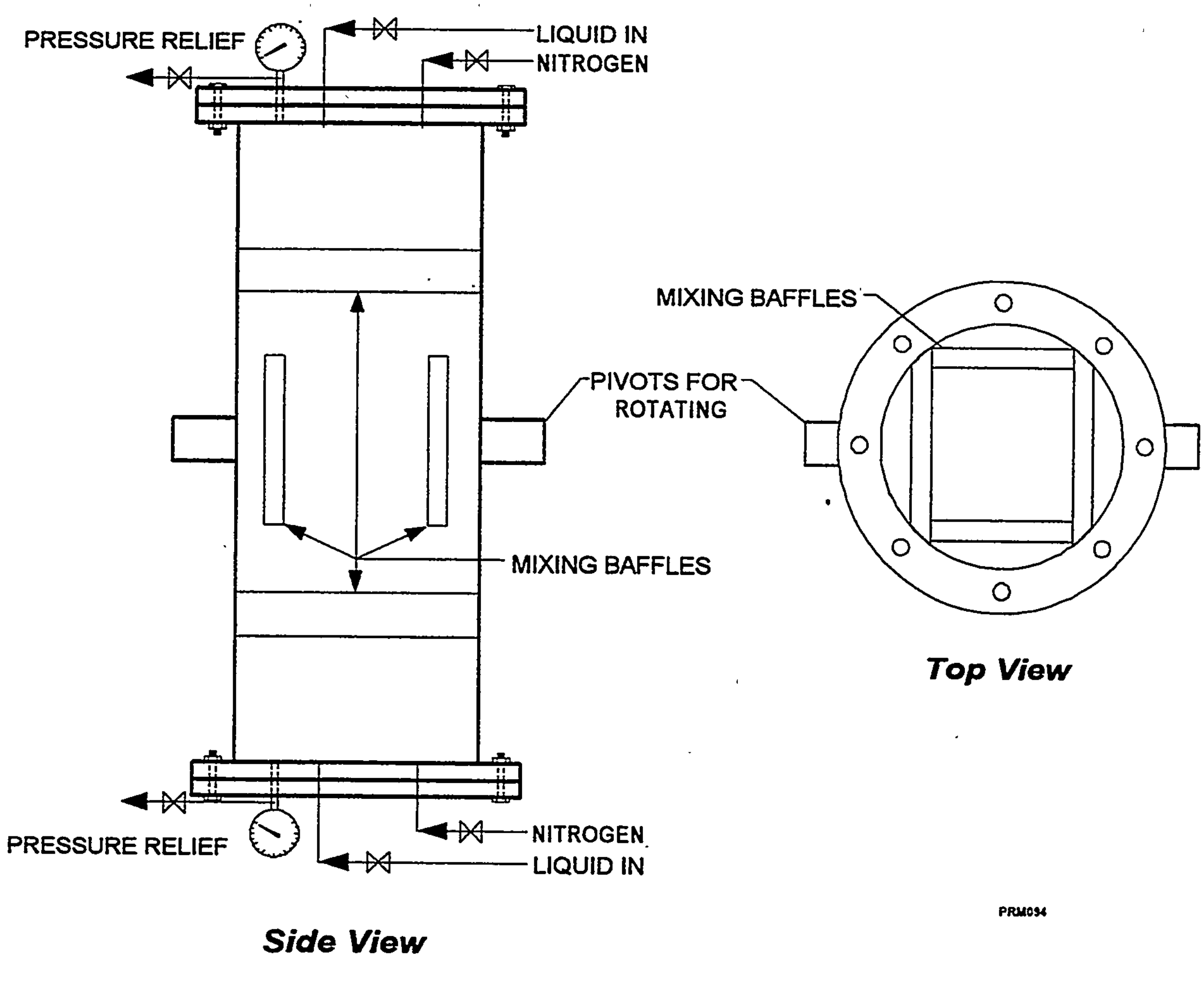



Fig. 7.6. Pd/Fe production chamber used for field bulk preparation of Pd/Fe.

- The reactor vessel was then rotated repeatedly. After approximately 5 min, the supernatant appeared clear and was drained off under nitrogen pressure.

- The Pd/Fe was immediately transferred to a nitrogen-purged treatment canister. After several minutes a small amount of black precipitate formed in the supernatant. (Subsequent analyses by JMC showed that the precipitate was pure Pd. Nevertheless, bulk analysis of the Pd/Fe indicated that coverage was the expected 0.05%. Because Pd was added in slight excess, it appeared that approximately 90% plated on the iron). The lid to the canister was screwed on and the contaminated water flow was initiated.

The entire production process required approximately 30 min and the only air contact that could have occurred was when the Pd/Fe was carried to the treatment canister. That activity required less than 1 min.

During this experiment, only 4 to 6 in. of Pd/Fe were to be used. Some baffles and screens were added to the field canisters to hold the material in place. A subsample of the material was also collected and shipped to the ORNL laboratory. Laboratory kinetic data (Fig. 7.7) indicated that this material was similar in reactivity to laboratory-prepared Pd/Fe, that is, twice as reactive as that provided by JMC and used in phase 2. In other words, the careful exclusion of oxygen did improve the reactivity of the Pd/Fe.

Treatment using the packed canister was then initiated. The preliminary results, those from the first 1 to 3 hrs of operation, indicated that treatment was approximately at the level expected. At that point, however, the treatment deteriorated significantly and remained at less than 50% removal for the next week. (Flow through the column was continued in order to observe whether the Pd/Fe solidified in the absence of the air contact that occurred in phase 2.) When the column was opened, there was no apparent solidification or oxidation of the Pd/Fe and no apparent reason why treatment was so much less than expected. To check for preferential pathways, a slow stream of nitrogen was injected into the bottom of the column. It was observed that all of the gas escaped around the side of the baffles instead of passing through the Pd/Fe. As noted above, these baffles and screens were inserted to hold the Pd/Fe in place because the columns were designed to hold quite a bit more material. Unfortunately, these did not seal as tightly as was necessary and permitted the contaminated water to flow around the Pd/Fe. At this point, funds for the overall field experiment had been expended and the project was terminated.

Although the field-prepared material was not tested under field conditions during phase 3, several important lessons were learned. First, although the supernatant was

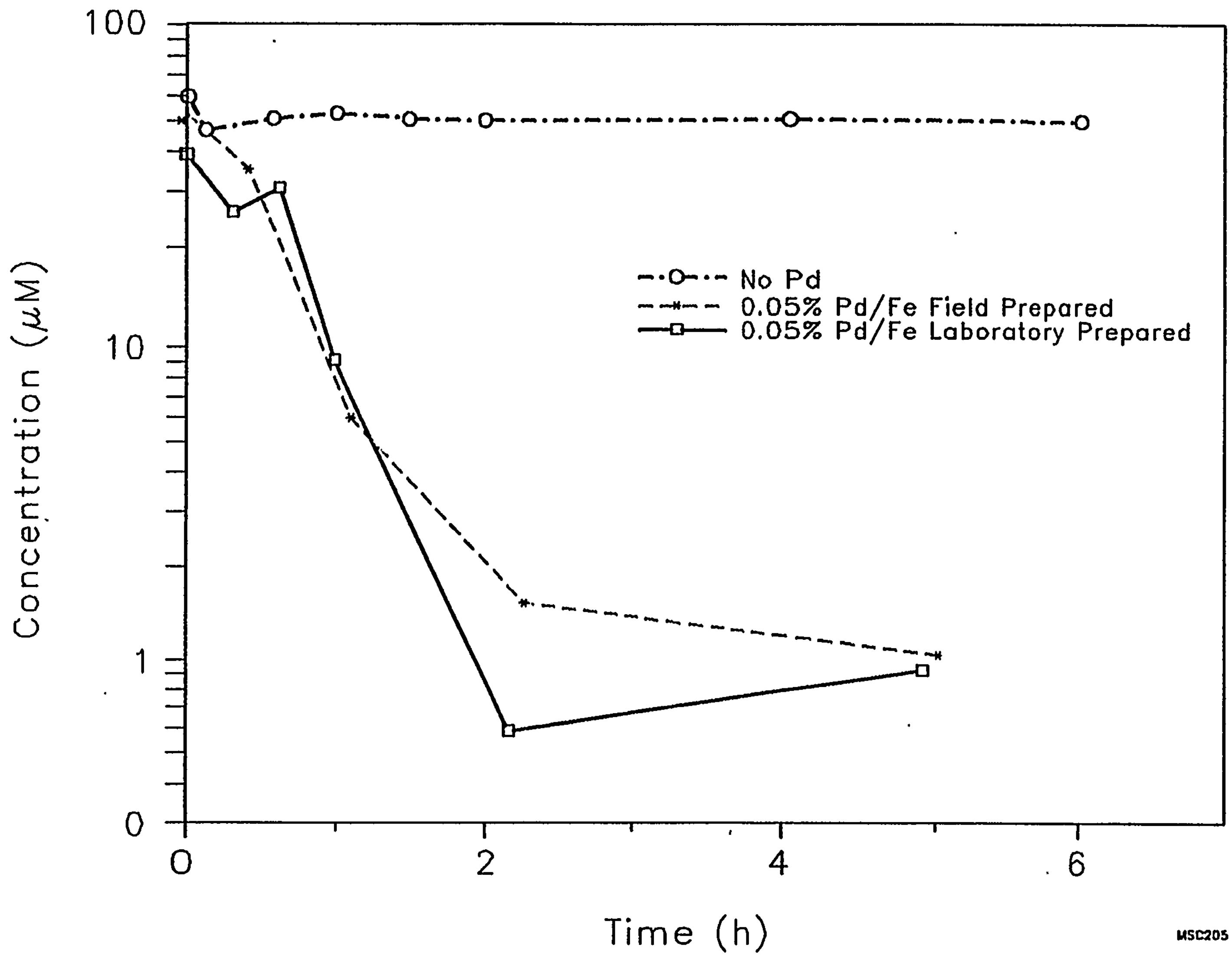



Fig. 7.7. Comparison of field and laboratory prepared Pd/Fe in laboratory batch tests.

clear, some Pd (10%) did not plate on the iron. Whether or not Pd precipitation is occurring in the laboratory is unknown. Perhaps the more rapid laboratory plating step results in more efficient plating or precipitation may be occurring but the amounts are too small to be noticed. Second, no solidification occurred, although the Pd/Fe was in contact with water for more than a week. Third, even with the improvements in the production procedure, it was not possible to perform the plating and rinsing steps nearly as quickly as in the laboratory.

## 7.6 Carbon Treatment

As noted in Sects. 7.2.2 and 7.5.2, the primary treatment system for the project was zero-valence iron for the removal of $Tc^{99}$ and carbon for the removal of VOCs. The groundwater flow was routed through the iron columns as shown in the treatment trailer schematic (Fig. 7.1) and then directed to three 55-gal drums containing GAC. The GAC was purchased from Calgon Carbon Corp., (Pittsburgh, Penn.).

The three GAC drums were connected in series and VOC concentrations were monitored in the influent and effluent to each drum. When the capacity of the first drum was used up (effluent TCE concentrations equal to the influent concentrations), the first drum was removed from service, and an unused drum was added at the end of the line. Eventually, bulk carbon that was in storage at PORTS was used. Spent carbon was simply vacuumed from the drums and replaced with new carbon. An iron/carbon system such as this could be deployed in the arm of the horizontal well and provide long-term and convenient simultaneous treatment of a mixed waste stream without generation of a mixed waste.

Treatment continued for 1781 hrs or approximately 74 days. Treated water that was reinjected totaled 584,418 gal. The average influent concentration was approximately 194 mg/L of TCE. Effluent TCE concentrations from the last drum in the line were typically less than 0.3 ppm. Thus, the total amount of TCE that was removed was approximately 78 gal. Data summarizing the treatment are shown in Table 7.5.

Longer operation would be necessary to determine if there is a decline in the concentration of TCE in the extracted water as suggested by Fig. 6.4. It is also possible that such a large mass of DNAPL is present that pumping for several years might be required to observe a significant decline.

# Table 7.5. X-701B water sample data: TCE concentration, mg/L

Begin @ 1000, 29-Sep-96

End @ 1350, 12-Dec-96, Elapsed time: 1781 hours, treated volume: 584,418 gal

| Sample Date | Sample time | Elapsed time, h | Treated volume, gal | Sample Nos. | Well 09G | Well 71G | Well 72G | Well 73G | Well 74G | Well 75G | Well 76G | Well 77G | Well 78G | Well 79G | Well 80G | Well 81G | Treatment influent | Treatment effluent | TCE treated daily, gal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5-Sep-96 | 1400 | 0 | 0 | W-006 - W-012 | NA | 0.7 | 66 | 480 | 586 | 400 | 119 | 88 | 381 | 0.1 | 0.1 | 20 | NA | NA | |
| 28-Sep-96 | 1400 | 0 | 0 | W-023 - W-026 | NA | NA | NA | 431.2 | 504 | 425.6 | 86.7 | NA | NA | NA | NA | NA | NA | NA | |
| 29-Sep-96 | 1740 | 7.4 | 2,757 | W-027 - W-030 | NA | NA | NA | 513.9 | 636.5 | 401.5 | 101.2 | NA | NA | NA | NA | NA | 139.9 | 0.1 | 0.28 |
| 30-Sep-96 | 1510 | 29 | 10,805 | W-031 - W-039 | NA | NA | NA | 582.2 | 795.4 | 449 | 156.9 | 98 | 575.6 | 0 | 0.2 | 43.6 | 208 | 0 | 1.23 |
| 30-Sep-96 | 1720 | 31.3 | 11,522 | W-040 - W-043 | NA | NA | NA | 489.3 | 630.9 | 693.8 | 100.7 | 100.7 | NA | NA | NA | NA | 204 | 0 | 0.11 |
| 30-Sep-96 | 2240 | 34.3 | 12,626 | W-044 - W-047 | NA | NA | NA | 438.7 | 529.6 | 692.2 | 86.7 | 86.7 | NA | NA | NA | NA | NA | NA | |
| 1-Oct-96 | 830 | 46.5 | 17,082 | W-048 - W-056 | NA | NA | NA | 584.6 | 806.3 | 680.9 | 120.5 | 120.5 | 664.7 | 0.3 | 0.2 | 46.9 | 228 | 0 | 0.75 |
| 1-Oct-96 | 1720 | 55.3 | 20,174 | W-057 - W-064 | NA | NA | NA | 590.9 | 720.6 | 778.6 | 138.1 | 55.2 | 621.8 | NA | 0.2 | 47.6 | NA | NA | |
| 2-Oct-96 | 900 | 71 | 25,902 | W-065 - W-072 | NA | NA | NA | 463.1 | 730.1 | 626.2 | 93.1 | 24.6 | 559.7 | NA | 0.4 | 62.2 | 136.5 | 0.1 | 0.58 |
| 2-Oct-96 | 2005 | 83.1 | 30,454 | W-073 - W-080 | NA | NA | NA | 534.3 | 792.3 | 725.4 | 86.2 | 23.1 | 660.9 | NA | 1.5 | 56.9 | 246.1 | 0 | 0.83 |
| 3-Oct-96 | 1000 | 96 | 35,117 | W-081 - W-088 | NA | NA | NA | 578 | 698 | 726 | 132 | 23 | 696 | NA | 0.7 | 54 | NA | NA | |
| 3-Oct-96 | 1800 | 104 | 38,043 | W-089 - W-096 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | |
| 4-Oct-96 | 840 | 118.5 | 43,347 | W-097 - W-105 | 792.5 | NA | NA | 215 | 837 | 780 | 130 | 10.4 | 616.7 | NA | 0.3 | 63.3 | 179.4 | 0.3 | 0.70 |
| 4-Oct-96 | 1800 | 128 | 46,822 | W-106 - W-115 | 783.1 | NA | NA | 224.2 | 879.5 | 752 | 103.6 | 18.6 | 688.1 | 0.3 | 0.3 | 67.1 | 200.5 | 0.3 | 0.51 |
| 5-Oct-96 | 919 | 143 | 49,200 | W-116 - W-125 | 778.4 | NA | NA | 345.5 | 872.6 | 739 | 98.5 | 11 | 620.2 | 0.4 | 0.8 | 77.3 | 211.1 | 0.07 | 0.37 |
| 5-Oct-96 | 1700 | 151 | 52,226 | W-126 - W-135 | 717.5 | NA | NA | 354 | 788 | 746 | 113.6 | 12.5 | 594.7 | 0 | 0.5 | 70.5 | 227 | 0.27 | |
| 6-Oct-96 | 830 | 166.5 | 57,652 | W-136 - W-145 | 701.9 | NA | NA | 755 | 1045 | 748 | 169 | 15.7 | 617.5 | 0 | 0.8 | 75.4 | 221.4 | 0.6 | 0.89 |

## Table 7.5. (continued)

| Begin @ 1000, 29-Sep-96 | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| End @ 1350, 12-Dec-96, Elapsed time: 1781 hours, treated volume: 584,418 gal | | | | | | | | | | | | | | | | | | | |
| Sample Date | Sample time | Elapsed time, h | Treated volume, gal | Sample Nos. | Well 09G | Well 71G | Well 72G | Well 73G | Well 74G | Well 75G | Well 76G | Well 77G | Well 78G | Well 79G | Well 80G | Well 81G | Treatment influent | Treatment effluent | TCE treated daily, gal |
| 6-Oct-96 | 2005 | 178 | 61,867 | W-146 - W-155 | 516 | NA | NA | 718.6 | 939.9 | 814 | 202.5 | 13.9 | 702.2 | 0 | NA | 75.3 | NA | 0.03 | |
| 7-Oct-96 | 850 | 191 | 66,462 | W-156 - W-165 | 810 | NA | NA | 750 | 930 | 811 | 220 | 13 | 724 | 0 | 0.8 | 79 | 223 | 0.04 | 0.76 |
| 7-Oct-96 | 1600 | 198 | 69,042 | W-166 - W-175 | 782 | NA | NA | 723 | 996 | 741 | 229 | 12 | 730 | NA | 0.7 | 86 | 219 | 0.02 | 0.42 |
| 8-Oct-96 | 840 | 214.5 | 75,122 | W-176 - W-184 | 813 | NA | NA | 739 | 905 | 729 | 233 | 15 | 717 | NA | 0.9 | 78 | 215 | 0.33 | 0.96 |
| 8-Oct-96 | 1700 | 223 | 78,127 | W-185 - W-194 | 837 | NA | NA | 699 | 927 | 687 | 231 | 12 | 748 | 0 | 1.2 | 82 | 212 | 0.19 | 0.47 |
| 9-Oct-96 | 930 | 239.5 | 84,006 | W-195 - W-204 | 769 | NA | NA | 685 | 973 | 622 | 215 | 11 | 760 | 0 | 1.1 | 80 | 194 | 0.07 | 0.84 |
| 9-Oct-96 | 1730 | 247.5 | 86,812 | W-205 | NA | NA | NA | NA | NA | 630 | NA | NA | NA | NA | NA | NA | 232 | 0.02 | 0.48 |
| 10-Oct-96 | 1030 | 264.5 | 92,977 | W-206 - W-207 | NA | NA | NA | NA | NA | 672 | NA | 11 | NA | NA | NA | NA | 229 | 0.02 | 1.04 |
| 11-Oct-96 | 1130 | 289.5 | 100,527 | W-208 - W-216 | 747 | NA | NA | 744 | 1006 | 583 | 238 | 11 | 767 | 0.1 | 0.6 | 79 | 239 | 0.05 | 1.33 |
| 12-Oct-96 | 930 | 311.5 | 108,632 | W-217 - W-226 | 730.9 | NA | NA | 622.4 | 911.5 | 613.7 | 213.3 | 7.8 | 709.7 | 0.08 | 1.5 | 81.8 | 219.3 | 0.02 | 1.31 |
| 12-Oct-96 | 1755 | 320 | 111,258 | W-239, 240 | NA | 17.9 | 95.7 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | |
| 13-Oct-96 | 900 | 335.5 | 116,647 | W-247 - W-258 | 811.9 | 19.6 | 91.5 | 763.9 | 941 | 564.4 | 216.3 | 6.4 | 714.9 | 0.06 | 1.8 | 83.2 | 192.5 | 0.09 | 0.76 |
| 14-Oct-96 | 1055 | 361 | 128,440 | W-264 - W-274 | 866.1 | 21.9 | 94.1 | 748.6 | 837.8 | 539.2 | 231.6 | 6 | 715.7 | NA | 1.8 | 88.6 | 214.4 | 0.02 | 1.86 |
| 15-Oct-96 | 1330 | 387.5 | 137,868 | W-277 - W-287 | 772.3 | 21.9 | 112.2 | 714.1 | 730.4 | 487.2 | 230.5 | 5.8 | 564.8 | NA | 1.9 | 70.6 | 206.4 | 0.1 | 1.43 |
| 16-Oct-96 | 1330 | 411.5 | 139,396 | W-288 - W-298 | 935.8 | 33.8 | 95.4 | 909.2 | 752.9 | 628.5 | 262.3 | 6.1 | 805.2 | NA | 1.7 | 81.1 | 249.3 | 0.15 | 0.28 |
| 17-Oct-96 | 1740 | 439.4 | 159,317 | W-299 - W-309 | 225 | 2.3 | 82.5 | 853 | 864 | 618 | 308 | 5.2 | 847 | NA | 3.6 | 7.2 | 225 | 0.2 | 3.30 |
| 18-Oct-96 | 1430 | 460.5 | 163,596 | W-310 - W-320 | 911 | 29.5 | 75.5 | 813 | 838 | 643 | 322 | 4.7 | 858 | NA | 2.5 | 74.9 | 249 | 0.07 | 0.79 |

**Table 7.5. (continued)**

Begin @ 1000, 29-Sep-96

End @ 1350, 12-Dec-96, Elapsed time: 1781 hours, treated volume: 584,418 gal

| Sample Date | Sample time | Elapsed time, h | Treated volume, gal | Sample Nos. | Well 09G | Well 71G | Well 72G | Well 73G | Well 74G | Well 75G | Well 76G | Well 77G | Well 78G | Well 79G | Well 80G | Well 81G | Treatment influent | Treatment effluent | TCE treated daily, gal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20-Oct-96 | 1000 | 504 | 164,609 | W-321 - W-331 | 859 | 25.5 | 71.7 | 813 | 834 | 586 | 309 | 5.7 | 860 | NA | 2.6 | 66 | 295 | 0.17 | 0.22 |
| 20-Oct-96 | 1850 | 513 | 165,932 | W-332 - W-340 | 897 | NA | NA | 830 | 838 | 556 | 278 | 5.2 | 781 | NA | 2.4 | 65.2 | 224 | NA | 0.22 |
| 21-Oct-96 | 1900 | 537 | 169,308 | W-341 - W-351 | 929 | 23.9 | 75.8 | 834 | 866 | 552 | 286 | 6.3 | 806 | NA | 2.7 | 66.1 | 233 | 0.12 | 0.58 |
| 22-Oct-96 | 1627 | 558.2 | 176,920 | W-352 - W-362 | 901.2 | 21.2 | 61.9 | 743 | 801.3 | 492.1 | 223.7 | 10.7 | 751 | NA | 2.5 | 65.7 | 153.7 | 0.1 | 0.86 |
| 23-Oct-96 | 1443 | 580.8 | 184,679 | W-363 - W-373 | 931.6 | 20.7 | 67.4 | 852.2 | 815.4 | 616.3 | 231.7 | 10.4 | 855.5 | NA | 2 | 66.2 | 175.2 | 0.1 | 1.00 |
| 24-Oct-96 | 1100 | 602 | 191,760 | W-374 - W-384 | 186.1 | 15.8 | 46.5 | 568.7 | 574.9 | 382.5 | 160.5 | 5.8 | 540.3 | NA | 2.4 | 39.8 | 186.6 | 0.1 | 0.97 |
| 25-Oct-96 | 1545 | 631 | 200,954 | W-385 - W-395 | 866.9 | 17.2 | 55 | 736.6 | 705.5 | 434.9 | 213.7 | 5.8 | 831.3 | NA | 5.8 | 56.2 | 146.6 | 0.1 | 0.99 |
| 26-Oct-96 | 1050 | 650 | 207,547 | W-396 - W-406 | 859.3 | 18.6 | 49.6 | 396.1 | 607.6 | 409.6 | 214.9 | 4.5 | 711.8 | NA | 2.6 | 54.8 | 161.3 | 0.1 | 0.78 |
| 27-Oct-96 | 1550 | 679 | 217,992 | W-407 - W-417 | 818.5 | 15.2 | 53.4 | 928.9 | 727.8 | 465.4 | 210.3 | 5.8 | 860.3 | NA | 3 | 53.1 | 168.9 | 0.1 | 1.30 |
| 28-Oct-96 | 1130 | 699 | 224,932 | W-418 - W-428 | 868.4 | 15.7 | 55.5 | 693.8 | 661.7 | 523.1 | 269.2 | 4.2 | 688.4 | NA | 3.3 | 55.6 | 183.1 | 0.1 | 0.94 |
| 29-Oct-96 | 1225 | 724 | 233,557 | W-429 - W-439 | 781 | 12.6 | 51.1 | 765.9 | 634 | 448.7 | 230 | 3.3 | 837.4 | NA | 3.6 | 53.6 | 187.9 | 0.3 | 1.19 |
| 30-Oct-96 | 1315 | 749 | 242,267 | W-440 - W-450 | 886.4 | 10.4 | 48.2 | 732 | 746.2 | 452 | 280.3 | 3.2 | 814.6 | NA | 3.6 | 55.1 | 224.6 | 0.1 | 1.44 |
| 31-Oct-96 | 945 | 769.5 | 249,472 | W-451 - W-461 | 765.8 | 18.1 | 40.6 | 643.3 | 603.5 | 497.6 | 274.5 | 3 | 772. | NA | 3.5 | 50.9 | 207.2 | 0.1 | 1.10 |
| 1-Nov-96 | 1200 | 796 | 258,637 | W-462 - W-472 | 918.5 | 14 | 37.2 | 686.8 | 695.1 | 471.7 | 252.9 | 3.2 | 730.4 | NA | 3.6 | 48.8 | 215.3 | 0 | 1.45 |
| 2-Nov-96 | 1200 | 820 | 266,844 | W-473 - W-483 | 828.3 | 13.5 | 40 | 655.2 | 664.7 | 467.7 | 246.8 | 2.8 | 752.1 | NA | 3.6 | 51.8 | 188.4 | 0 | 1.14 |
| 7-Nov-96 | 1800 | 946 | 298,848 | W-484 - W-495 | 852.1 | 10.6 | 43.3 | 751.5 | 686.1 | 419.9 | 266.2 | 3.3 | 850.6 | 0.1 | 4 | 50.6 | 178.2 | 0.2 | 4.20 |
| 8-Nov-96 | 1800 | 970 | 304,920 | W-496 - W-507 | 735.5 | 10.9 | 39.8 | 708.3 | 662.5 | 391.7 | 242.5 | 3.1 | 777.8 | 0.8 | 5.4 | 48 | 188.4 | 0.2 | 0.84 |

# Table 7.5. (continued)

Begin @ 1000, 29-Sep-96

End @ 1350, 12-Dec-96, Elapsed time: 1781 hours, treated volume: 584,418 gal

| Sample Date | Sample time | Elapsed time, h | Treated volume, gal | Sample Nos. | Well 09G | Well 71G | Well 72G | Well 73G | Well 74G | Well 75G | Well 76G | Well 77G | Well 78G | Well 79G | Well 80G | Well 81G | Treatment influent | Treatment effluent | TCE treated daily, gal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9-Nov-96 | 1500 | 991 | 310,242 | W-508 - W-519 | 547.2 | 10.8 | 34.2 | 715.5 | 102.5 | 439.3 | 239.6 | 3.1 | 768.2 | 0.6 | 4.6 | 47.4 | 186.2 | 0.1 | 0.73 |
| 10-Nov-96 | 1700 | 1017 | 320,242 | W-520 - W-531 | 793.6 | 11.8 | 31 | 656.9 | 657 | 415.5 | 266.2 | 3 | 812.8 | 0.1 | 6 | 52 | 207.5 | 0.7 | 1.53 |
| 11-Nov-96 | 1500 | 1039 | 328,542 | W-532 - W-543 | 772.8 | 10.2 | 31.1 | 724.3 | 1055.2 | 417 | 236.6 | 2.8 | 784.8 | 0.1 | 6.3 | 52.6 | 208.5 | 0.2 | 1.26 |
| 13-Nov-96 | 800 | 1080 | 342,242 | W-544 - W-555 | 798.3 | NA | NA | 766.8 | 1312.9 | 417.8 | 237.7 | 2.4 | 552.4 | 0.7 | 6.4 | 54.9 | 206.6 | 0.2 | 2.09 |
| 14-Nov-96 | 900 | 1105 | 350,542 | W-556 - W-567 | 838.7 | 9.7 | 29.9 | 788.2 | 1149.7 | 374.2 | 246 | 2.2 | 884.6 | 1 | 7.5 | 51.9 | 157.6 | 0.1 | 0.96 |
| 15-Nov-96 | 900 | 1129 | 358,742 | W-568 - W-579 | 892.1 | 7.4 | 28.2 | 801.4 | 1235.8 | 408.3 | 238.1 | 2.4 | 822.5 | 0.7 | 6.6 | 37.7 | 213.4 | 0.4 | 1.29 |
| 16-Nov-96 | 900 | 1153 | 366,742 | W-580 - W-591 | 868.2 | 9.4 | 25 | 745.5 | 584.5 | 367.3 | 203.1 | 2.7 | 683.5 | 0.2 | 8.7 | 47.1 | 174.5 | 0.1 | 1.03 |
| 17-Nov-96 | 1400 | 1182 | 376,142 | W-592 - W-603 | 803.4 | 8.1 | 24.5 | 675.2 | 581 | 356.3 | 203.6 | 5.1 | 697.8 | 0.4 | 8.2 | 49.8 | 152.3 | 0.1 | 1.06 |
| 19-Nov-96 | 1400 | 1230 | 384,642 | W-604 - W-615 | 519.1 | 7.7 | 26.1 | 551.7 | 558.8 | 344.2 | 209.7 | 6 | 651.4 | 0.2 | 8.2 | 47.4 | 109.2 | 3.4 | 0.68 |
| 20-Nov-96 | 1600 | 1256 | 392,842 | W-616 - W-627 | 709.1 | 7.7 | 20.6 | 666.2 | 553.8 | 340.6 | 189.9 | 5.3 | 680.8 | 0.2 | 9.2 | 53.2 | 157.8 | 1.3 | 0.95 |
| 21-Nov-96 | 1400 | 1278 | 403,042 | W-628 - W-639 | 722.4 | 6.7 | 21.6 | 714 | 536.8 | 344.9 | 195.4 | 4.6 | 722.8 | 0.2 | 9.9 | 46.1 | 167.9 | 5.6 | 1.26 |
| 22-Nov-96 | 800 | 1296 | 408,642 | W-640 - W-651 | 728.4 | 7.6 | 22.3 | 624.1 | 541.9 | 332.2 | 198.4 | 5.4 | 729.4 | 0.2 | 10.7 | 52.5 | 171.5 | 1.7 | 0.71 |
| 24-Nov-96 | 1800 | 1352 | 427,742 | W-652 - W-663 | 639.1 | 6.8 | 19.7 | 587.9 | 507.2 | 310.3 | 196.2 | 6.7 | 619.8 | 0.2 | 11.9 | 56.8 | 167.3 | 0.2 | 2.36 |
| 25-Nov-96 | 835 | 1366.6 | 433,642 | W-664 - W-675 | 654.3 | 7.4 | 18.9 | 779.4 | 539.5 | 307.5 | 193.8 | 6.8 | 793.7 | 0.2 | 11.7 | 53.3 | 138.2 | 2 | 0.60 |
| 5-Dec-96 | 812 | 1606.2 | 513,679 | W-676 - W-687 | 785.8 | 5.4 | 11.8 | 713.9 | 405.8 | 323.8 | 201.9 | 9.1 | 762.5 | 0 | 15.5 | 41.2 | 154.9 | 2.9 | 9.14 |
| 6-Dec-96 | 900 | 1631 | 522,184 | W-688 - W-699 | 665.2 | 5.3 | 9.9 | 663.6 | 321.2 | 313.9 | 166.8 | 8.2 | 624.6 | 0 | 14.5 | 32.4 | 166.7 | 0.2 | 1.05 |
| 7-Dec-96 | 814 | 1654.2 | 530,300 | W-700 - W-711 | 793.8 | 6.1 | 10.8 | 663.2 | 408.8 | 308.1 | 208.8 | 6.7 | 721 | 0 | 13.2 | 38.7 | 171.9 | 0.1 | 1.03 |

## Table 7.5. (continued)

Begin @ 1000, 29-Sep-96

End @ 1350, 12-Dec-96, Elapsed time: 1781 hours, treated volume: 584,418 gal

| Sample Date | Sample time | Elapsed time, h | Treated volume, gal | Sample Nos. | Well 09G | Well 71G | Well 72G | Well 73G | Well 74G | Well 75G | Well 76G | Well 77G | Well 78G | Well 79G | Well 80G | Well 81G | Treatment influent | Treatment effluent | TCE treated daily, gal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8-Dec-96 | 836 | 1678.6 | 538,920 | W-712- W-723 | 751.8 | 5.7 | 11.1 | 793.8 | 432.7 | 305.3 | 202.6 | 5.1 | 733.7 | 0 | 14.9 | 40.4 | 163.8 | 0.2 | 1.04 |
| 9-Dec-96 | 830 | 1702.5 | 547,317 | W-724 - W-735 | 735.5 | 5.8 | 10.3 | 723.7 | 381.1 | 286.1 | 191.5 | 3.9 | 722.2 | 0 | 12.5 | 37.4 | 169.5 | 0.1 | 1.05 |
| 10-Dec-96 | 850 | 1726.83 | 555,780 | W-736 - W-747 | 795.3 | 6.7 | 9.9 | 687 | 384.2 | 326.3 | 196.5 | 3.5 | 719.8 | 0 | 14.6 | 33.5 | 168.4 | 0 | 1.05 |

# 8. Discussion, Recommendations, and Cost Summary

This section provides a review of the drilling method, materials used, and potential applications of the horizontal recirculation approach.

## 8.1 Advantages of Dual Recirculating Wells

The inherent disadvantages of vertical wells have been enumerated by Plummer et al. (1997).

- A vertical well must be located directly over the contaminated plume, and its placement is limited by surface obstructions, such as buildings, lakes, and rivers.
- Hydrogeologic features and contaminant distributions are frequently oriented on a near horizontal plane, thereby reducing the effectiveness of vertical wells.
- A vertical well can connect aquifers that are located at different vertical depths by crossing an impermeable layer that separates them, thereby acting as a conduit for cross contamination.
- A series of vertical wells is required to remediate a contaminated plume, especially in low-permeability media. Therefore, larger plumes require additional vertical wells to remediate the site.
- Vertical wells are limited in their ability to intersect vertical fractures.

Kaback et al. (1989b) noted several advantages of horizontal well placement at the Savannah River Site:

- Improved access to the subsurface
- Reduced operating expense
- Increased surface area contact with the contaminant
- Improved efficiency for water bearing formations

- Increased accessibility to plumes located under surface obstructions.

These advantages and disadvantages are consistent with the experiences obtained in this project. In addition, based on the hydraulic and tracer testing conducted in the X-701B area and the CTS area, advantages and disadvantages were identified for the horizontal well recirculation system as compared to conventional vertical well systems. These advantages and disadvantages are presented below followed by a brief discussion.

***Advantages of horizontal recirculation***

- Increased groundwater flow velocities between horizontal recirculating well pairs
- Higher probability of intersecting preferential flow zones in the subsurface
- Reduced treatment times for DNAPL source areas
- Ease of installation under buildings and other surface obstructions
- Relatively low operation and maintenance (O&M) costs compared with a multiple-well system

***Disadvantages***

- Higher installation costs compared with vertical well systems
- Approximately 40% of potential treatment enhancers would be lost downgradient of the injection well.

The optimal situation for a horizontal well recirculation system is in a DNAPL source area. The horizontal wells should be located on opposite sides of the DNAPL source. The increased hydraulic gradient, with the addition of chemical enhancers such as surfactants, chemical oxidants, or biological treatment additives can be used to reduce the source mass and decrease the treatment time.

The major advantage of the horizontal well recirculation system is the ability to uniformly increase the hydraulic gradient and subsequently increase pore water velocities between the wells. Based on test results from the CTS and X-701B, a relatively uniform hydraulic gradient is established between the horizontal wells and the contaminated zone is flushed at least thirty times more efficiently than is possible without a pumping well. However, the effects of heterogeneity have an important impact on the flow field. As noted for the tracer tests described in Sect. 6, the majority of flow between the horizontal wells occurred in a preferential flow zone near the southern end of the wells.

Depending upon location and spacing, individual vertical wells may or may not intersect distinct preferential flow zones in the subsurface. Due to the long continuous filter lengths, however, the probability of intersecting a permeable sand stringer or lens significantly increases with horizontal wells. This advantage is of particular importance when chemical enhancers are being injected into the subsurface for remedial purposes. The higher probability of horizontal wells to intersect preferential flow zones increases the likelihood that the chemical enhancers will interact with zones that contain DNAPL.

Another important advantage of horizontal wells is the ability to install the wells in crowded industrial areas. Accurate drilling techniques allow the installation of wells under buildings and other surface obstructions. Regardless of surface conditions, installation of an efficient interceptor system using horizontal wells is possible. Depending on the site, it may not be possible to place conventional vertical wells in optimal locations.

With a horizontal well recirculation system, only one pump is required to extract water from the interceptor well, circulate the water through a treatment system, and reinject the water into the downgradient horizontal well. Conversely, individual pumps are required for each conventional vertical well. Furthermore, a more elaborate piping system is needed to route the water from the vertical wells to the treatment system and then reinject the water into a series of downgradient vertical wells. The net result is lower O&M costs associated with the long-term operation of a horizontal well recirculation system as compared to a vertical well system.

Finally, based on flow net analysis, it appears that approximately 40 % of the water injected in the downgradient horizontal well is lost to the natural groundwater flow system. This means that 40 % of chemical enhancers would be ineffective in treating source mass. Possible remedies to improve the treatment efficiency could be to install a set of backstop wells downgradient of the horizontal injection well. Alternately, the horizontal injection well could be installed into the DNAPL source. Water not recaptured by the pumping well would then treat contaminants downgradient of the injection well.

### 8.2 Cost Summary

The overall project cost for the X-701B horizontal well project from October 1995 to January 1997 (16 months) was approximately:

| | |
|---|---|
| $1,012,000 | Drilling contract, MK Ferguson contract administration |
| $425,000 | PORTS plant support (project and waste management, analytical, etc.) |
| $227,000 | ORNL funding from PORTS |
| $607,000 | ORNL funding from EM-50 |
| $60,000 | Laboratory research at ORNL and U of A |
| $2,331,000 | Total |

Research required to perform the field demonstration was conducted simultaneously with the design, construction, and field operations tasks. Thus, to accurately segregate design and construction, O&M, and life cycle costs, it was necessary to apportion PORTS plant support and ORNL funding from PORTS and EM-50 according to the level of effort associated with each aspect of the project. The design and construction phase of the project occurred October 1995 through May 1996 (8 months). Thus, the design and construction cost was computed as follows:

| | |
|---|---|
| $1,012,000 | Drilling contract, MK Ferguson contract administration |
| $212,000 | 8/16 PORTS plant support (assuming plant support was roughly constant during the 16 month duration of the project) |
| $209,000 | 4/16 of ORNL funding from PORTS and the Office of Science and Technology (design and build treatment system, field work during well installation) |
| $1,433,000 | total design and construction (see Table 8.1) |

Similarly, the O&M cost for the 97-day field test was computed as follows:

| | |
|---|---|
| $54,000 | 1 ORNL person, 8 hr/day labor for 97 days ($70/hr) |
| $40,000 | Materials (carbon, iron, etc.) |
| $80,000 | 3/16 PORTS plant support |
| $174,000 | total operation and maintenance |

The figure, $724,000, shown in Table 8.1 represents the research aspects of the project that were conducted during fiscal year 1997. The research tasks included re-development of the horizontal wells at the CTS, installation of monitoring wells at X-701B, pump tests, laboratory research using Pd/Fe for treatment of TCE, field research using Pd/Fe for treatment of TCE, data evaluation, and preparation of reports. Also included is the remainder of the PORTS plant support, the remainder

**Table 8.1. PORTS facilities for treatment of groundwater contaminated with TCE**

| Facility | X-622 | X-622T | X-623 | X-624 | Horizontal recirculation |
|---|---|---|---|---|---|
| **Design and construction** | | | | | |
| *Treatment method* | pH adjustment, iron removal, activated carbon | pH adjustment, activated carbon | pH adjustment, air stripping with activated carbon polish | pH adjustment, air stripping with activated carbon polish | activated carbon, iron filings, Pd/Fe fillings |
| *Operation method and frequency* | Automatic controls Continuous operation | Manned facility As-needed operation | Automatic controls Continuous operation | Manned facility Work-day operation | Automatic controls Continuous operation |
| *Design and construction cost* | $ 3,000,000 | $ 100,000 | $ 4,500,000 | $ 1,000,000 | $ 1,433,000 |
| *Research cost* | not applicable | not applicable | not applicable | not applicable | $ 724,000 |
| **O&M** | | | | | |
| *Total gal treated* | 7,124,010 gal | 9,822,440 gal | 2,207,430 gal | 2,611,250 gal | 555,780 gal |
| *Period of time* | 12 months FY96 | 12 months FY96 | 12 months FY96 | 12 months FY96 | 97 days (Sept-Dec '96) |
| *Processing rate* | 40 gal/min | 20 to 30 gal/min | 40 gal/min | 50 gal/min | 6 gal/min |
| *O&M cost* | $ 1,623,520 | $ 1,490,080 | $ 533,760 | $ 556,000 | $174,000 |
| *Cost per gal treated* | $ 0.23 | $ 0.15 | $ 0.24 | $ 0.21 | $ 0.31 |

of the ORNL funding from PORTS and EM-50, and the $60,000 laboratory research listed above.

Finally, to perform an accurate cost/benefit analysis, it is necessary to consider the highest, practical flow rate that was indicated by aquifer tests at the site. In other words, to assess the costs and benefits of the horizontal recirculation system, the operational flow rate was assumed to be 12 gal/min rather than the 6 gal/min that was used in the demonstration. The O&M costs were then separated into material costs, labor and plant support. The material cost for the field test was approximately $40,000 (for carbon, iron, etc.) per 555,780 gallons treated ($0.072/gal) and the labor and plant support cost was approximately $134,000 for the 97 day test ($1380/day). Doubling the flow rate would not significantly affect these costs. For a 12-month period, therefore, the O&M cost would be approximately:

(6,307,200 gal/yr)($0.072/gal) + ($1380/day)(365days/yr) = $957,820/yr

The treatment cost per gallon, including design and construction plus O&M would be:

($1,433,000 + $957,820)/6,307,200 gal = $0.38/gal for a 12 month period

It is important to note that of the five treatment systems evaluated in Table 8.1, only the system used in the horizontal recirculation test can remove radioactive contaminants as well as volatile organics. Treatment of the mixed contaminant stream was conducted with zero-valence iron for removal of $Tc^{99}$ and with activated carbon for removal of TCE and other halocarbons. Small-scale testing of an innovative treatment process for TCE using Pd/Fe was also performed. The overall concept, to treat an aqueous-mixed waste without producing another mixed waste, was successfully demonstrated. The stream of $Tc^{99}$ and TCE contacted zero-valence iron initially. Reducing conditions caused by the reaction of iron with water caused the $Tc^{99}$ to precipitate rapidly. Indeed, all of the $Tc^{99}$ in the more than 580,000 gal of water was removed by approximately 12 in. of coarse iron particles. Because zero-valence iron also reduces TCE, albeit slowly, the remaining solid waste at the project's termination was not a mixed waste. After storage for a few days the residual TCE was degraded leaving only $Tc^{99}$ on the Fe. During operation TCE was removed by the carbon following passage through the Fe. Because the water no longer contained $Tc^{99}$, after flowing through the Fe, the waste carbon could be handled as a hazardous waste with no concern for radioactivity.

Table 8.1 compares the costs for the horizontal well recirculation system with four groundwater treatment systems at PORTS. The other groundwater treatment systems use air stripping and/or activated carbon for the removal of dissolved TCE. The design and construction costs associated with the horizontal well recirculation system are comparable with the design and construction costs for the four traditional groundwater treatment systems. The O&M cost for the horizontal well recirculation system is somewhat higher than for the other four systems, although this cost is still of the same order of magnitude. The higher O&M cost is in part due to the relatively low flow rate of 6 gal/min for the horizontal recirculation test compared with the higher flow rates of 20 to 50 gal/min for the traditional groundwater treatment systems. The lower flow rate was necessary for the experimental treatment system. If the flow rate through the horizontal recirculation treatment system were doubled as described above, the O&M costs would decrease, because the material costs per gallon of water treated would remain approximately the same, while the costs for operator labor and plant support per gal of water treated would decrease by roughly 50%.

Finally, it is instructive to compare the cost of this installation to projects performed at locations other than Portsmouth. Unfortunately, making such cost comparisons is difficult because cost data are presented so differently from site-to-site. A report entitled, *A Compendium of Cost Data for Environmental Remediation Technologies* (DuTeaux 1996) provides the opportunity for some limited cost comparisons. Table 8.2 presents cost data for two systems, listed in that report, that are of similar capacity to the horizontal recirculation installation. The data demonstrate that the capital costs compare favorably and that O&M costs are also in the same range. However, these data need to be considered within the context of the facts that the horizontal recirculation system is treating mixed contaminants whereas the other sites are treating only organics. Furthermore, horizontal recirculation has significant advantages in terms of hydraulic efficiency and possibilities for enhancing treatment and removal. Considering all aspects, therefore, these data indicate that the horizontal recirculation system is less expensive than conventional approaches.

**Table 8.2. Comparison of capital costs and operating costs of horizontal recirculation with similarly-sized projects at other facilities**

| Site | Technology | Capital Cost | Annual Operating Costs |
|---|---|---|---|
| DOE Kansas City Plant | Pump-and-treat with UV | $1,383,400 | $355,200 |
| Fort Drum Fuel Area | Pump-and-treat w/GAC | $958,780 | $129,400 |
| In Situ Treatment/Recirculation project/ PORTS | Horizontal wells/iron/GAC | $1,433,000 | $174,000 (for 97 days) |

## 8.3 Recommendations

### 8.3.1 Additional DNAPL Characterization

The work performed in this project demonstrated that DNAPL is present between the horizontal wells. There are, however, no reliable estimates of the amount present. Consequently, the overall performance characteristics of the horizontal recirculation system and any subsequent remedial activities cannot be assessed quantitatively. The poor delineation of the DNAPL can be remedied by an integrated sampling and analysis approach that relies on improved sampling techniques, field analysis of samples, and a flexible quality assurance (QA) program (Kearl et al. 1996). Specifically, conventional split-spoon sampling can be used but subsamples for VOC analysis should be collected with a micro-corer as soon as the split-spoon is opened in the field. The microcore is deposited immediately into a vial containing hexane. Samples are then taken directly to a gas chromatograph for analysis. The chromatograph, which is set up on-site, is laboratory quality and is equipped with an auto-sampler. The QA program should emphasize referee analyses as opposed to the extensive performance checks and documentation typically required (Korte and Brown 1993). With this approach, a sample through-put of 100 per-day is achieved in the field with an estimated cost of $15/sample (Kearl et al. 1996). A large number of borings can be performed, and with daily analytical results to direct the selection of boring locations, the extent of the DNAPL can be accurately determined. Improving the knowledge of the DNAPL distribution will permit improved performance assessments and will assist the decision-making process regarding long-term disposition of the X-701B site.

### 8.3.2 Additional Operation of the Present System

The presently installed horizontal recirculation system should be operated for an additional period of time. The system operated successfully for approximately 74 days during the fall of 1996. (The length of operation was extended beyond the 30 days specified in the original test plan because of additional funding provided by PORTS.) No clogging or other hydraulic problems were observed. Additional pumping would enable the following issues to be addressed:

- More operating time would improve the estimation of O&M costs.

- Pumping rates up to the theoretical limit (approximately 12 gal/min), as described in Sect. 5, should be attempted. Such pumping would validate the hydraulic analyses performed, permit determination of O&M costs under different conditions, and permit a determination of whether the TCE removal rate changes with the pumping rate.

### 8.3.3 Use of Enhancing Fluids

Although more characterization of the DNAPL distribution is needed, the characterization of the site's hydrology is unusually good. Thus, the application of enhancing fluids to remediate the DNAPL source with the present horizontal recirculation system is recommended. Examples of enhancing fluids include surfactants which could be used to mobilize and recover the DNAPL and in-situ treatment agents to destroy the DNAPL in-place. In either case, a new treatment or recovery system would have to be designed to address the different nature of the effluent stream and its consequent effects on the commingled $Tc^{99}$.

## 8.4 Summary

The original goal of the project, to demonstrate coupled, simultaneous, in situ, treatment of a mixed waste stream in conjunction with enhanced aquifer flushing by means of horizontal recirculation, was satisfied. In actual fact, treatment was performed above-ground, but a series of canisters were used that effectively simulated a system that could be installed in the arm of a horizontal well. The aboveground system was used because there would have been increased cost associated with the initial installation and budget cuts required some changes in the project's scope. In addition, the regulatory reasons for initially planning in situ treatment (resistance to reinjection) were not a problem at PORTS. In situ treatment should still be considered at states or facilities where regulatory, security, or economic (heating, cooling, etc.) considerations warrant such an approach.

The project has also resulted in the establishment of two excellent test facilities at PORTS. The CTS (Muck et al. 1996) provides a clean, well-characterized site that has already been the location of three pilot tests: multi-point injection, pneumatic fracturing, and horizontal recirculation. The X-701B installation, described in this project, provides an excellent test bed for further testing of enhanced pumping and treating using horizontal recirculation with or without enhancing fluids. The X-701B installation, of course, may also be a key component in the ultimate remedy for the operable unit.

The project also provided testing of two innovative treatment methods: zero-valence iron for removal of $Tc^{99}$ and Pd/Fe for destruction of TCE. $Tc^{99}$ removal with iron was shown to be highly efficient and trouble-free. Treatment with Pd/Fe was shown to be effective but this project also indicated that additional research is needed to understand fully problems with manufacture and long-term use. Zero-valence iron for removal of $Tc^{99}$ and carbon for removal of TCE was shown, however, to provide a

This project provided the first test of horizontal recirculation which was shown to be a very effective approach to performing pump and treat of a thin, interbedded, aquifer zone. With respect to flushing of the contaminated zone, horizontal recirculation provided a hydraulic enhancement of 30 as compared to ambient conditions. In addition, the capital and O&M costs of the installation were comparable or less than conventional systems which do not have the hydraulic efficiency nor the means of treating a mixed waste.

Other unique features of this project include:

- first full-scale field use in the U.S. of a novel, ductile, polyethylene filter instead of conventional drill pipe,
- first field test of Pd/Fe for treatment of VOCs,
- first comparison of a bromide tracer test, colloidal borescope data, and contamination patterns under recirculation conditions,
- field results demonstrating that jetting and surging were a better approach for developing the horizontal wells as compared to the manufacturer's recommended method of slow overpumping,
- participation of three private firms (RCT, JMC, Schumacher/Flo Tex).

In conclusion, the project successfully demonstrated both an integrated approach to hydraulic control and groundwater treatment and successfully integrated various needs of two DOE entities (EM-50 and EM-40). Moreover, the work attracted the participation and investment of private companies who obtained operational and research data for use in their own marketing, production, and research programs. It is now anticipated that the resulting facilities and lessons-learned will be a key feature in the resolution of remedial activities at X-701B, elsewhere at the PORTS facility, and throughout DOE.

## 9. References

Anderson, M.R., Johnson, R.L., and J.F. Pankow. 1992. Dissolution of Dense Chlorinated Solvents into Ground Water: 1. Dissolution from a Well-Defined Residual Source. *Ground Water,* **30**(2):250-256.

Ashraf, M. S., B. Izadi, and B. King. 1997. Transport of bromide under intermittent and continuous ponding conditions. *J. Environ. Qual.*, **26**:69-75.

Blanford, W. J., M. L. Brusseau, and E. J. Klingel. 1997. Evaluation of an in-well aeration system to remediate a groundwater contamination site. *Division of Environmental Chemistry Preprints of Extended Abstracts, April 1997*: **37**(1):231.

Clausen, J. L., W. L. Richards, N. E. Korte, and L. Liang. 1995. ORNL/MMES Research into remedial applications of zero-valence metals: 3) Removal of TCE, cis-1,2-DCE, vinyl chloride, and technetium. In *American Chemical Society Division of Environmental Chemistry,* presented at the 209th ACS National Meeting, April 2-7, 1995, Anaheim, California, **35**(1):755.

Cohen, R. M., J. W. Mercer, and J. Matthews. 1993. *DNAPL Site Evaluation.* CRC Press, Boca Raton, Florida.

Driscoll, F. G. 1979. *Groundwater and Wells.* 2nd Ed., Johnson Well Division, ISBN 0-9616456-0-1, St Paul.

DuTeaux, S.B. 1996. *A Compendium of Cost Data for Environmental Remediation Technologies,* LA-UR-96-2205. Los Alamos National Laboratory, Los Alamos, New Mexico.

Ferris, J. G. 1950. Quantitative method for determining groundwater characteristics for drainage design. *Agricultural Engineering,* **31**(6):285-291.

Gilman, J. R., and J. R. Jargon. 1992. Evaluating horizontal vs vertical well performance. *World Oil,* June, pp. 55-60.

Gu, B., K. E. Dowlen, L Liang, and J. L. Clausen. 1996. Efficient separation and recovery of technetium-99 from contaminated groundwater. *Sep. Technol.*, **6**:123-132.

Kaback, D. S., B. B. Looney, J. C. Corey, L. M. Wright, and J. L. Steele. 1989a. Horizontal wells for in-situ remediation of groundwater and soils. In *Proceedings NWWA Outdoor Action Conference,* Orlando, pp. 121-135.

Kaback, D. S., B. B. Looney, J. C. Corey and L. M. Wright. 1989b. *Well completion report on installation of horizontal wells for groundwater remediation tests.* WSRC-RP-89-784. August, Aiken South Carolina: Westinghouse Savannah River Co.

Kearl, P. M. 1997. Observations of particle movement in a monitoring well using the colloidal borescope. *Journal of Hydrology*, in press.

Kearl, P. M., N. Korte, J. Zutman, and M. Stites. 1996. Using an integrated approach for quantifying VOC source areas for site remediation. *Waste Management*, **15**(8):1-9.

Kearl, P. M., N. E. Korte, M. Stites, and J. Baker. 1994. Field comparison of micropurging vs. traditional ground water sampling. *Ground Water Monitoring and Remediation,* Fall, 183-190.

Korte, N. E., L. Liang, B. Gu, M. T. Muck, J. L. Zutman, R. M. Schlosser, R. L. Siegrist, T. C. Houk and Q. Fernando. 1997a. *In Situ Treatment of Mixed Contaminants in Groundwater: Application of Zero-Valence Iron and Palladized Iron for Treatment of Groundwater Contaminated with Trichloroethene and Technetium-99.* Oak Ridge National Laboratory, Grand Junction, Colo.

Korte, N. E., L. Liang, R. Muftikian, C. Grittini, and Q. Fernando. 1997b. The Dechlorination of Hydrocarbons: Palladized iron utilised for ground water purification. *Platinum Metals Review*, **41**(1):2-7.

Korte, N. E., R. L. Siegrist, M. Ally, B. Bischoff, W. Bostick, J. M. Strong-Gunderson, P. Kearl, L. Liang, D. Marsh, A. Mattus, A. Palumbo, J. Stockdale, P. Taylor, and O. F. Webb. 1994. *In Situ Treatment of Mixed Contaminants in Groundwater: Review of Candidate Processes*, ORNL/TM-12772, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Korte, N. and D. Brown. 1993. Referee Analyses -- A Better Approach than Data Validation. *Environmental Management*, **17**(2):277-280.

Langseth, D. E. 1990. Hydraulic performance of horizontal wells. In *Superfund '90,* Proceedings of the 11th National Conference, November, pp. 398-408.

Law Engineering. 1982. *Soil and Groundwater Investigations for the GCEP Landfill Pathways Analysis.* Law Engineering Testing Company, Atlanta, Georgia.

Liang, L., O. R. West, N. E. Korte, J. D. Goodlaxson, D. A. Pickering, J. L. Zutman, F. J. Anderson, C. A. Welch, and M. J. Pelfrey. 1996. *The X-625 Groundwater Treatment Facility. A Field-Scale Test of Trichloroethylene Dechlorination Using Iron Filings for the X-120/X-749 Groundwater Plume.* Oak Ridge National Laboratory, Oak Ridge, Tenn.

Lohman, S.W. 1979. Ground-Water Hydraulics. U.S. Geological Survey Professional Paper 708. U.S. Government Printing Office, Washington D. C.

Mackenzie, P. D., T. M. Sivavec, and D. P. Horney. 1997. Extending Hydraulic Lifetime of Iron Walls. Presented at International Containment Technology Conference and Exhibition, St. Petersburg, Florida, February 9 - 12.

Muck, M. T., P. M. Kearl, R. L. Siegrist, N. E. Korte, R. M. Schlosser, M. E. Mumby, D. T. Davenport, D. W. Greene, D. A. Pickering, C. A. Muhr, and J. Strong-Gunderson. 1996. *Pilot Test of a Horizontal Well Recirculation System at the Clean Test Site, Portsmouth Gaseous Diffusion Plant.* Oak Ridge National Laboratory, Grand Junction, Colorado.

Muck, M. T., N. E. Korte, L. Liang, D. Marsh, J. L. Zutman, and J. Clausen. 1995. *Technology Screening Report for Tc Removal from Groundwater Portsmouth Uranium Enrichment Plant, Piketon, Ohio.* Oak Ridge National Laboratory, Grand Junction, Colorado.

Muftikian, R., Q. Fernando, and N. E. Korte. 1995. A method for the rapid dechlorination of low molecular weight chlorinated hydrocarbons in water. *Water Research* **24**(10):2434-2439.

ORNL. 1994. *In Situ Treatment of Mixed Contaminants in Groundwater, Project Description.* ORNL/FPO-94/53, Oak Ridge National Laboratory, Oak Ridge, Tenn.

PEI. 1992. Horizontal wells inject new life into mature field. Staff report, *Petroleum Engineers International,* **64**(4):49-50.

Plummer, C. R., J. D. Nelson, and G. S. Zumwalt. 1997. Horizontal and vertical well comparison for in situ air sparging. *Ground Water Monitoring and Remediation,* Winter, pp. 91-96.

Riley, R. G., J. M. Zachara, and F. J. Wobber. 1992. *Chemical Contaminants on DOE Lands and Selection of Contaminant Mixtures for Subsurface Science Research.* DOE/ER-0547T.

Schafer, D. C. 1996. Determining 3D Capture Zones in Homogenous Anisotropic Aquifer. *Ground Water*, **34**(4):628-639.

Schwille, F. 1988. *Dense Chlorinated Solvents In Porous and Fractured Media: Model Experiments*. Lewis Publishers, Chelsea, Michigan.

Siegrist, R. L., M. I. Morris, O. R. West, D. D. Gates, D. A. Pickering, R. A. Jenkins, T. J. Mitchell, D. W. Greene, C. A. Muhr, S. Herbes, T. M. Gilliam, H. L. Jennings, A. J. Lucero, J. L. Zutman, and others. 1993. Full-Scale Field Demonstration and Testing of Physicochemical Processes for *In Situ* Treatment of Soil Contaminated by Volatile Organic Compounds in the Presence of Radioactive Substances. Presented at *Waste Management '93*, Tucson, Arizona, February 28 - March 4, 1993.

U.S. DOE. 1997. *Annual Report for 1996 Groundwater Monitoring at the Portsmouth Gaseous Diffusion Plant, Piketon, Ohio.* U.S. Department of Energy, Piketon, Ohio.

U.S. DOE. 1996. *Phase I: Paducah Gaseous Diffusion Plant Waste Area Group 6 Industrial Hydrogeologic Study*. DOE/OR/07-1478&D2. U. S. Department of Energy, Paducah, Kentucky.

U.S. DOE. 1994a. *Quadrant II RFI Report for Portsmouth Uranium Enrichment Plant, Piketon, Ohio. Volume 1 (draft)*. U.S. Department of Energy, Office of Environmental Restoration and Waste Management. Piketon, Ohio.

U.S. DOE. 1994b. *X-701B Draft Cleanup Alternatives Study/Corrective Measures Study Report for the Portsmouth Gaseous Diffusion Plant, Piketon, Ohio.* U.S. Department of Energy, Office of Environmental Restoration and Waste Management. Piketon, Ohio.

U.S. EPA. 1992. Dense Nonaqueous Phase Liquids: A Workshop Summary. EPA/600/R-92/030. U.S. Environmental Protection Agency, Washington, D.C.

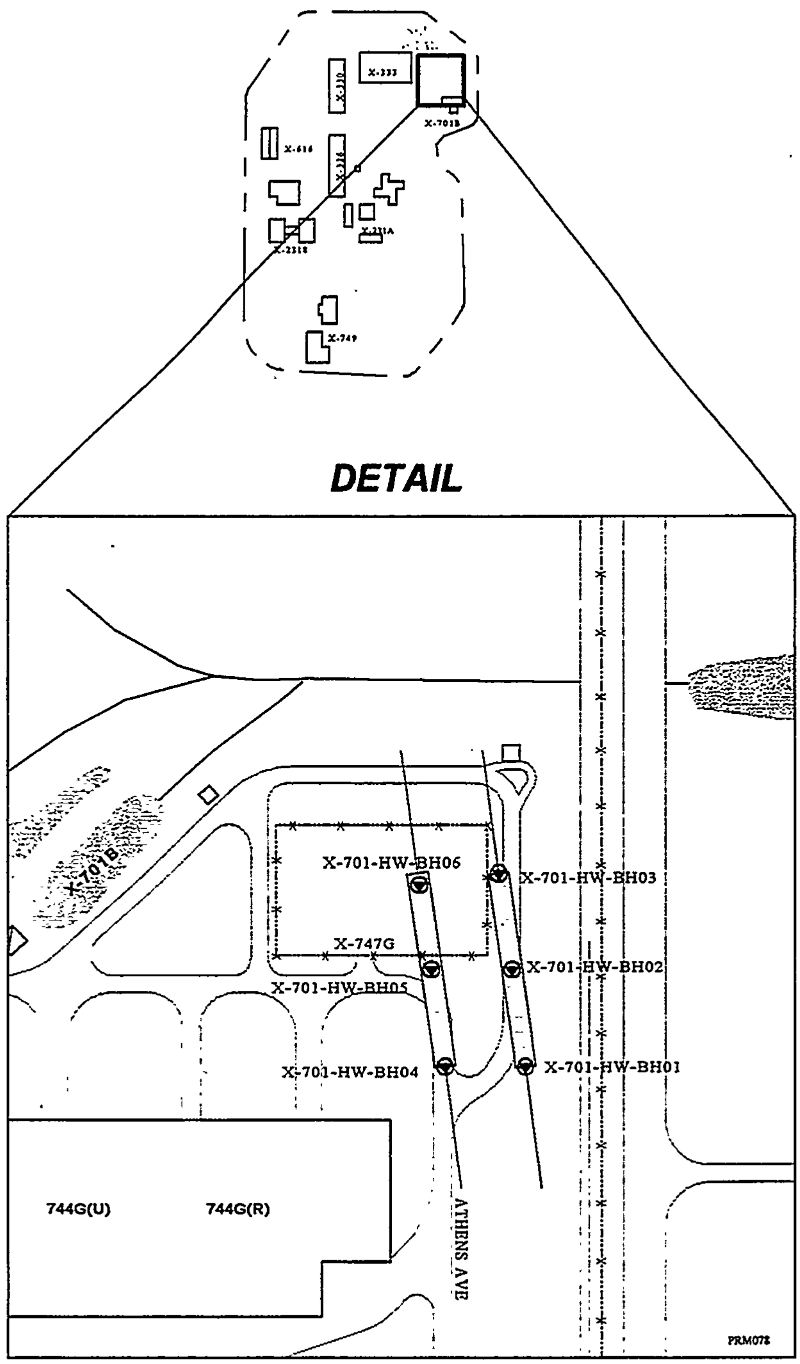
West, O. R., L. Liang, W. L. Holden, N. E. Korte, Q. Fernando, and J. L. Clausen. 1996. *Degradation of Polychlorinated Biphenyls (PCBs) Using Palladized Iron*, ORNL/TM-13217, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

# Appendix A

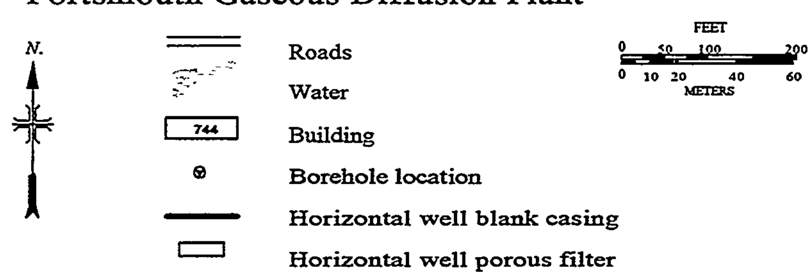
## Geologic Logs for Boreholes at X-701B

## Appendix A
## Northing and Easting coordinate data for X-701B horizontal well boreholes

| Borehole No. | Northing | Easting |
|---|---|---|
| X-701-HW-BH01 | 10473.04 | 10895.45 |
| X-701-HW-BH02 | 10587.31 | 10880.00 |
| X-701-HW-BH03 | 10700.73 | 10864.71 |
| X-701-HW-BH04 | 10473.09 | 10802.45 |
| X-701-HW-BH05 | 10587.02 | 10787.02 |
| X-701-HW-BH06 | 10687.25 | 10773.57 |




X701 Horizontal Well
Portsmouth Gaseous Diffusion Plant



# Borehole Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: R.M. Schlosser Date: 11/08/95 Page: 1 OF 1

Hole No.: 701-HW-BH01 Ground Elevation: 671.542

Total Depth: 31' Rig Type: AMS 16000 Location: S end screen, east well.

Auger Size: NA Sample Type: Geoprobe "Megabore 2" OD X 4'

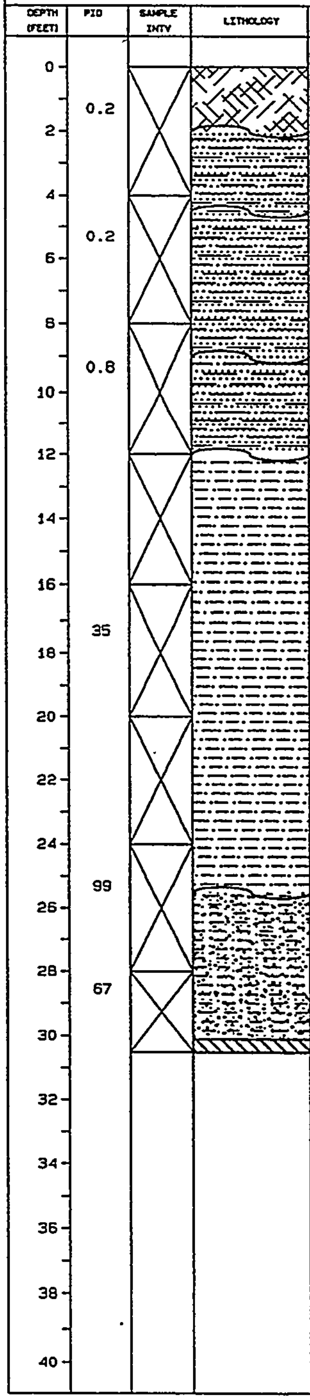
Project: PORTS X701B Data Verified By: Date:

| DEPTH (FEET) | PID | SAMPLE INTV | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|
| 0 | | | | |
| | 0.4 | | | FILL: 0.5-1" limestone gravel. |
| 2 | | | | |
| 4 | | | | ML SILTY CLAY: yellowish brown (10YR5/6), mottled light gray (10YR7/1), some roots, blocky, dry, some scattered small pebbles, becoming very dark gray at 6', soft, friable, some roots and black Fe staining. |
| 6 | | | | |
| 8 | | | | |
| | 0.4 | | | |
| 10 | | | | |
| 12 | | | | ML SILTY CLAY: brownish yellow (10YR6/6) mottled strong brown (5YR5/5-5/6), some light gray (10YR7/1) mottling throughout, scattered cobbles at 14.5', some black Fe nodules. |
| | 0.4 | | | |
| 14 | | | | ML SILT: light yellowish brown mottled strong brown, wet. dark Fe staining at 14.8' and 15.2' |
| 16 | | | | |
| | 0.8 | | | |
| 18 | | | | |
| | | | | ML SILT: strong brown (7.5YR5/6), soft, mottled reddish brown (5YR5/4), soft, wet, slightly micaceous, some Fe staining, scattered large gravels at 21' and 21.8'. |
| 20 | | | | |
| 22 | | | | ML SILT: as above. |
| 24 | | | | GM GRAVELLY SILT: brownish yellow (10YR6/8), some pebbles to 3/8", cobbles to 1.5", becoming increasingly gravelly and less silty with depth. |
| 26 | | | | |
| 28 | | | | |
| | 0.7 | | | GM SILTY GRAVEL: color as above, angular pebbles and cobbles to 1.5" in a silt matrix, not well consolidated or cemented. |
| 30 | | | | SH SHALE: black (10YR2/1), soft at contact, fraible at 30.5', dry, good well defined partings. Refusal at 31' |
| 32 | | | | Contaminated soil returned to hole. Grouted to surface using neat cement. |
| 34 | | | | |
| 36 | | | | |
| 38 | | | | |
| 40 | | | | |

# Borehole Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: R.M. Schlosser  Date: 11/08/95  Page: 1 OF 1
Hole No.: 701-HW-BH02  Ground Elevation: 671.32
Total Depth: 30.5'  Rig Type: AMS 16000  Location: center screen, east well.
Auger Size: NA  Sample Type: Geoprobe "Megabore 2" OD X 4'
Project: PORTS X701B  Data Verified By: ____  Date: ____




DESCRIPTION

FILL: 0.5-1" limestone gravel.

ML SILTY CLAY: yellowish brown (10YR5/6), roots, blocky, dry, some Fe staining throughout.

ML SILTY CLAY: very dark gray (10YR3/1), soft, dry, some scattered roots and vessicles, some black Fe nodules

ML SILTY CLAY: brownish yellow (10YR6/6) mottled strong brown. at 11.5', scattered 1-1.5" gravels

ML SILT: light yellowish brown mottled strong brown, wet. At 15.5' and 16.5', 1-2" thick

ML SILT: as above, occassionally gypsiferous.

ML SILT: varved will small layers of light gray sand at 22'.

GM SILTY GRAVEL: brownish yellow (10YR6/6), pebbles to 3/8", cobbles to 1.5", becoming less silty at

GM GAVELLY SILT: less gravel from 29.5-30'

SH SHALE: black (10YR2/1), well weathered, dry below contact.
Refusal at 30.5'

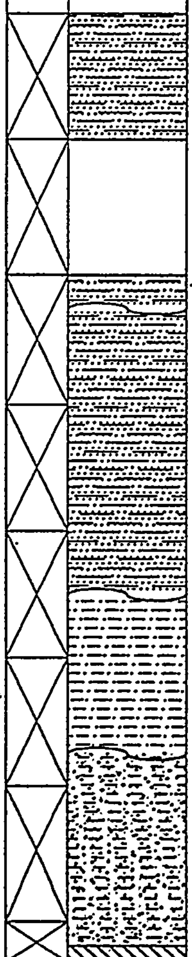
Contaminated soil returned to hole.
Grouted to surface using neat cement.

# Borehole Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: R.M. Schlosser  Date: 11/09/95  Page: 1 OF 1
Hole No.: 701-HW-BH03  Ground Elevation: 669.91
Total Depth: 29.3' Rig Type: AMS 16000  Location: N end screen, east well
Auger Size: NA  Sample Type: Geoprobe "Megabore 2" OD X 4'
Project: PORTS X701B  Data Verified By: ____________ Date: ______

| DEPTH (FEET) | PID | SAMPLE INTV | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|
| 0–4 | 0.2 | | | ML SILTY CLAY: yellowish brown (10YR5/6), mottled light gray, abundant vessicles and organics. |
| 4–8 | 1.4 | | | LOST CORE 4'-8' |
| 8–12 | 0.4 | | | ML SILTY CLAY: very dark gray (10YR3/1), soft, friable, dry, scattered Fe nodules.<br>ML SILTY CLAY: as above, very ozidized, with abundant Fe staining, sacttered Fe nodules. |
| 12–16 | 0.2 | | | ML SILTY CLAY: as above, becoming less oxidized, becoming ; less silty, slightly gypsiferous. |
| 16–20 | 0.7 | | | ML SILT: strong brown (7.5YR5/6) . soft, mottled light gray, becomonmg light gray (10YR7/1), very clean, moist to wet. |
| 20–24 | 0.4 | | | GM SILTY GRAVEL: cobbles to 2" in a brownish yellow to strong brown silt matix. |
| 24–28 | 0.3 | | | |
| 28–29.3 | 3.7 | | | SH SHALE: black (10YR2/1), well weathered, sticky, dry below contact.<br>Refusal at 29.3' |



Contaminated soil returned to hole.
Grouted to surface using neat cement.

**orn1** OAK RIDGE NATIONAL LABORATORY

# Borehole Summary Information

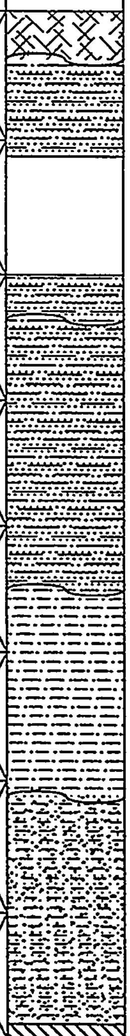
Prepared By: R.M. Schlosser  Date: 11/09/95  Page: 1 OF 1

Hole No.: 701-HW-BH04  Ground Elevation: 673.49

Total Depth: 32'  Rig Type: AMS 16000  Location: S end screen, west well

Auger Size: NA  Sample Type: Geoprobe "Megabore 2" OD X 4'

Project: PORTS X701B  Data Verified By: ______  Date: ______



| DEPTH (FEET) | PID | SAMPLE INTV | DESCRIPTION |
|---|---|---|---|
| 0–4 | 0.8 | 0–4 | FILL: Road base, crushed limestone gravel.<br>ML SILTY CLAY: FILL. |
| 4–8 | 0.6 | 4–8 | LOST CORE 4.5'-8' |
| 8–12 | 0.3 | 8–12 | ML SILTY CLAY: very dark gray (10YR3/1), soft, friable, dry.<br>ML SILTY CLAY: reddish yellow (10YR6/6) mottled light gray (10YR7/1), abundant Fe staining, some black oxides present. |
| 12–16 | 0.5 | 12–16 | ML SILTY CLAY: predominantly light gray mottled strong brown.<br>ML SILTY CLAY: as above gravel 3" thick at 15'. |
| 16–20 | 4.5 | 16–20 | ML SILT: brownish yellow (10YR6/6), mottled reddish brown (5YR5/4), micaceous, some Fe staining small gravel layer at 21.6' |
| 20–24 | 1.6 | 20–24 | |
| 24–28 | 3.7 | 24–28 | GM SILTY GRAVEL: strong brown (7.5YR5/6-5/8), cobbles to 2", sandstone and limestone, angular, becoming les silty with depth then at 29.5 becoming very silty again to GRAVELLY SILT. |
| 28–32 | 3.7 | 28–32 | SH SHALE: black, very soft to 31.7', well defined partings, dry belo contact. |

Contaminated soil returned to hole.
Grouted to surface using neat cement.

# Borehole Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

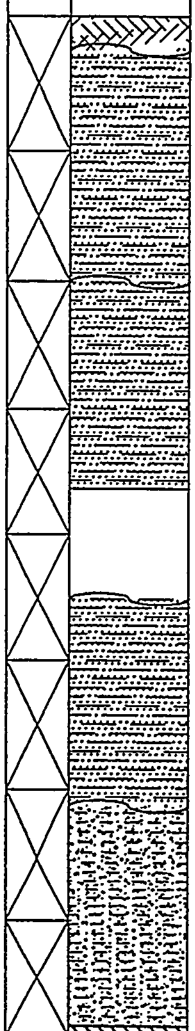
Prepared By: R.M. Schlosser Date: 11/09/95 Page: 1 OF 1

Hole No.: 701-HW-BH05 Ground Elevation: 672.34

Total Depth: 31.5' Rig Type: AMS 16000 Location: Center of west well

Auger Size: NA Sample Type: Geoprobe "Megabore 2" OD X 4'

Project: PORTS X701B Data Verified By: Date:



| DEPTH (FEET) | PID | DESCRIPTION |
|---|---|---|
| 0 | | |
| | 0.2 | FILL: Road base, crushed limestone gravel. |
| 2 | | ML SILTY CLAY: brown (7.5YR5/2), dry, structureless some root mass and small roots. |
| 4 | | |
| | 0.3 | |
| 6 | | |
| 8 | | ML SILTY CLAY: reddish yellow (7.5YR6/6) mottled light gray (10YR7/2), abundant Fe staining. At 11.0', 2" bedded 1.5" gravels. |
| | 0.3 | |
| 10 | | |
| 12 | | |
| | 0.4 | ML SILTY CLAY: as above, Abundant pebble Fe nodules |
| 14 | | |
| 16 | | LOST CORE 14.5' TO 18' |
| | 4.9 | |
| 18 | | |
| 20 | | ML SILT: reddish yellow (7.5YR6/6) , some scattered black oxidized specs, wet. |
| | 117 | |
| 22 | | |
| | | GM GRAVEL: 3" layer 3/4"-1" limestone, angular |
| 24 | | |
| | | GM SILTY GRAVEL: strong brown (7.5YR5/6-5/8), well consolidated, Fe stained throughout, cobbles to 1.5", in a silt matrix. Becoming increasingly siltier from 30.6' to contact with Sunbury. |
| 26 | | |
| 28 | | |
| | 241 | |
| 30 | | |
| | | SH SHALE: black, very soft at contact, becoming and fissile with depth. Very sharp contact. |
| 32 | | |
| 34 | | |
| 36 | | |
| 38 | | |
| 40 | | |

# Borehole Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: R.M. Schlosser Date: 11/10/95 Page: 1 OF 1

Hole No.: 701-HW-BH06 Ground Elevation: 672.21

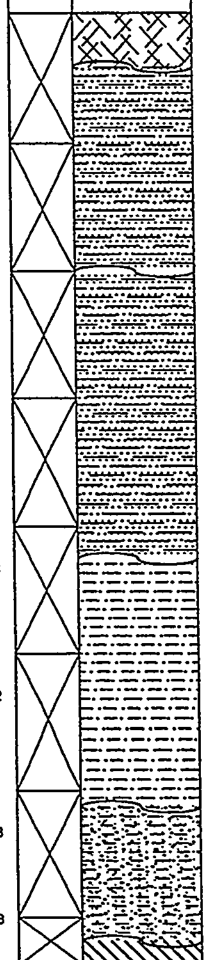
Total Depth: 29.5' Rig Type: AMS 16000 Location: N end screen, west well.

Auger Size: NA Sample Type: Geoprobe "Megabore 2" OD X 4'

Project: PORTS X701B Data Verified By: Date:

| DEPTH (FEET) | PID |
|---|---|
| 0 | |
| | 0.4 |
| 2 | |
| 4 | |
| | 0.3 |
| 6 | |
| 8 | |
| | 0.4 |
| 10 | |
| 12 | |
| | 0.4 |
| 14 | |
| 16 | |
| | 0.3 |
| 18 | |
| 20 | |
| | 0.2 |
| 22 | |
| 24 | |
| | 0.3 |
| 26 | |
| 28 | 0.3 |
| 30 | |
| 32 | |
| 34 | |
| 36 | |
| 38 | |
| 40 | |

SAMPLE INTV / LITHOLOGY



DESCRIPTION

FILL: 0.75-1" limestone gravel.

ML SILTY CLAY: yellowish brown (7.5YR5/2), dry, abundant roots.

ML: SILTY CLAY: as above.

ML SILTY CLAY: brownish yellow (10YR6/6) mottled light gray (10YR7/1), abundant black Fe nodules

ML SILTY CLAY: as above.

ML SILT: light gray, very dense, hard, occassinally appears crystalline to siltstone, gravels at 19' and 21.5', small pebbles to occassional .75 to 1" cobble.

ML SILT: strong brown (7.5YR5/6), soft, mottled reddish brown (5YR5/4), soft, wet, slightly micaceous, some Fe staining.

GM SILTY GRAVEL: soft, predominantly silty in upper becoming increasingly gravelly with depth, abundant Fe staining on fractured surfaces, less gravelly with depth at bottom to gravelly silt.

SH SHALE: black (10YR2/1), soft at contact, becoming more competent with depth.
Total depth at 29.5'

Contaminated soil returned to hole.
Grouted to surface using neat cement.

# Appendix B

## Vendor Information for Schumacher Porous Filters

SCHUMACHER
Umwelt- und Trenntechnik
Ein Unternehmen der Kraftanlagen-Gruppe

# Well filters for remediation of contaminated soils and groundwater

SCHUMACHER
Umwelt- und Trenntechnik
Ein Unternehmen der Kraftanlagen-Gruppe

# In situ remediation of contaminated soils

The in situ cleaning of contaminated soils is a very urgent task in environmental protection. SCHUMACHER developed new parts for clean up techniques to be used for soils and groundwater. A new porous well filter consisting of pure polyethylene is very useful especially in fine grain soil types.

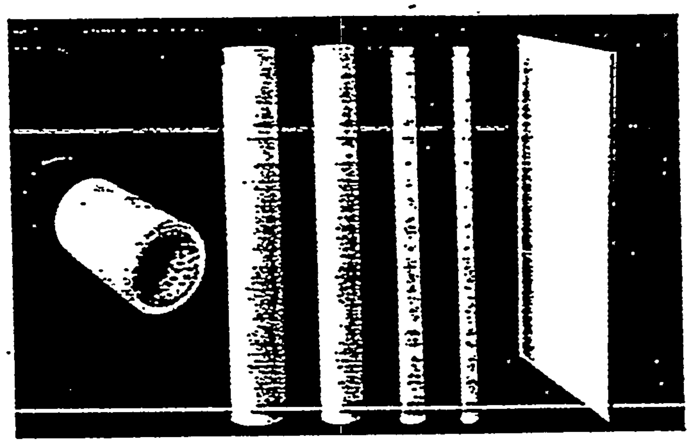
SCHUMACHER well filters have very specific advantageous properties for well design in the saturated and unsaturated zone.

Proving ground for horizontal filter wells

## Properties

- homogeneous pore size distribution
- same chemical resistance as high density polyethylene
- hydrophobic character
  oliophilic behaviour
- low weight
- high permeability for water and air

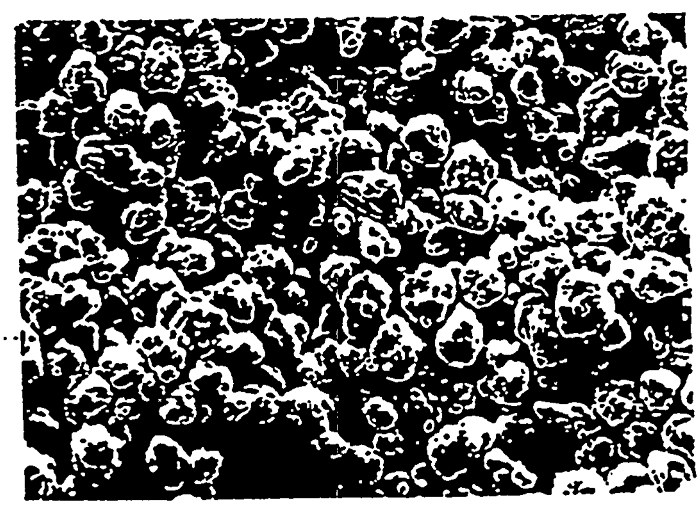
These properties show excellent advantages compared to conventional well screens.



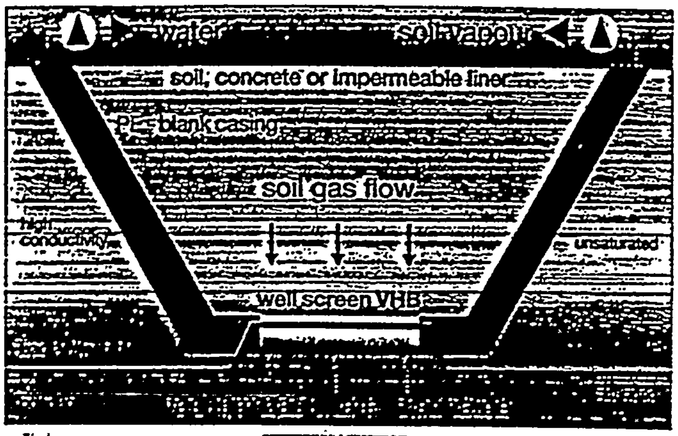
SCHUMACHER filter elements

## Advantages

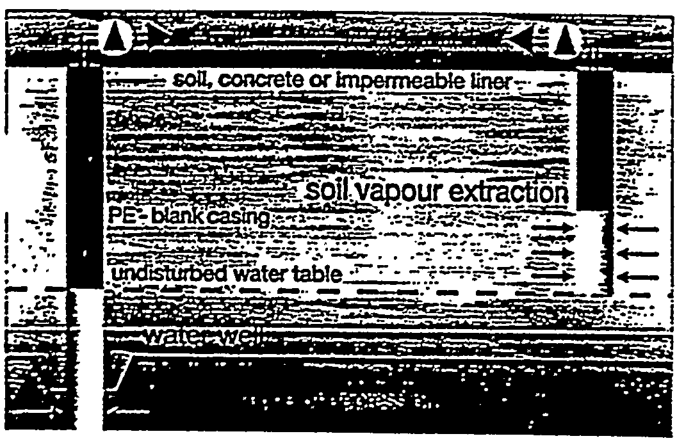
- the homogeneous pore size distribution supports a laminar fluid flow through the filter across its total surface
- clogging and incrustation are avoided
- the hydrophobic character can be used to keep soil water outside the well
- the permeability of the filter to oil ensures an excellent separation of groundwater and oil



SEM photography of fracture surface

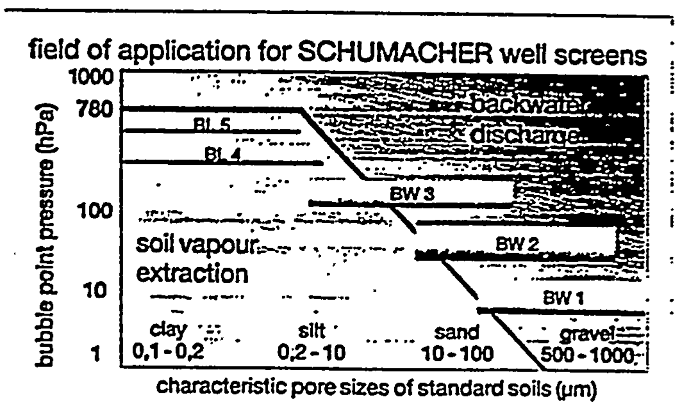



Horizontal filter well




Vertical filter well

- SCHUMACHER well filters are physiologically unobjectable.
- High mechanical strength allows the application in vertical and horizontal wells.
- Low weight and the standardized connections make transportation and installation very cost effective.
- The homogeneous porosity of SCHUMACHER well filters makes a gravel pack unnecessary and minimizes drilling diameters.
- Due to their ductility, SCHUMACHER well filters adapt to curved and horizontal wells by guided trenchless horizontal drillings (FlowTex-System).




Field of application of SCHUMACHER filter wells

**Applications**

SCHUMACHER well filters are produced with five different water entry values and five different permeabilities, covering a wide spectrum of applications. Especially under difficult conditions in fine grain soil types a contamination treatment can be carried out with

- soil vapour extraction
- back water discharge
- groundwater discharge
- gas or nutrient injection

SCHUMACHER
Umwelt- und Trenntechnik
Ein Unternehmen der Kraftanlagen-Gruppe

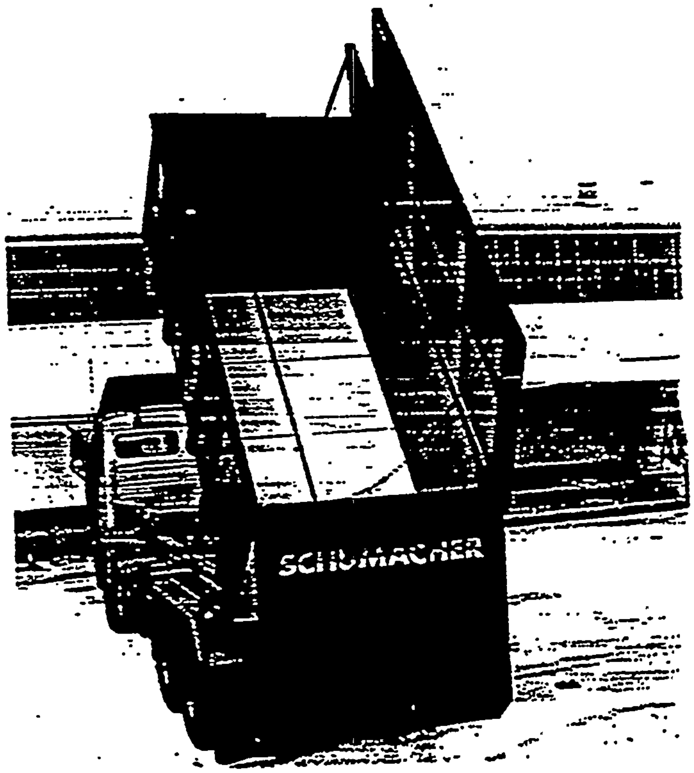
# Ex situ remediation of contaminated soils

Ex situ techniques can also be supported by SCHUMACHER filter media. Excavated contaminated soil is cleaned in a mobile container system.

The container features two different sections:

The large one is equipped with a permeable layer of porous polyethylene for the extraction of soil vapour and other fluids.

The smaller section accomodates the process engineering components such as activated carbon barrels, catalytic combustion, blower, or power generator.



Container system for ex situ remediation

## Advantages

- very flexible for different types of contaminations and fluids
- riskless and safe transportation with conventional container trucks
- "on the road" soil vapour extraction avoids contamination of the atmosphere
- applications in on-site and off-site remediation

## Construction principles

1. The extraction section is filled with contaminated soil.
2. The contaminated soil air is extracted by passing the evacuated porous layer of the container.
3. The soil air cleaning is carried out in the small section, using the required techniques.
4. After decontamination, the soil can be used for refilling, or has to be deposited on a land fill.


**Germany**

Schumacher Umwelt- und Trenntechnik GmbH

ır Flügelau 70
ɹ-74564 Crailsheim
Tel.: 07951/302-0
Tlx: 74372 schcr d
Fax: 07951/26807

**France**

Schumacher DMF S.A.

Z.I. 25, Rue Gay Lussac
B.P. 38
95502 Gonesse Cedex
Tél.: 1/39.85.93.14
Tlx: 688018
Fax: 1/39.85.91.62

**Japan**

Nihon Schumacher K.K.

Toyo Bldg. 12-20
Jingumae 6-Chome
Shibuya-Ku, Tokyo
Tel.: 81/3/34091531
Tlx: 25561
Fax: 81/3/34861678

**U.S.A**

Schumacher Filters America Inc.

P.O. Box 8040
Asheville
NC 28 814-8040
Tel.: 704/252/9000
Fax: 704/253/7773

# Appendix C

## Geologic Logs and Completion Diagrams for Monitoring Wells at X-701B

**ornl** OAK RIDGE NATIONAL LABORATORY

# Well Summary Information

Prepared By: M.E. Mumby  Date: 06/24-25/96  Page: 1 OF 1

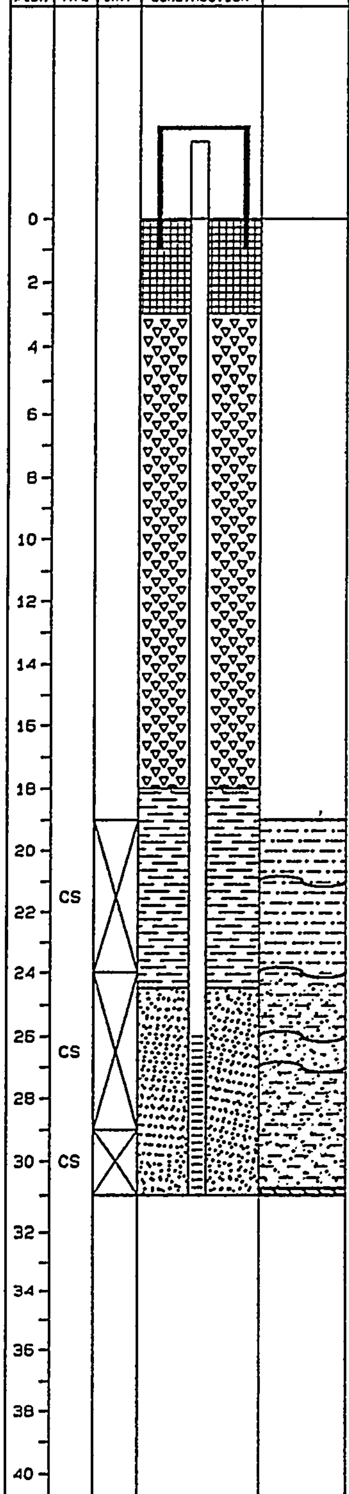
Hole No.: X701-71G  Casing Elevation: 673.88'  Ground Elevation: 671.33

Total Depth: 31.0'  No. of Compl.: 1  Rig Type: CME-550 ATV  Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25"  Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR  Data Verified By: M.T. Muck  Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




Auger to 19.0'.

ML **SANDY SILT:** light gray (5Y 6/1), soft, wet, sand is predominantly very fine grained sub-rounded quartz with scattered fine grained quartz, occasional FeO staining.

ML **SILT:** brownish yellow (10YR 6/8), firm, moist, slightly sandy, occasional lenses of sandy silt up to 2" thick, sandy silt lenses are wet, increasing FeO staining with depth.

GM **SILTY GRAVEL:** dark yellowish brown (10YR 3/6), sub-rounded to sub-angular weathered sandstone gravels up to 2" in a slightly sandy silt matrix wet, gravelly sand layer from approximately 26 to 27', saturated, lithified in the top three inches, sand in this zone is fine to coarse grained quartz and chert, heavily FeO stained, grades back to a silty gravel below 27', decrease in moisture content from 27 to 30.8'.

Top of Sunburry Shale 30.8'.

T.D. 31.0

**orn1** OAK RIDGE NATIONAL LABORATORY

# Well Summary Information

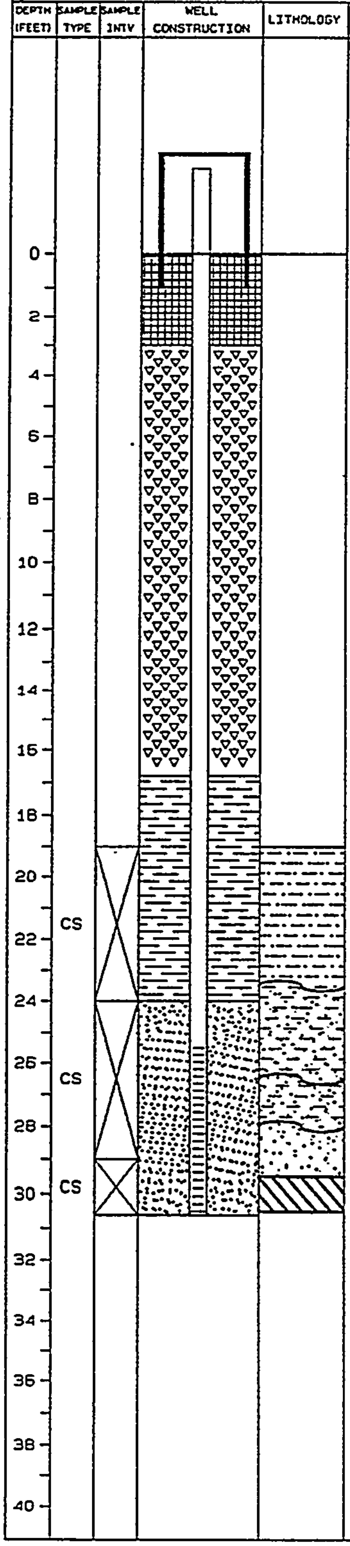
Prepared By: M.E. Mumby  Date: 06/24/96  Page: 1 OF 1

Hole No.: X701-72G  Casing Elevation: 673.83'  Ground Elevation: 671.39'

Total Depth: 30.6'  No. of Compl.: 1  Rig Type: CME-550 ATV  Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25"  Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR  Data Verified By: M.T. Muck  Date: 07/08/96




DESCRIPTION

Auger to 19.0'.

ML **SILT:** yellowish brown (10YR 5/8), soft, firm, wet, 3 distinct lenses of light gray (5Y 6/1) sandy silt with scattered well rounded gravel to 1.5".

GM **SILTY GRAVEL:** dark yellowish brown (10YR 3/6) subangular to subrounded sandstone gravels to 1.5" in a sandy silt matrix, wet, entire interval is heavilly FeO stained, grades to a gravel sand silt mixture at 26.5', becomes very sandy from 28.0 to 29.5', saturated, sands are predominantly medium to coarse grained, subrounded sandstone, quartz and occasional chert, very faint solvent odor.

Top of Sunburry Shale 29.5'.

**SHALE:** black, slightly weathered, dry, sharp contact with overlying Galia.

T.D. 30.6'.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby  Date: 06/21/96  Page: 1 OF 1

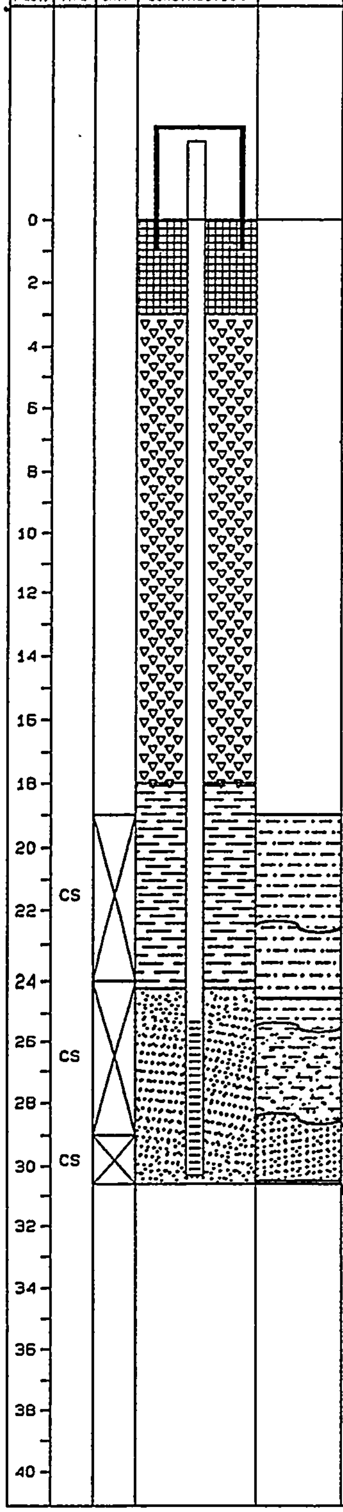
Hole No.: X701-73G  Casing Elevation: 674.85'  Ground Elevation: 672.30'

Total Depth: 30.6'  No. of Compl.: 1  Rig Type: CME-550 ATV  Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25"  Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR  Data Verified By: M.T. Muck  Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




Auger to 19.0'.

ML SILT: brownish yellow (10YR 6/6), soft, becoming wet at approximately 23', moderate solvent odor below 23', sandy from 22.5 to approximately 24.0', sand is very fine grained subrounded to rounded quartz, common FeO staining, scattered weathered sandstone gravels to 1", grades to a yellowish brown silty sand at 24.5', sand becomes fine to medium grained subrounded predominantly quartz, abundant FeO staining common gravels (Aprrox 20%) to 1.5".

GM SILTY GRAVEL: yellowish to dark yellowish brown (10YR 5/8-4/6), subangular to subrounded predominantly sandstone gravels to 2" with scattered to > 4" in a sandy silt to silt matrix wet in the silty zones, saturated in the sandy silt zones, sands are medium to coarse grained, very strong solvent odor.

SW SAND: color as above, very coarse to very fine upward fining sequence of sand, from approximately 28.5 to 30.5', saturated, sand consists of subangular to subrounded quartz, sandstone, and occasional chert, common sandstone gravels (20-25%) near bottom of interval, grades back to to a silty gravel at 30.5'.

Refusal at 30.6', large cobble, cannot auger through even without sampler, small amount of weathered shale on auger bit teeth.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 06/22/96 Page: 1 OF 1

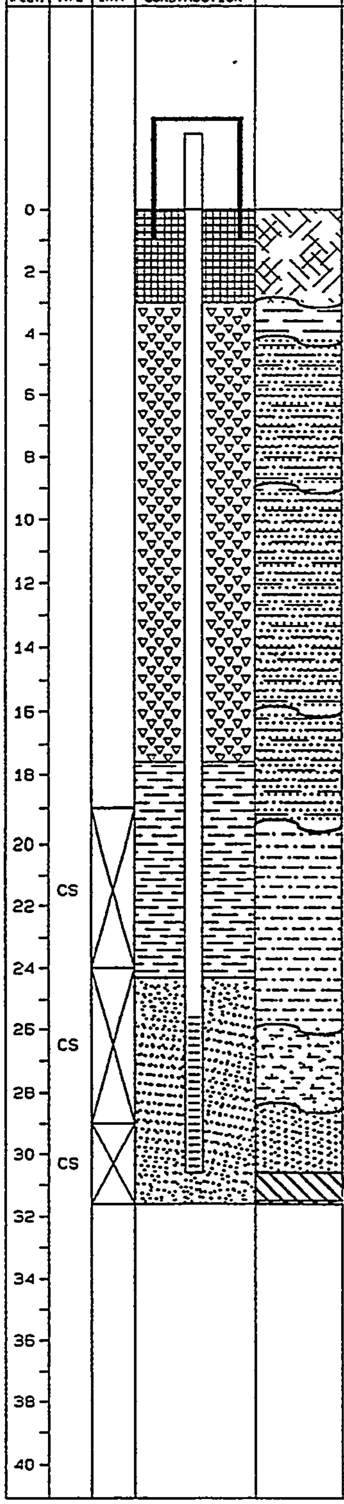
Hole No.: X701-74G Casing Elevation: 674.14' Ground Elevation: 671.64'

Total Depth: 31.6' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




FILL: angular limestone roadbase to 6" becomes predominatly silty clay to 3' with abundant intermixed gravel, scattered organic debris.

CH CLAY: strong brown (7.5YR 5/8) soft, moist, fat, scattered MnO staining, appears reworked.

CL SILTY CLAY: dark gray (5Y 4/1), firm, blocky texture, moist, common organic debris, occasional FeO staining, occasional very small roots <1mm.

CL SILTY CLAY: grayish brown (10YR 4/2), firm, blocky, slightly moist, grading to a yellowish brown (10YR 5/8) with a light gray mottle, abundant FeO staining, gravelly from 12 to 14', very large cobble at 14.0' >4".

ML CLAYEY SILT: brownish yellow (10YR 6/6), hard, slightly moist, common FeO staining, slightly sandy.

ML SILT: light yellowish brown to yellowish brown (2.5Y 6/4-10YR 6/4) with yellowish brown becoming more prominant with depth, firm, wet, sandy, common FeO staining, sand is very fine grained quartz, scattered fine grained chert, sand content increasing with depth.

Poor recovery from 24 to 29', Gallia top is present at approximately 26', moderate solvent odor.

GM SILTY GRAVEL: brownish yellow (10YR 6/8), subangular to subrounded with occasional rounded predominantly sandstone gravel to 1.5", occasional >4", in a slightly sandy silt matrix, wet, strong solvent odor.

SW SAND: color as above, very coarse to very fine upward fining sequence of sand, consists of subangular to subrounded quartz, sandstone and some chert with common sandstone gravels to .75" near bottom of interval, saturated, exact top unknown had approximately 1' of very fine silty sand up the augers when running in for the 29 to 30.6' sample interval, extremely strong solvent odor, weathered shale at 30.6', sharp contact, becomes dry and hard at 31.5'.

T.D. 31.6'.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 06/21/96 Page: 1 OF 1

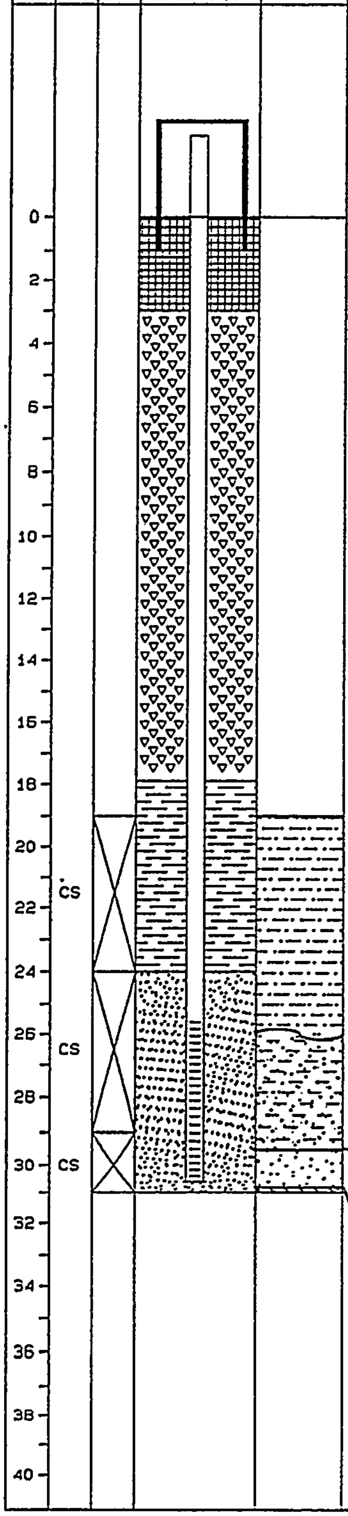
Hole No.: X701-75G Casing Elevation: 674.06' Ground Elevation: 671.38'

Total Depth: 31.0' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




ML SILT: yellowish brown (10YR 5/8), firm, moist, sandy, sand is very fine grained subrounded to round quartz, abundant FeO staining scattered round weathered sandstone gravels to .75", grades to a brown (10Yr 5/3) silty sand at approximately 24'.

GM SILTY GRAVEL: dark brown (7.5YR 4/4), subangular to subrounded predominantly sandstone gravels to 1.5" in a sandy silt matrix, sand is medium to coarse grained quartz, sandstone and some chert, wet, entire interval is heavily FeO stained, very strong solvent odor.

GW GRAVEL: dark yellowish brown (10YR 4/6) subrounded weathered sandstone gravels to .75", slightly sandy with predominantly medium to coarse grained sand, saturated, interval fines upward to a very fine grained silty sand at approximately 29.5', extremely strong solvent odor.

Top of shale 30.8', fairly sharp contact.

BEDROCK: slightly weathered black fissile shale.

T.D. 31.0'.

orn1 OAK RIDGE NATIONAL LABORATORY

# Well Summary Information

Prepared By: M.E. Mumby Date: 06/23/96 Page: 1 OF 1

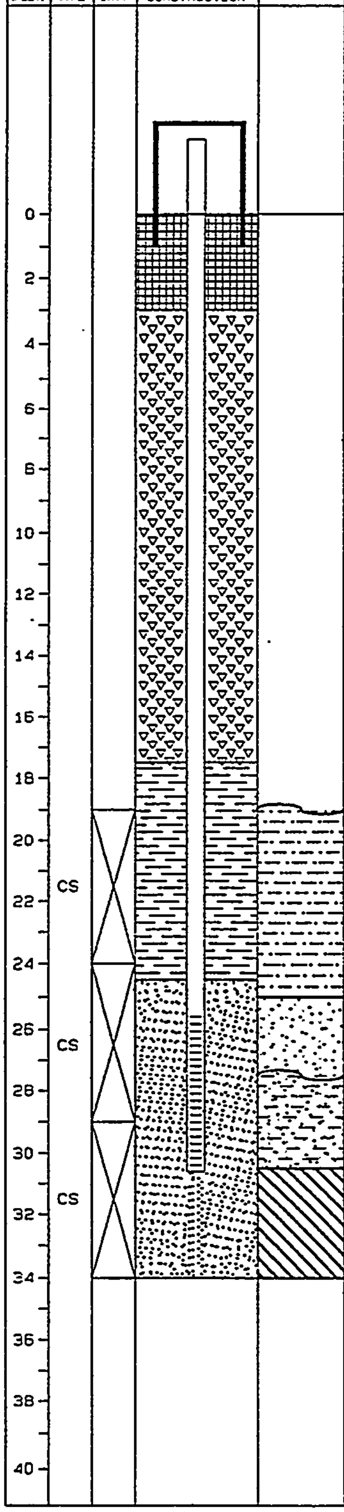
Hole No.: X701-76G Casing Elevation: 674.56' Ground Elevation: 671.92'

Total Depth: 34.0' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




ML SILT: brownish yellow (10YR 6/6), firm, occasionaly very dense, moist, becoming wet by 20', common lenses of light yellowish brown (10YR 6/4) silty sand, noticeably more free water is present in these zones, sand is very fine to fine grained subrounded quartz and chert, no solvent odor.

ML SILT: as above increasing sand content, gravelly zone from 25 to 26', heavily FeO stained, wet, no solvent odor.

GM SILTY GRAVEL: yellowish brown (10YR 5/8) angular to subrounded predominantely sandstone gravels to 1" in a slightly sandy silt matrix, wet, moderate FeO staining, common shale fragments from 29 to 30.5', slight solvent odor.

Top of shale 30.5'.

BEDROCK: weathered light gray shale from 30.5 to 31.0', becoming black, fissile, dry, very hard from 31 to 34'.
T.D. 34.0'.

**ornl** OAK RIDGE NATIONAL LABORATORY

# Well Summary Information

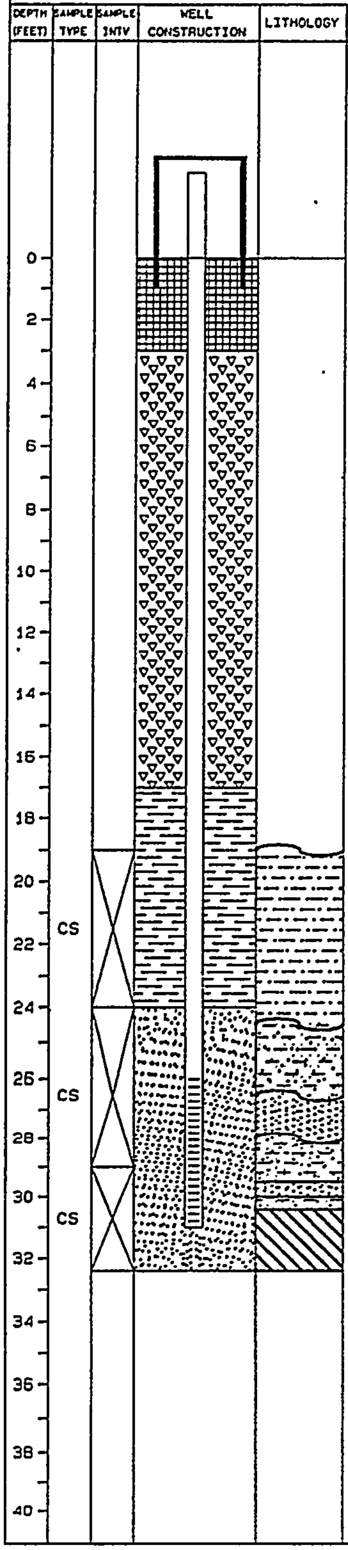
Prepared By: M.E. Mumby  Date: 06/22/96  Page: 1 OF 1

Hole No.: X701-77G  Casing Elevation: 674.80'  Ground Elevation: 672.15'

Total Depth: 32.4' No. of Compl.: 1 Rig Type: CME-550 ATV  Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR  Data Verified By: M.T. Muck  Date: 07/08/96




DESCRIPTION

ML SILT: brownish yellow (10YR 6/8), soft, moist, becoming wet at approximately 20'; slightly sandy, scattered thin lenses of silty sand, sand is very fine to fine grained, slightly FeO stained.

GM SILTY/SANDY GRAVEL: yellowish brown (10YR 5/8), subangular to subrounded with occasional round predominantly sandstone gravels in a sandy silt matrix, wet, grades to a gravelly sand from 26.5 to 28.0', saturated, abundant FeO staining on sand grains and the gravels, grades back to a silty gravel from 28 to 29.5'.

SW GRAVELLY SAND: color as above, sand is fine to coarse grained, subrounded, saturated, gravels are up to 1" in diameter, grades back to a silty gravel from 30 to 30.4'.

Top of Sunburry Shale 30.4'.

BEDROCK: slightly weathered black fissile shale, dry, hard.

T.D.32.4'.

## Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 06/20/96 Page: 1 OF 1

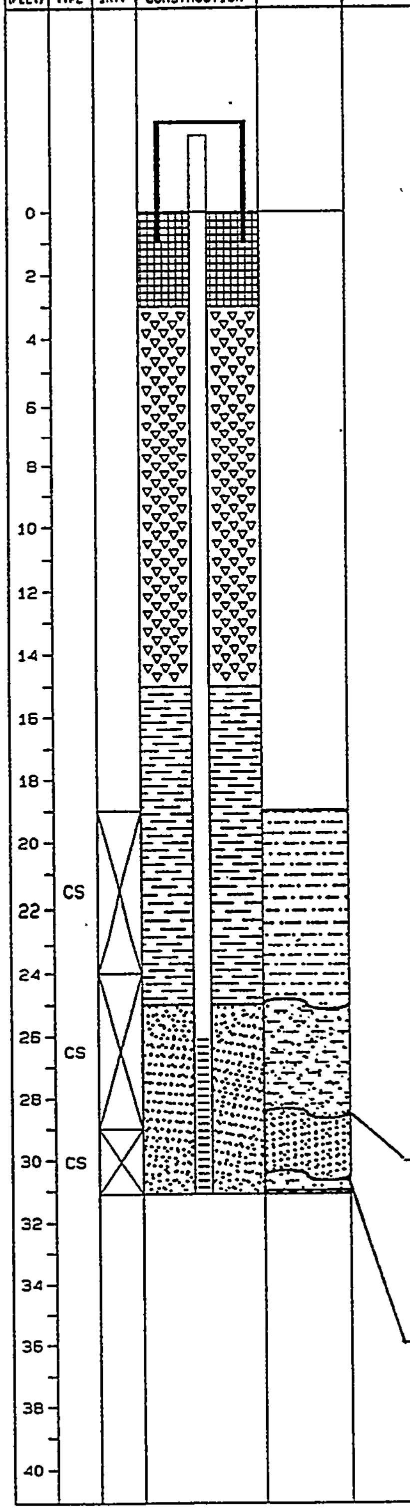
Hole No.: X701-78G Casing Elevation: 674.40' Ground Elevation: 671.97'

Total Depth: 31.1' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




ML SILT: yellowish brown (10YR 5/6), firm to moderately firm, very moist, becoming wet at approximately 20', abundant FeO staining and scattered nodules, some slight cementation, sandy, sand is very fine predominantly quartz.

GM SILTY GRAVEL: yellowish to dark yellowish brown (10YR 5/8-4/6), subangular to subrounded sandstone gravels to 2" with occasional >4" in a sandy silt/silt matrix, wet, saturated in the sandy silt zones, sands are medium to coarse grained, very strong solvent odor..

SW SAND: color as above, very coarse to very fine subrounded upward fining sand, fairly clean (<12%fines) in the medium to coarse grained sands, becomes silty in the fine to very fine grained sands at the top of the interval, scattered sandstone gravels to .75", most prominant near bottom of interval, saturated, extremely strong solvent odor.

Top of Sunburry Shale 31.0'.

T.D. 31.1'.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 06/20/96 Page: 1 OF 1

Hole No.: X701-79G Casing Elevation: 677.46' Ground Elevation: 674.87'

Total Depth: 34.5' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

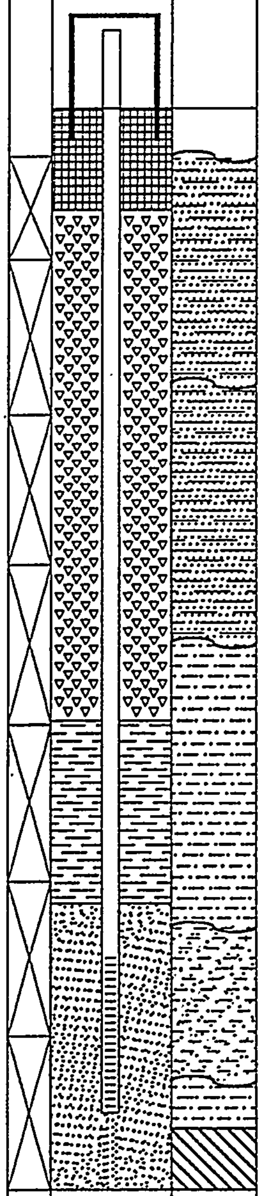
Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION

Depth scale (feet): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40

Sample type: CS (at approx. 3, 7, 12, 17, 22, 27, 32 ft)



Auger to 1.5', limestone roadbase.

No sample from 1.5 to 4.5'.

CL SILTY CLAY: yellowish brown (10YR 5/8) with a gray (10YR 5/1) mottle throughout, firm, moist, fairly high plasticity to 6', scattered FeO staining, occasional chert grains.

CL SILTY CLAY: predominantly as above, decreasing gray mottle, increasing silt content with depth scattered very weathered sandstone and limestone gravels to 1", common FeO and MnO staining.

ML SILT: yellowish brown (10YR 5/6-5/8), firm, wet from 17.5 to approximately 20', very sandy in this zone, sand is very fine grained quartz, decreasing sand and moisture content below 20', increasing sand and moisture again at 24'.

GM SILTY GRAVEL: dark yellowish brown (10YR 4/6), subrounded to rounded very weathered sandstone gravels in a slightly sandy silt matrix, wet, gravels range in size from very fine to 2", grades to a gravelly silt at approximately 31'.

BEDROCK: shale, black, firm to hard, fairly weathered to 32.25', becoming very hard and less weathered below 32.5'.

T.D. 34.5'.

**ornl** OAK RIDGE NATIONAL LABORATORY

# Well Summary Information

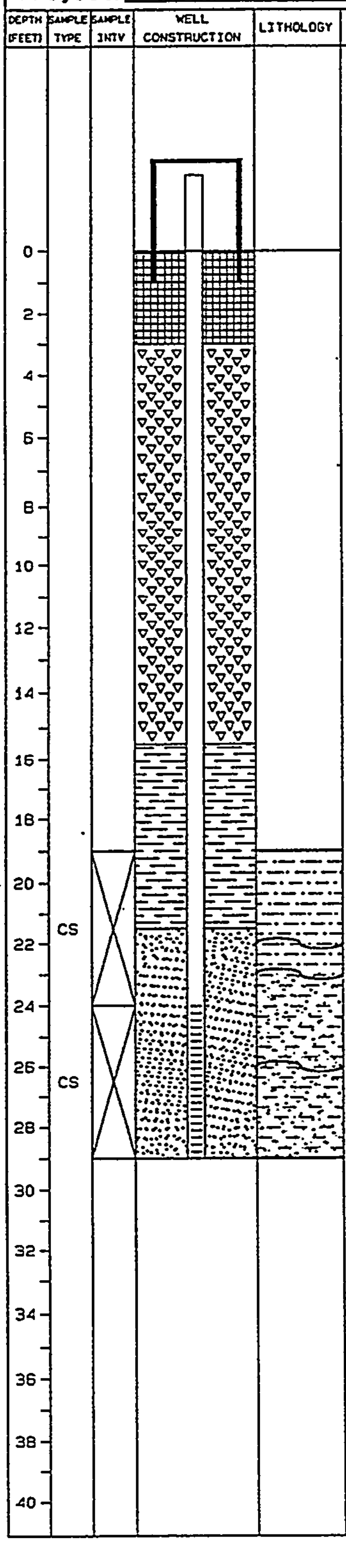
Prepared By: M.E. Mumby  Date: 06/23/96  Page: 1 OF 1

Hole No.: X701-80G  Casing Elevation: 672.35'  Ground Elevation: 669.82'

Total Depth: 29.0'  No. of Compl.: 1  Rig Type: CME-550 ATV  Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25"  Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR  Data Verified By: M.T. Muck  Date: 07/08/96




DESCRIPTION

Auger to 19.0'.

ML SILT: light gray (5Y 6/1), soft, wet, slightly sandy, occasional FeO staining, common very small roots and root pores, 1mm and smaller, grades to a yellowish brown (10YR 5/8) at approximately 22', roots absent, increasing FeO staining.

GM SILTY GRAVEL: dark yellowish brown (10YR 3/6), subrounded to subangular weathered predominantly sandstone gravels to 2" in a slightly sandy silt matrix, wet, heavily FeO stained, grades to a gravel, sand, silt mixture at approximately 26', wet, gravels range in size from very fine to 2", sands are medium to coarse grained, subangular, entire interval is heavily FeO stained, no solvent odor.

T.D. 29.0', approximately 2" of black weathered shale in sampler shoe.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 06/19/96 Page: 1 OF 1

Hole No.: X701-81G Casing Elevation: 672.86' Ground Elevation: 669.85'

Total Depth: 28.5' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

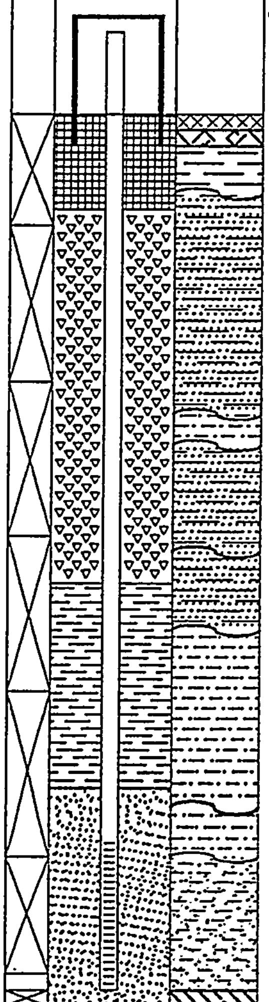
Auger Size: 8.25" x 4.25" Sample Type: 4" x 5' Continuous Barrel

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 07/08/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|

Depth (feet): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40

Sample type: CS (at approx. 2'), CS (6'), CS (11'), CS (16'), CS (21'), CS (25.5'), CS (28')



FILL: grass and humus to .5', angular gravel roadbase to 1.0'.

CH CLAY: yellowish brown (10YR 5/4), soft, very moist, fat, common small root pores and organic debris, grades to a silty clay at 2.5'.

CL SILTY CLAY: yellowish brown (10YR 5/6-5/8), common light gray mottle, firm, moist, scattered chert gravels to .5", common FeO staining.

ML SILT: light olive brown (2.5Y 5/3), soft, moist fairly homogeneous, scattered FeO staining.

CL SILTY CLAY: as above, abundant FeO and MnO staining and some nodules.

ML CLAYEY SILT: light yellowish brown (7.5YR 6/4), soft, moist with moisture content increasing with depth, common FeO staining, large limestone cobble >4" at 15.5'.

ML SILT: color as above, soft, wet, sandy, sand is predominantly very fine grained quartz, with common medium grained chert, scattered FeO staining, faint relict bedding is present in some zones (varves?), poor recovery on the 18.5 to 23.5' sample interval.

GM SILTY/SANDY GRAVEL: yellowish brown (10YR 5/8), subangular to subrounded predominantly sandstone gravels from very fine to 2" in a silt/sand matrix, saturated, sand is predominantly medium to coarse grained with less than 10% fine grained, gravels are heavily FeO stained, lithified from 27to 27.5'.

NOTE: could not auger through lithified zone below below 27.5' with sampler in augers. Pulled sampler and augered to 28.0'. Ran sampler back in and drilled to 28.5'.

T.D. 28.5 in weathered black shale.

# Well Summary Information

**ornl** OAK RIDGE NATIONAL LABORATORY

Prepared By: M.E. Mumby Date: 09/19/96 Page: 1 OF 1

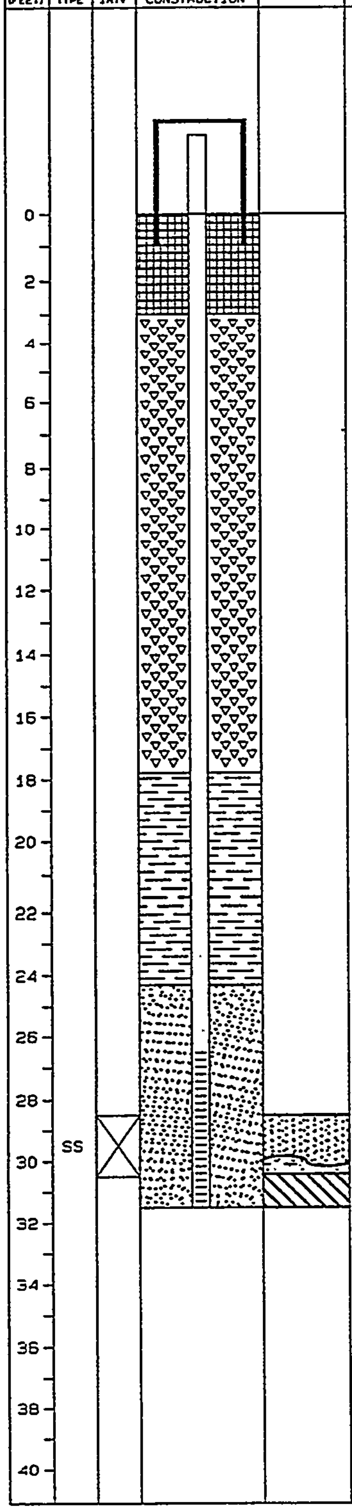
Hole No.: X701-82G Casing Elevation: ______ Ground Elevation: ______

Total Depth: 31.5' No. of Compl.: 1 Rig Type: CME-550 ATV Location: X-701b Horz. Wells

Auger Size: 8.25" x 4.25" Sample Type: 1.5" x 2.0' Split Spoon

Project: X-701b ISTR Data Verified By: M.T. Muck Date: 09/30/96

| DEPTH (FEET) | SAMPLE TYPE | SAMPLE INTV | WELL CONSTRUCTION | LITHOLOGY | DESCRIPTION |
|---|---|---|---|---|---|




**SW SAND:** dark yellowish brown (10YR 4/6), very coarse to fine grained subrounded upward fining sequence of sand, wet, scattered fine gravel, abundant FeO staining, very strong solvent odor, grades to a silty gravel at 30', decrease in moisture content, scattered weathered shale fragments.

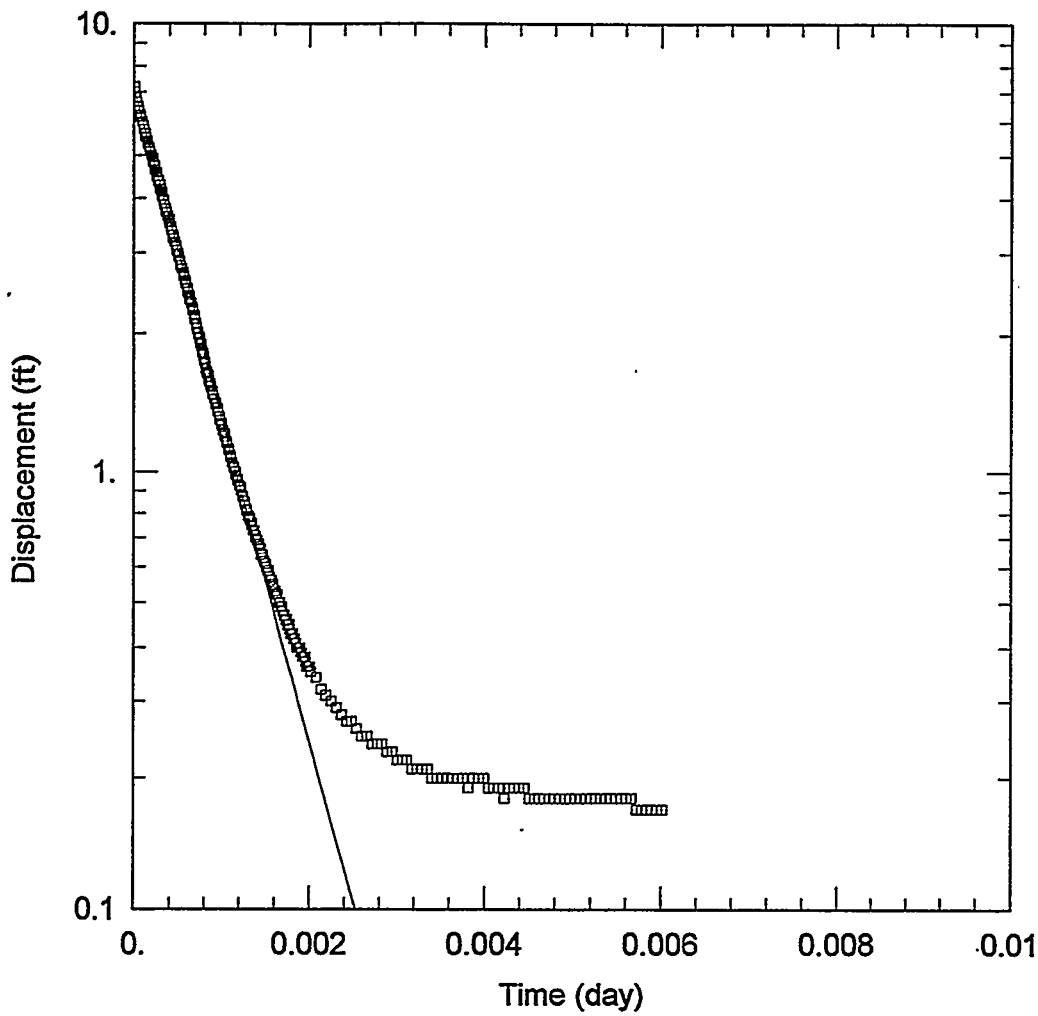
Top of Sunburry Shale 30.4'.

**BEDROCK:** very dark gray to black weathered shale to 31, becomes increasingly competent below 31'.

T.D. 31.5'.

# Appendix D

## Single Well Hydraulic Test Data




X701B-073G TEST 1

Data Set:
Date: 03/27/97 | Time: 08:03:13

AQUIFER DATA

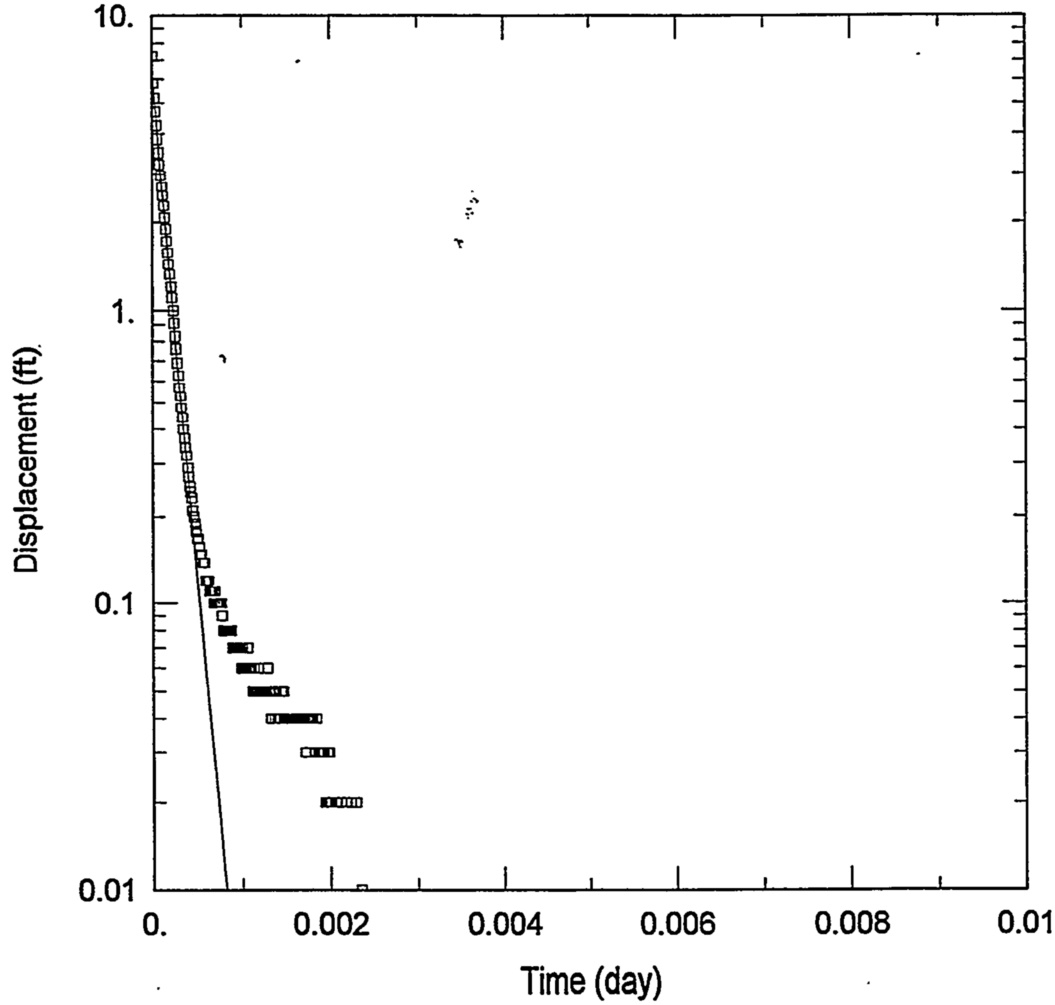
Saturated Thickness: 6 ft | Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 7.2 ft | Water Column Height: 16.36 ft
Casing Radius: 0.08333 ft | Wellbore Radius: 0.5 ft
Screen Length: 5. ft | Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined | K = 39.58 ft/day
Solution Method: Bouwer-Rice | y0 = 7.091 ft




X701B-74G TEST 1

Data Set: C:\AQTE\74G-1.AQT
Date: 03/27/97 Time: 09:07:10

AQUIFER DATA

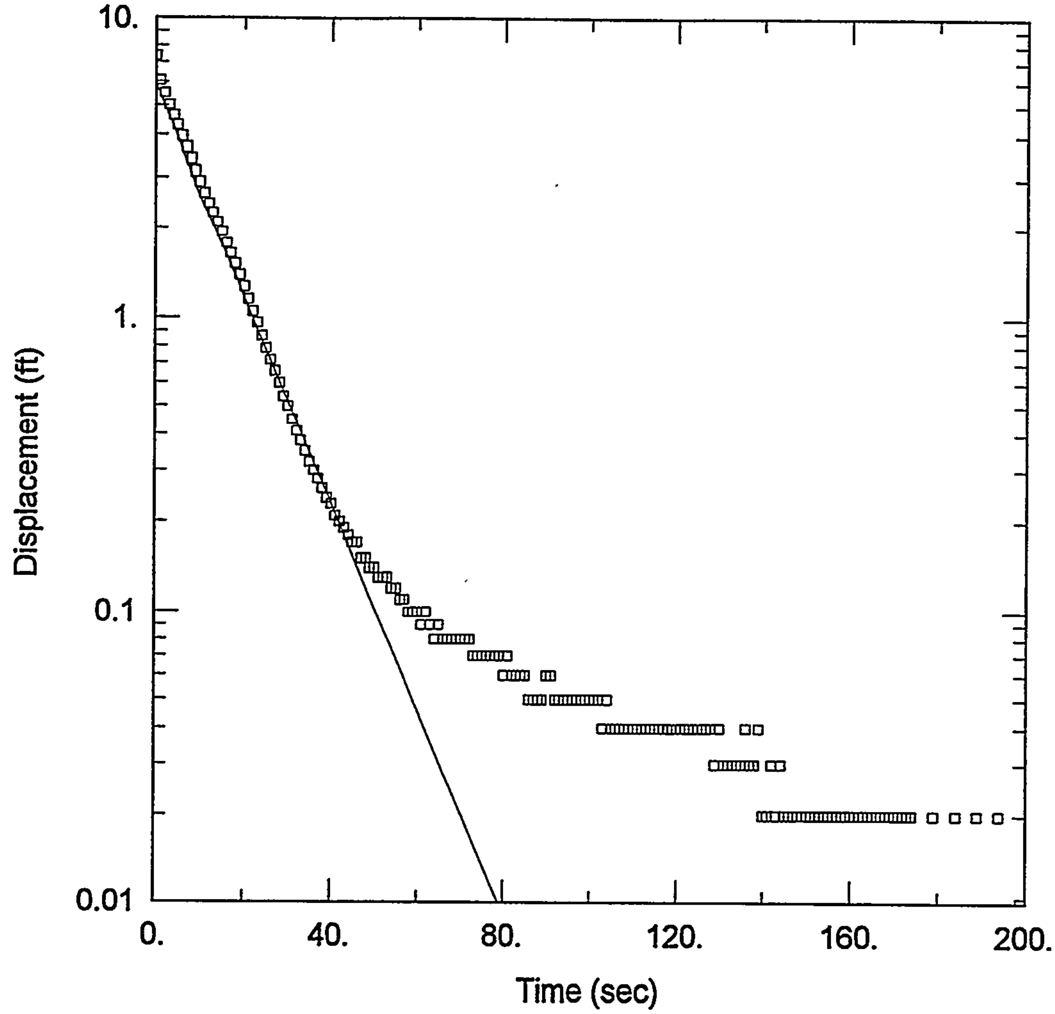
Saturated Thickness: 4.5 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 7.23 ft Water Column Height: 15.6 ft
Casing Radius: 0.08333 ft Wellbore Radius: 0.5 ft
Screen Length: 5. ft Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined K = 182.8 ft/day
Solution Method: Bouwer-Rice y0 = 6.181 ft




## X701B-074G TEST 2

Data Set: C:\AQTE\74G-1.AQT
Date: 03/27/97
Time: 09:19:48

## AQUIFER DATA

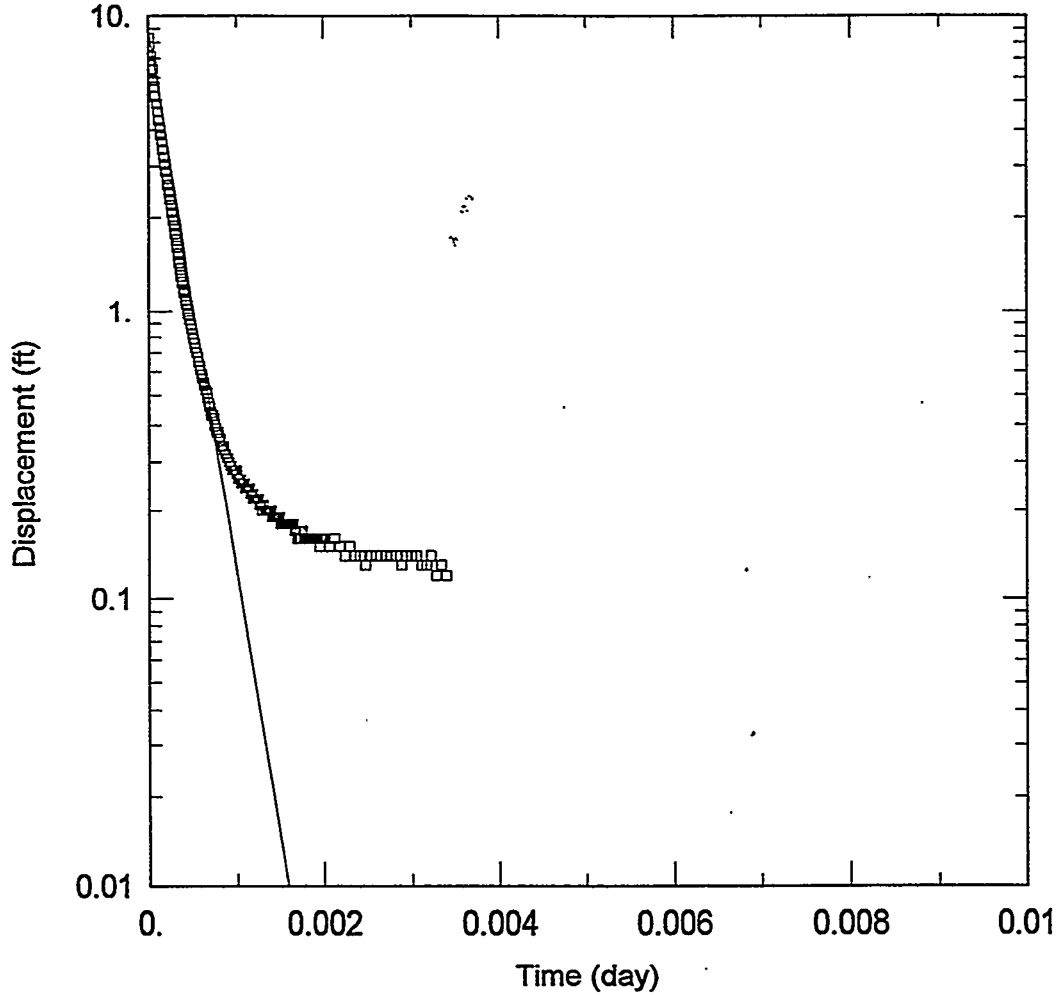
Saturated Thickness: 4.5 ft
Anisotropy Ratio (Kz/Kr): 1.

## WELL DATA

Initial Displacement: 7.36 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 15.6 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

## SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 0.001878 ft/sec
y0 = 5.843 ft




X701B-075G TEST 1

Data Set: C:\AQTE\75G-1.AQT
Date: 03/27/97 Time: 11:01:37

AQUIFER DATA

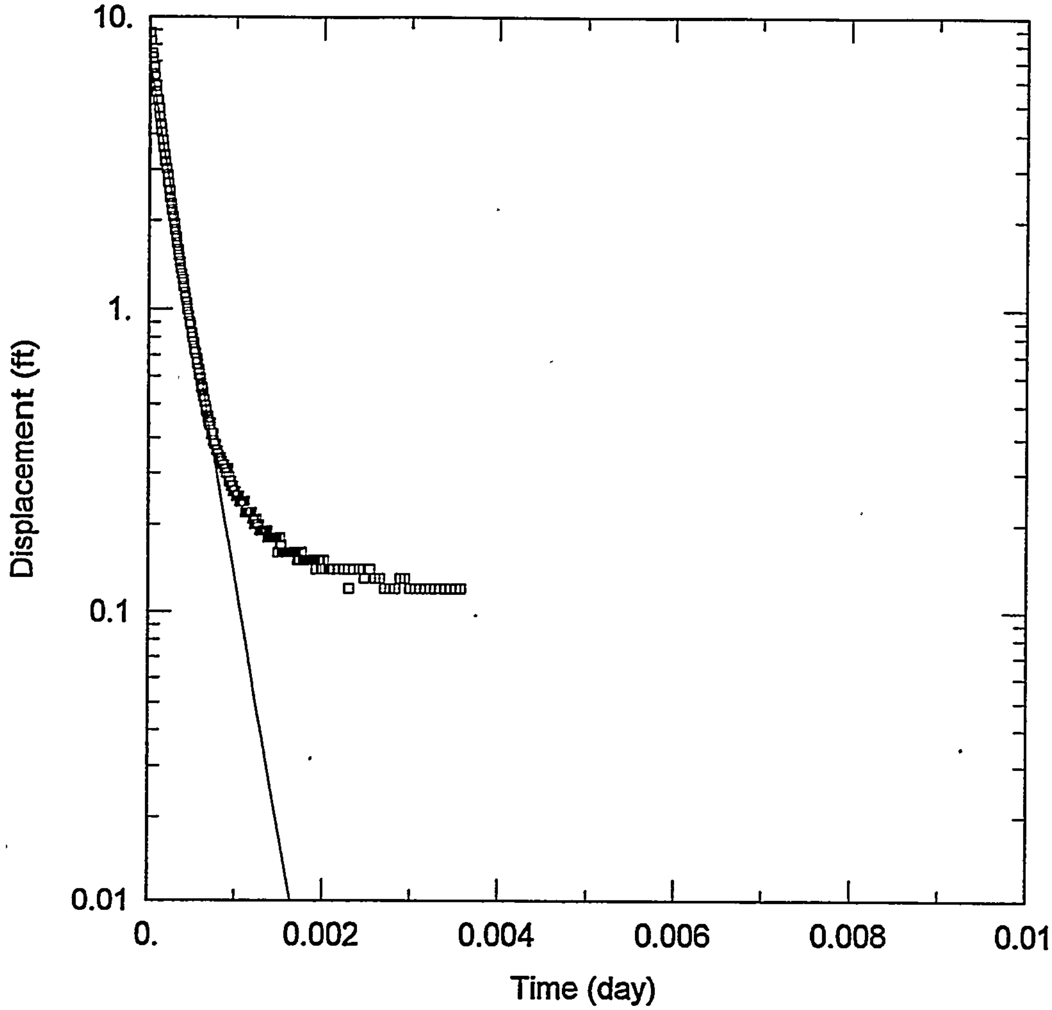
Saturated Thickness: 4.75 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 8.36 ft Water Column Height: 15.58 ft
Casing Radius: 0.08333 ft Wellbore Radius: 0.5 ft
Screen Length: 5. ft Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined K = 99.04 ft/day
Solution Method: Bouwer-Rice y0 = 8.771 ft




X701B-075G TEST 2

Data Set: C:\AQTE\75G-2.AQT
Date: 03/27/97
Time: 10:00:21

AQUIFER DATA

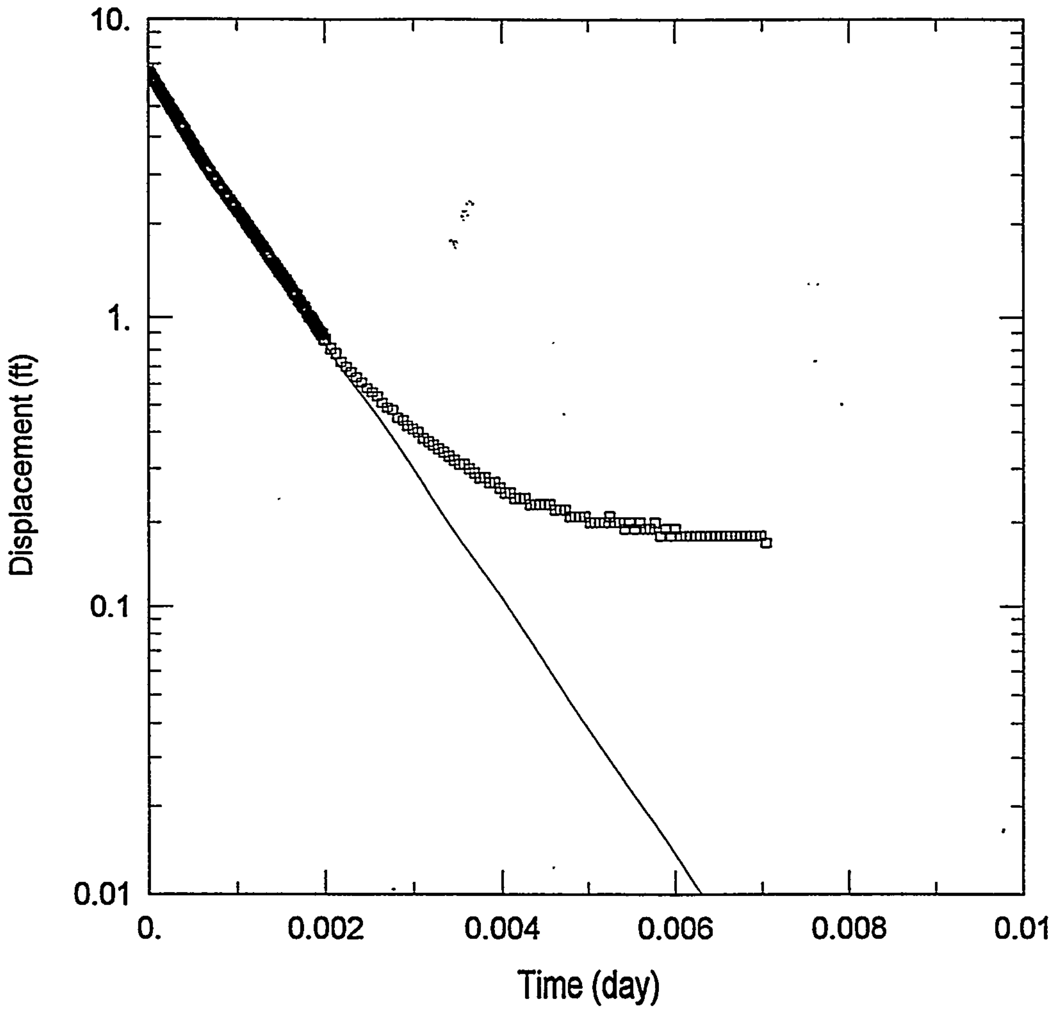
Saturated Thickness: 4.75 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 8.8 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 15.58 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 92.64 ft/day
y0 = 6.945 ft




X701B-076G TEST 1

Data Set: C:\AQTE\76G-1.AQT
Date: 03/27/97 Time: 11:04:14

AQUIFER DATA

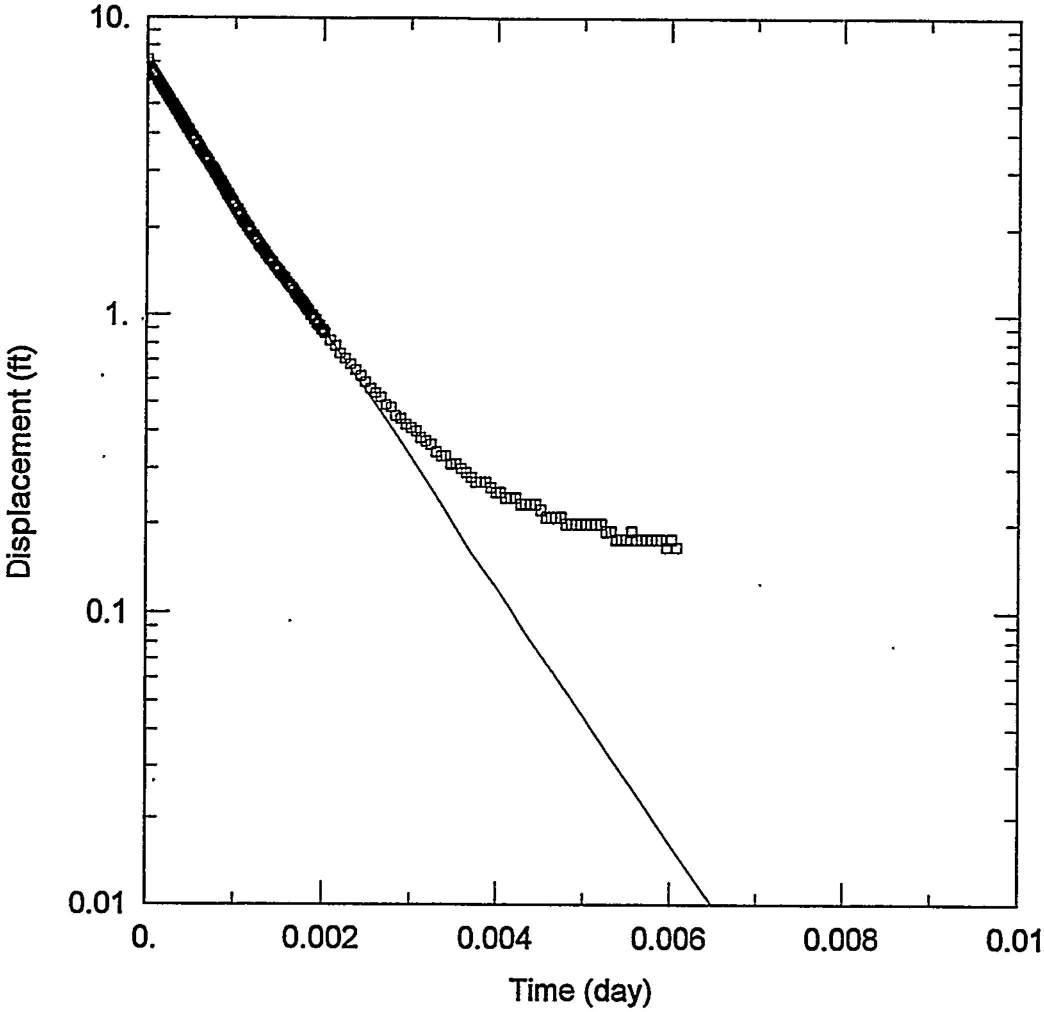
Saturated Thickness: 3.0 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 6.75 ft Water Column Height: 16.3 ft
Casing Radius: 0.08333 ft Wellbore Radius: 0.5 ft
Screen Length: 5. ft Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined K = 24.2 ft/day
Solution Method: Bouwer-Rice y0 = 6.619 ft




701B-076G TEST 2

Data Set: C:\AQTE\76G-2.AQT
Date: 03/27/97 Time: 10:44:36

AQUIFER DATA

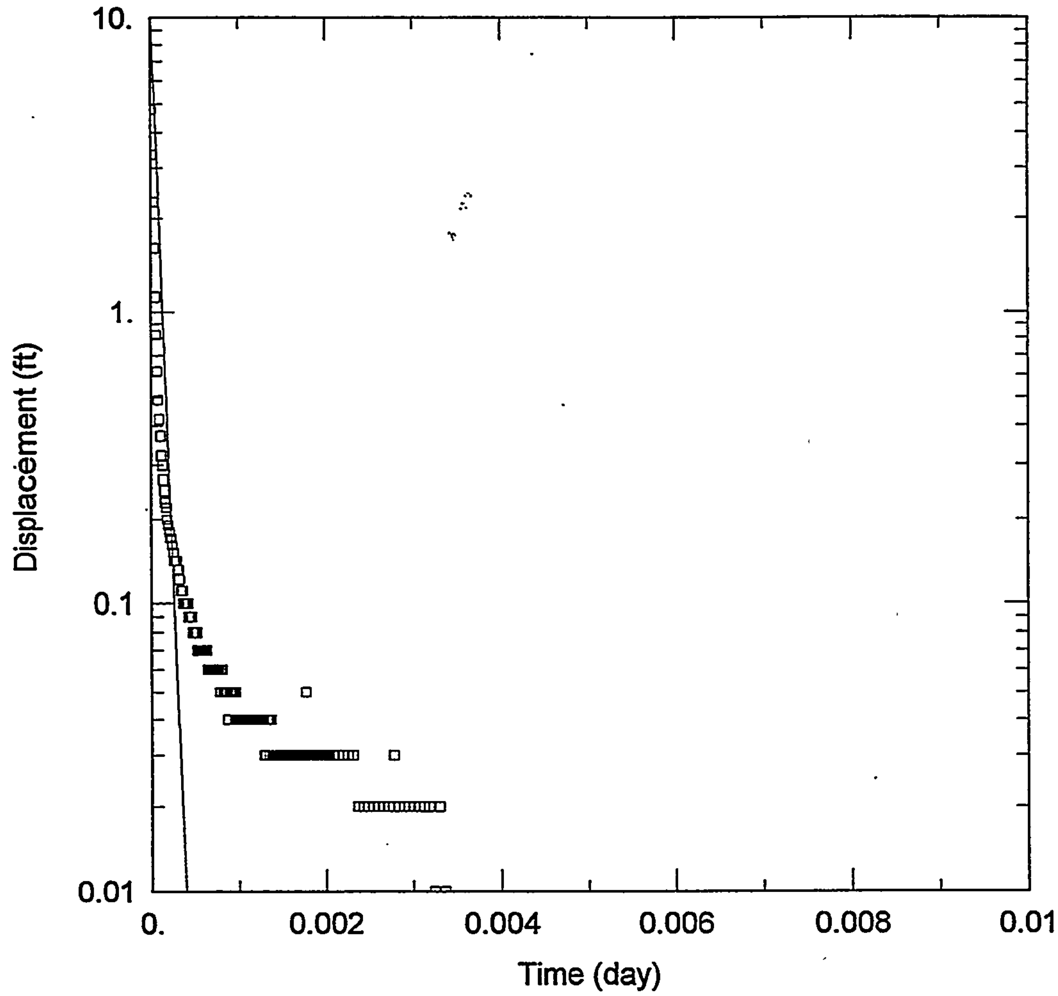
Saturated Thickness: 3.0 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 7.11 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 16.3 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 23.53 ft/day
y0 = 6.683 ft




X701B-077G TEST 1

Data Set: C:\AQTE\77G-1.AQT
Date: 03/27/97 Time: 10:18:23

AQUIFER DATA

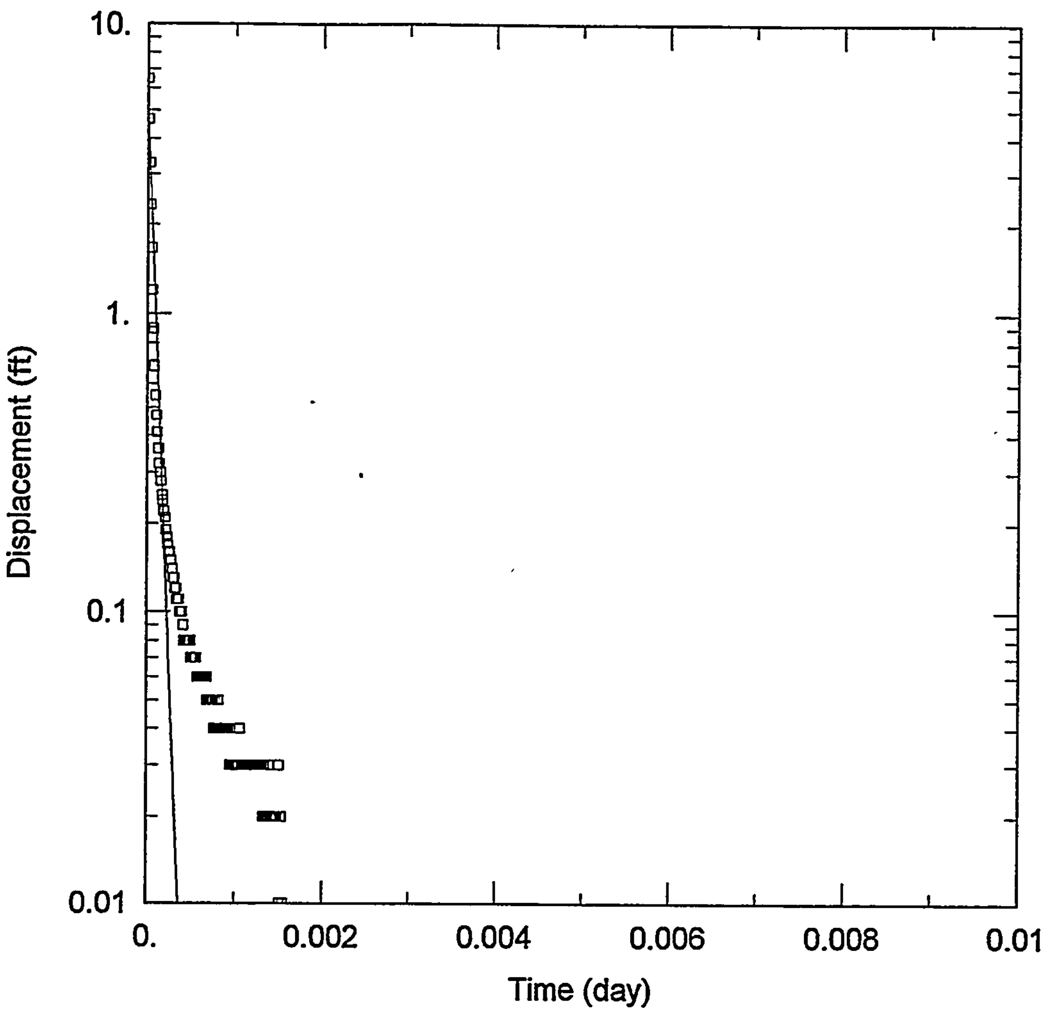
Saturated Thickness: 6. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 4.79 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 16.38 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 411.1 ft/day
y0 = 10.06 ft




X701B-077G TEST 2

Data Set: C:\AQTE\77G-2.AQT
Date: 03/27/97 Time: 11:06:56

AQUIFER DATA

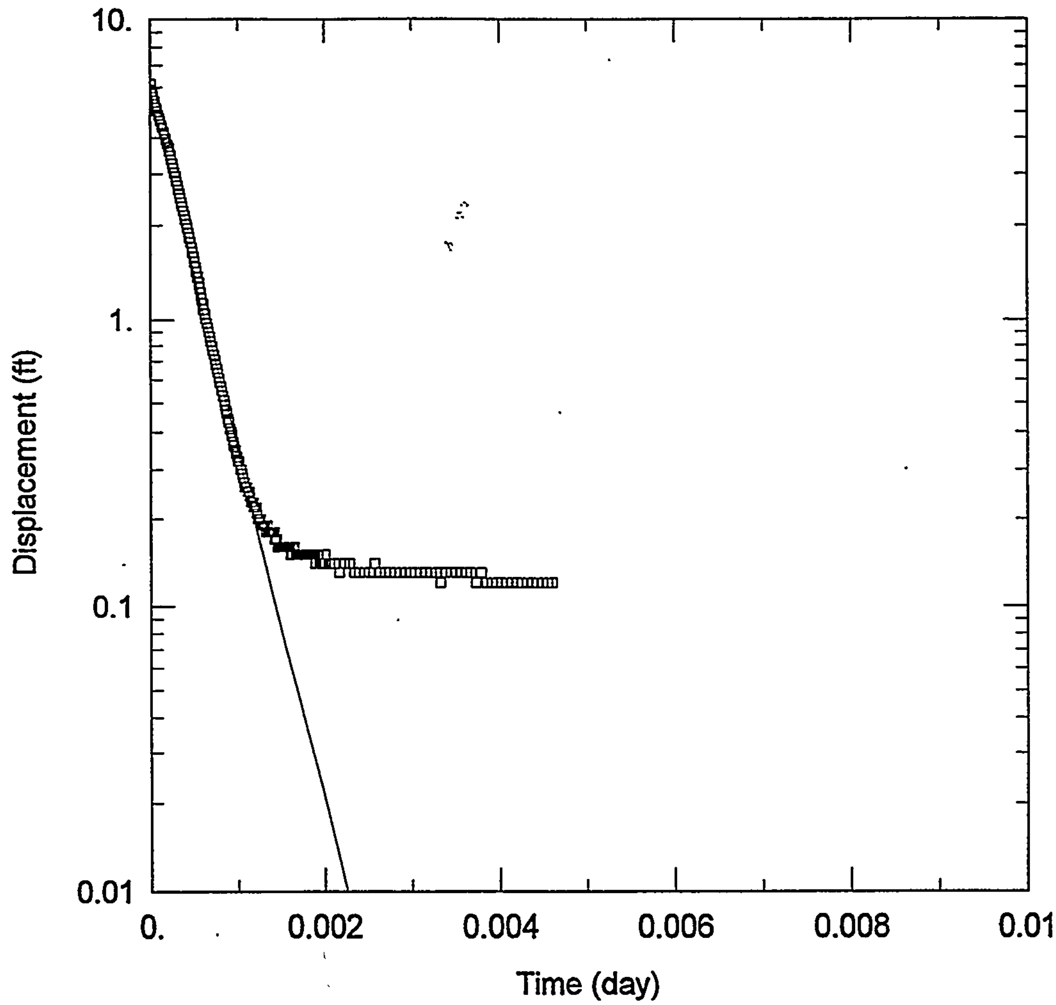
Saturated Thickness: 6. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 6.5 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 16.38 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 393.2 ft/day
y0 = 4.823 ft




## X701B-078G TEST 1

Data Set: C:\AQTE\78G-1.AQT
Date: 03/27/97 Time: 11:09:10

## AQUIFER DATA

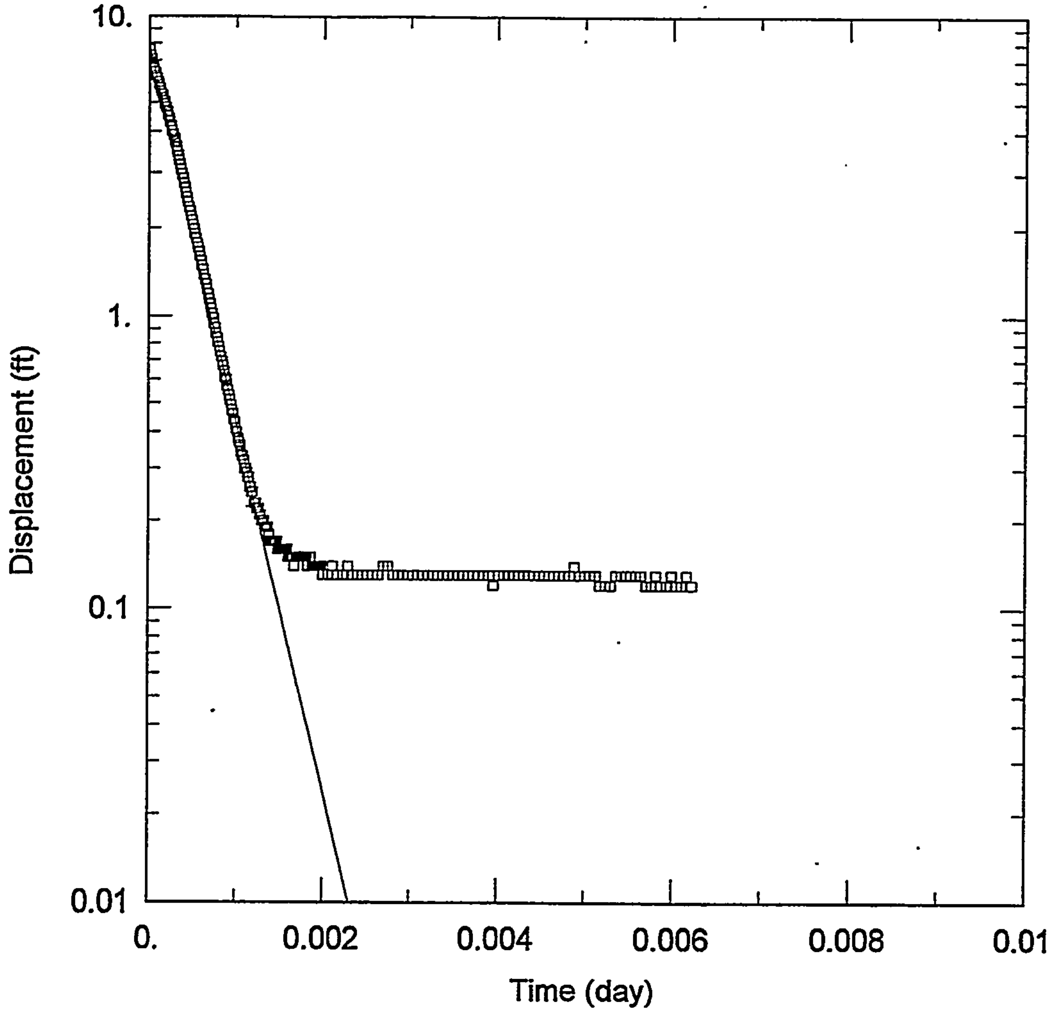
Saturated Thickness: 6. ft Anisotropy Ratio (Kz/Kr): 1.

## WELL DATA

Initial Displacement: 6.13 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 15.88 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

## SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 65.51 ft/day
y0 = 5.732 ft




X701B-078G TEST 2

Data Set: C:\AQTE\78G-2.AQT
Date: 03/27/97
Time: 10:26:04

AQUIFER DATA

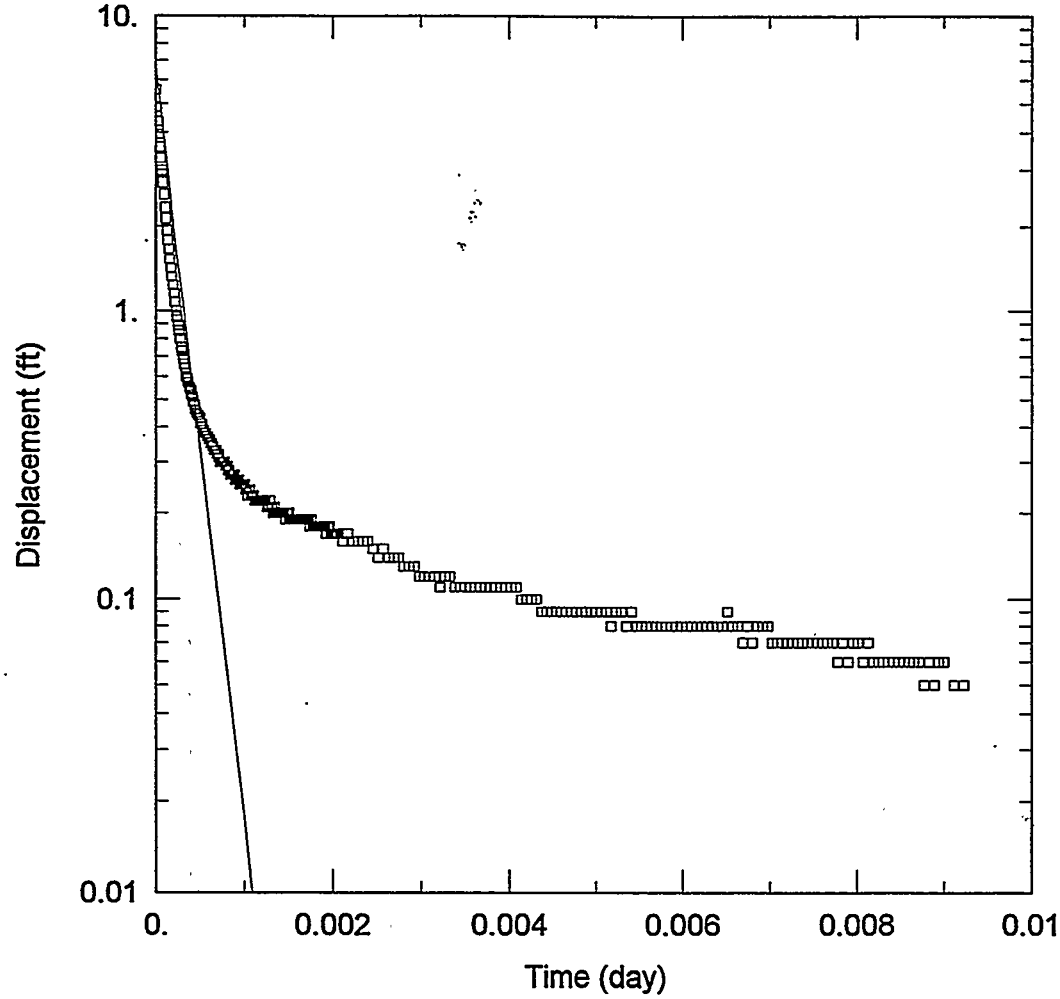
Saturated Thickness: 6. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

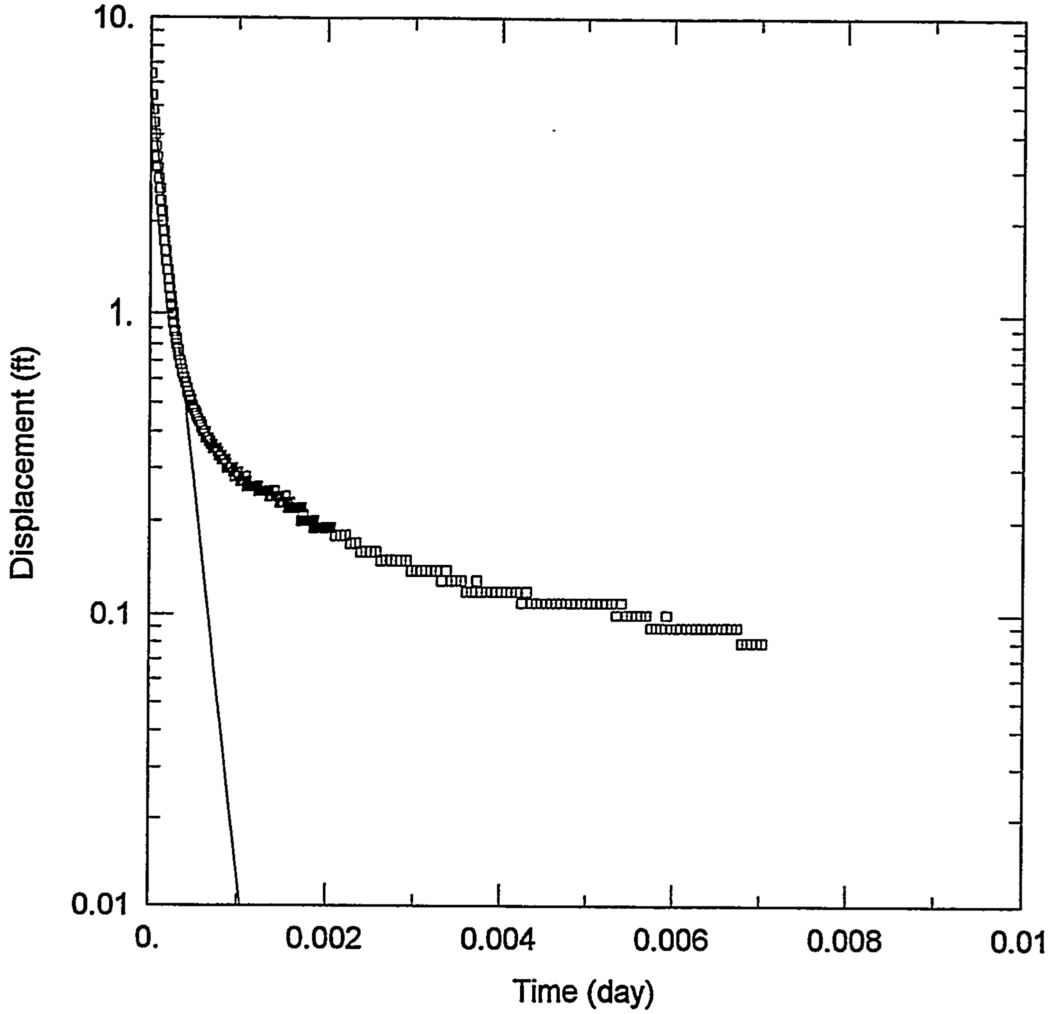
Initial Displacement: 7.6 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 15.88 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 67.45 ft/day
y0 = 7.792 ft




| X701-079G TEST 1 | |
|---|---|
| Data Set: C:\AQTE\79G-1.AQT | |
| Date: 03/27/97 | Time: 10:27:40 |
| **AQUIFER DATA** | |
| Saturated Thickness: 6.5 ft | Anisotropy Ratio (Kz/Kr): 1. |
| **WELL DATA** | |
| Initial Displacement: 5.58 ft | Water Column Height: 18.3 ft |
| Casing Radius: 0.08333 ft | Wellbore Radius: 0.5 ft |
| Screen Length: 5. ft | Gravel Pack Porosity: 0.4 |
| **SOLUTION** | |
| Aquifer Model: Confined | K = 142.6 ft/day |
| Solution Method: Bouwer-Rice | y0 = 6.632 ft |




X701B-79G TEST 2

Data Set: C:\AQTE\79G-2.AQT
Date: 03/27/97
Time: 13:22:29

AQUIFER DATA

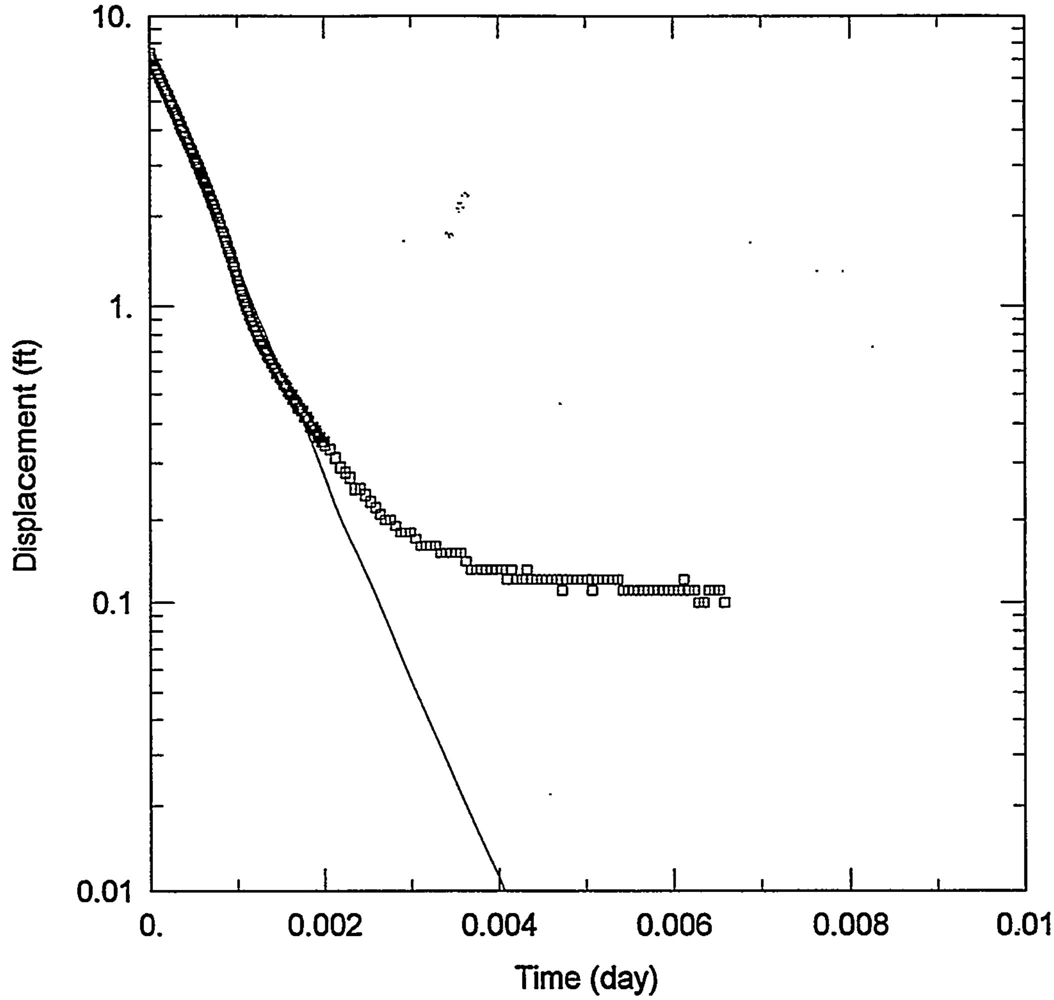
Saturated Thickness: 6.5 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 6.44 ft
Casing Radius: 0.083 ft
Screen Length: 5. ft
Water Column Height: 18.33 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 146.6 ft/day
y0 = 5.732 ft




X701B-080G TEST 1

Data Set: C:\AQTE\80G-1.AQT
Date: 03/27/97
Time: 10:30:30

AQUIFER DATA

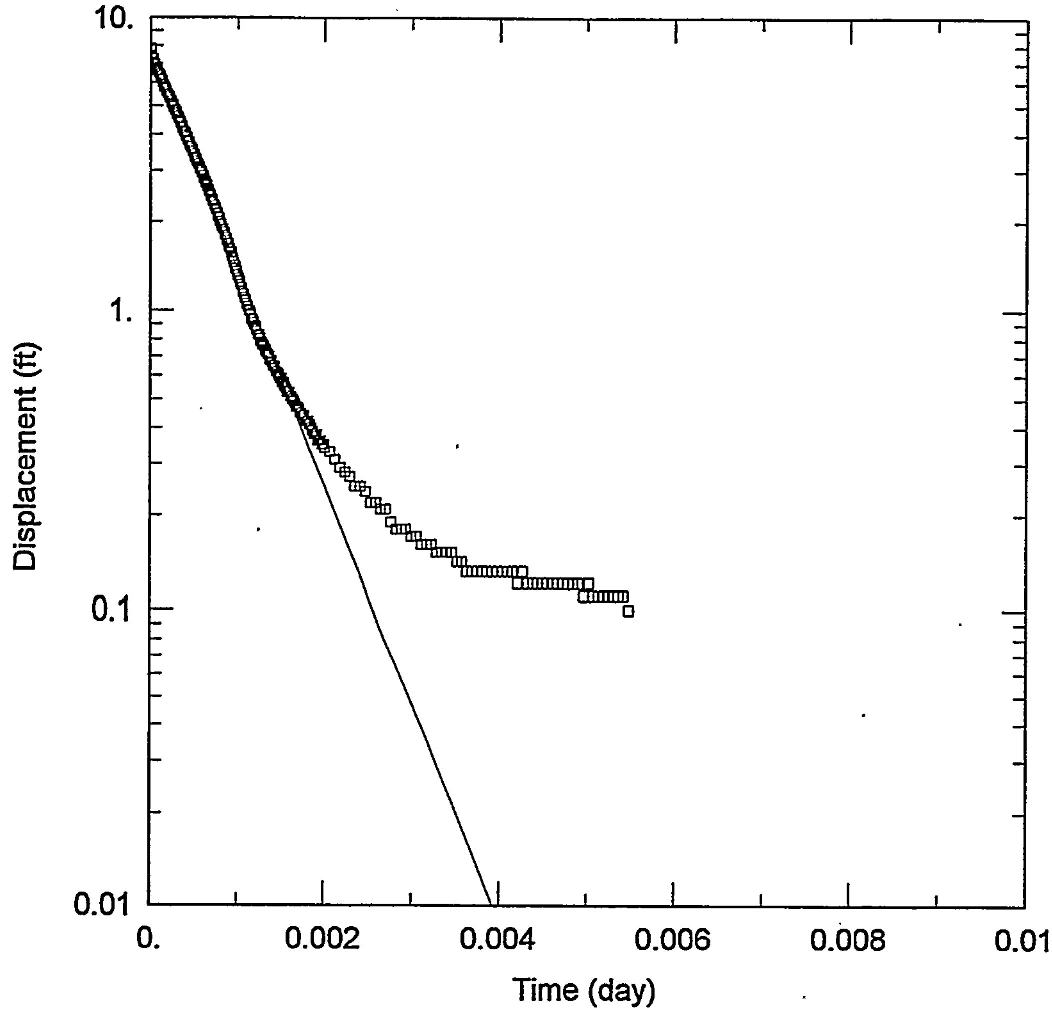
Saturated Thickness: 6. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 7.36 ft
Water Column Height: 14.18 ft
Casing Radius: 0.08333 ft
Wellbore Radius: 0.5 ft
Screen Length: 5. ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
K = 31.68 ft/day
Solution Method: Bouwer-Rice
y0 = 6.813 ft




X701B-080G TEST 2

Data Set: C:\AQTE\80G-2.AQT
Date: 03/27/97 Time: 11:12:20

AQUIFER DATA

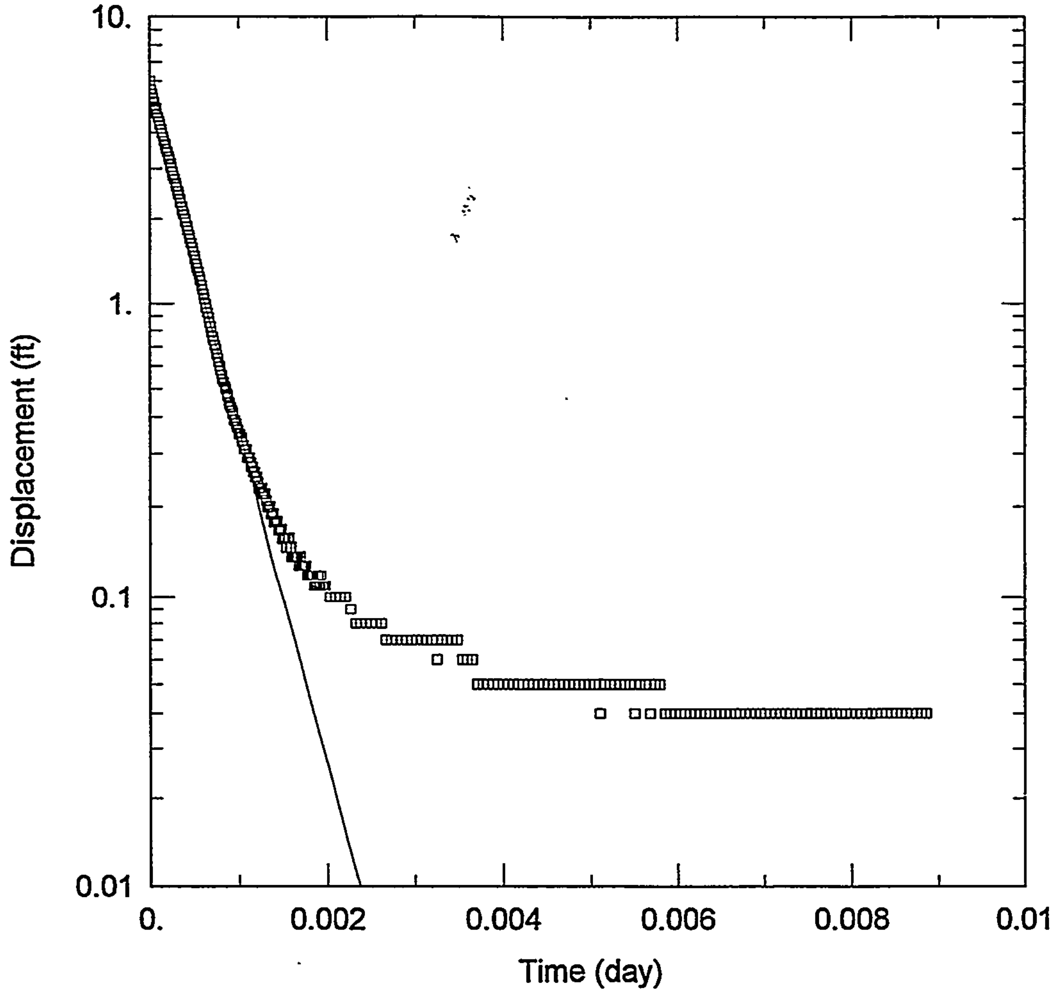
Saturated Thickness: 6. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 7.86 ft Water Column Height: 14.18 ft
Casing Radius: 0.08333 ft Wellbore Radius: 0.5 ft
Screen Length: 5. ft Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined K = 38.29 ft/day
Solution Method: Bouwer-Rice y0 = 7.337 ft




X701B-081G TEST 1

Data Set: C:\AQTE\81G-1.AQT
Date: 03/27/97
Time: 11:00:20

AQUIFER DATA

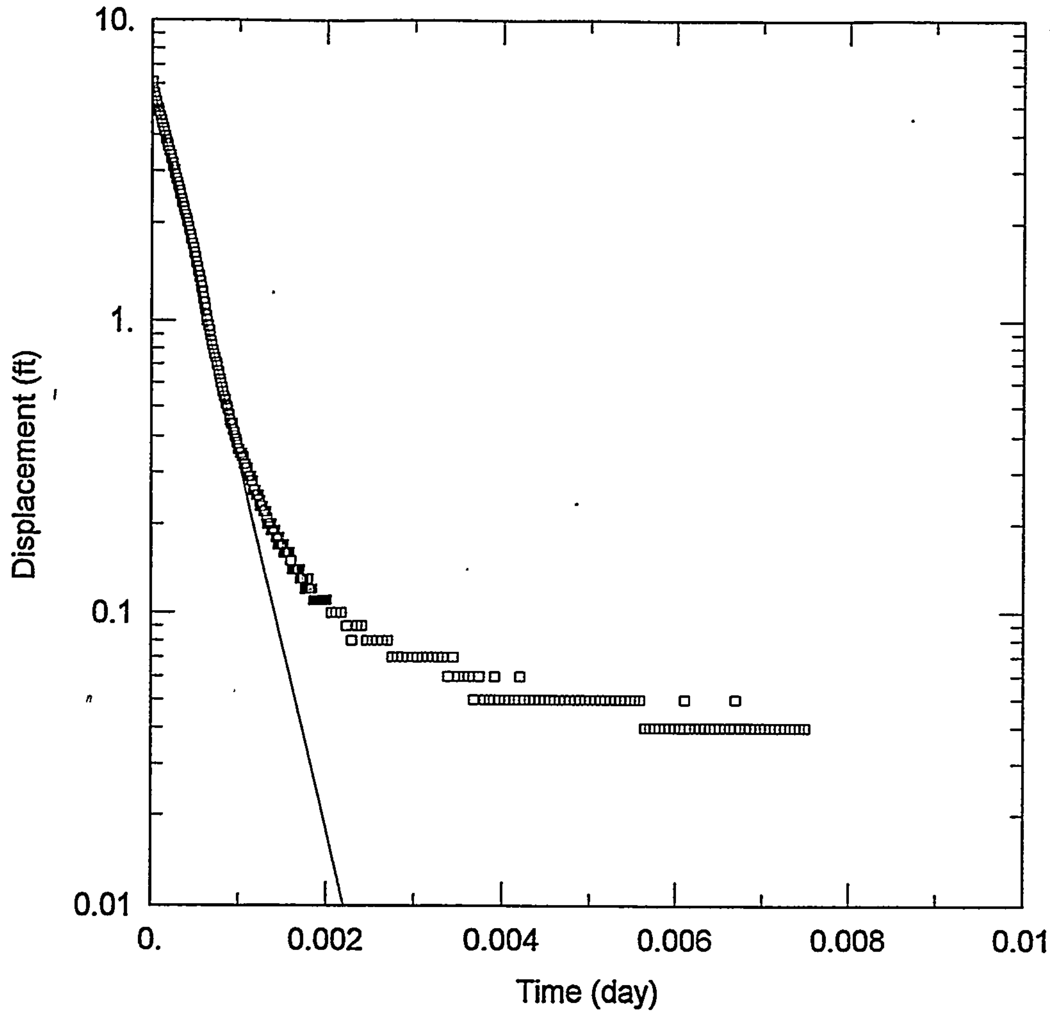
Saturated Thickness: 4.5 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 6.02 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 14.66 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 60.18 ft/day
y0 = 5.012 ft




X701B-081G TEST 2

Data Set: C:\AQTE\81G-2.AQT
Date: 03/27/97 Time: 11:14:42

AQUIFER DATA

Saturated Thickness: 4.5 ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

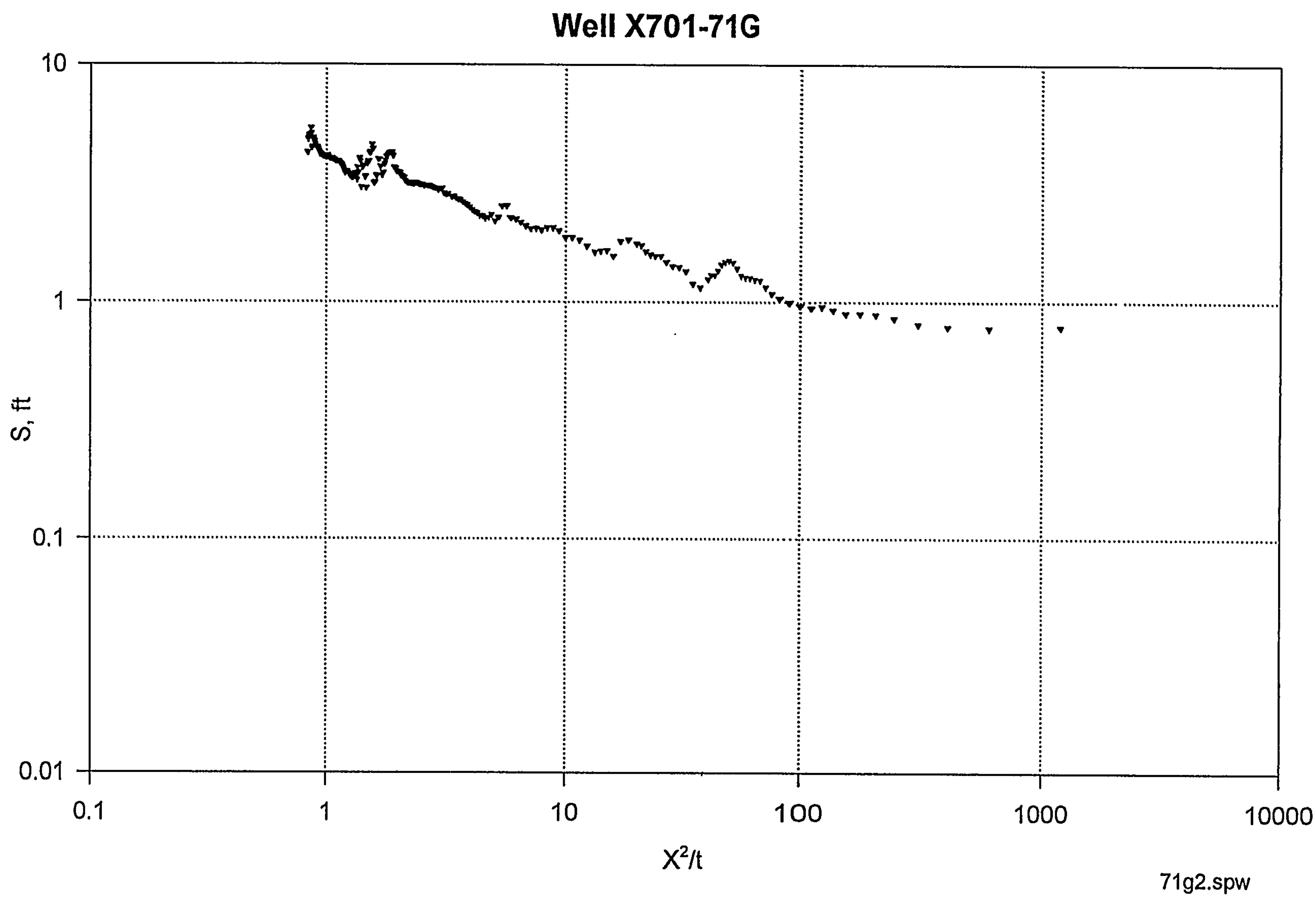
Initial Displacement: 6.09 ft
Casing Radius: 0.08333 ft
Screen Length: 5. ft
Water Column Height: 14.66 ft
Wellbore Radius: 0.5 ft
Gravel Pack Porosity: 0.4

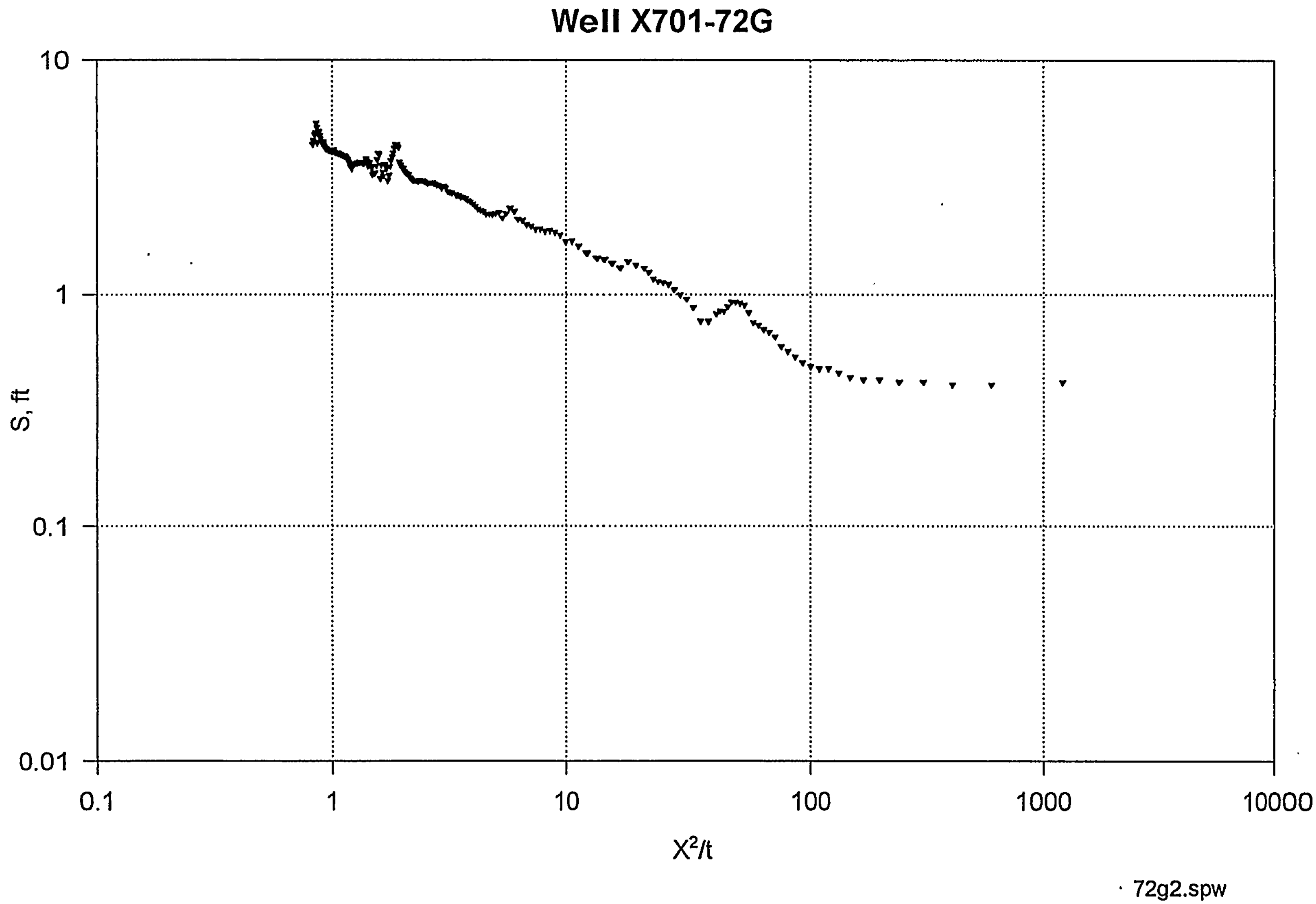
SOLUTION

Aquifer Model: Confined
Solution Method: Bouwer-Rice
K = 66.68 ft/day
y0 = 5.98 ft

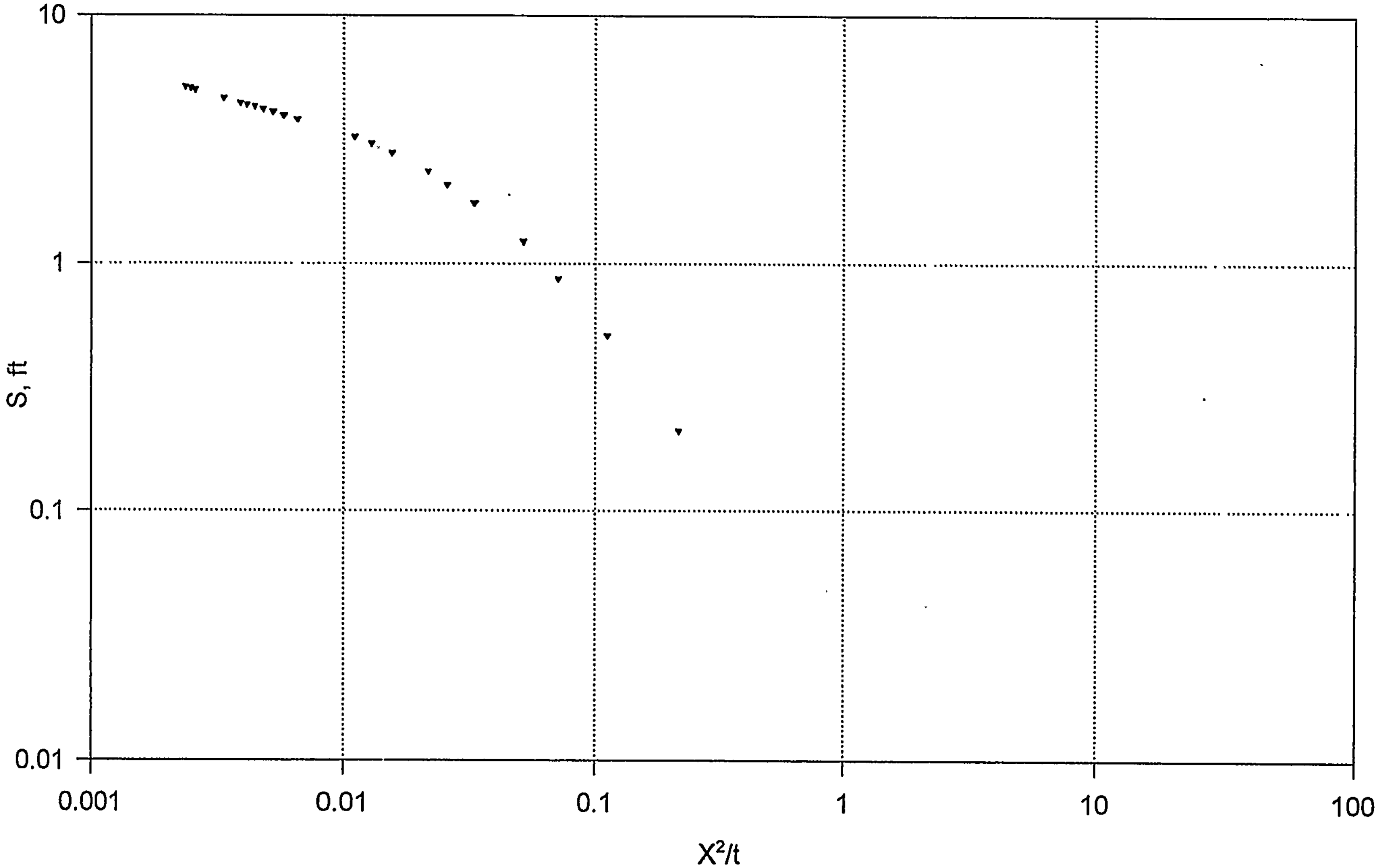
**Appendix E**

**Pressure Transducer Data from the West Horizontal Well Pumping Test**

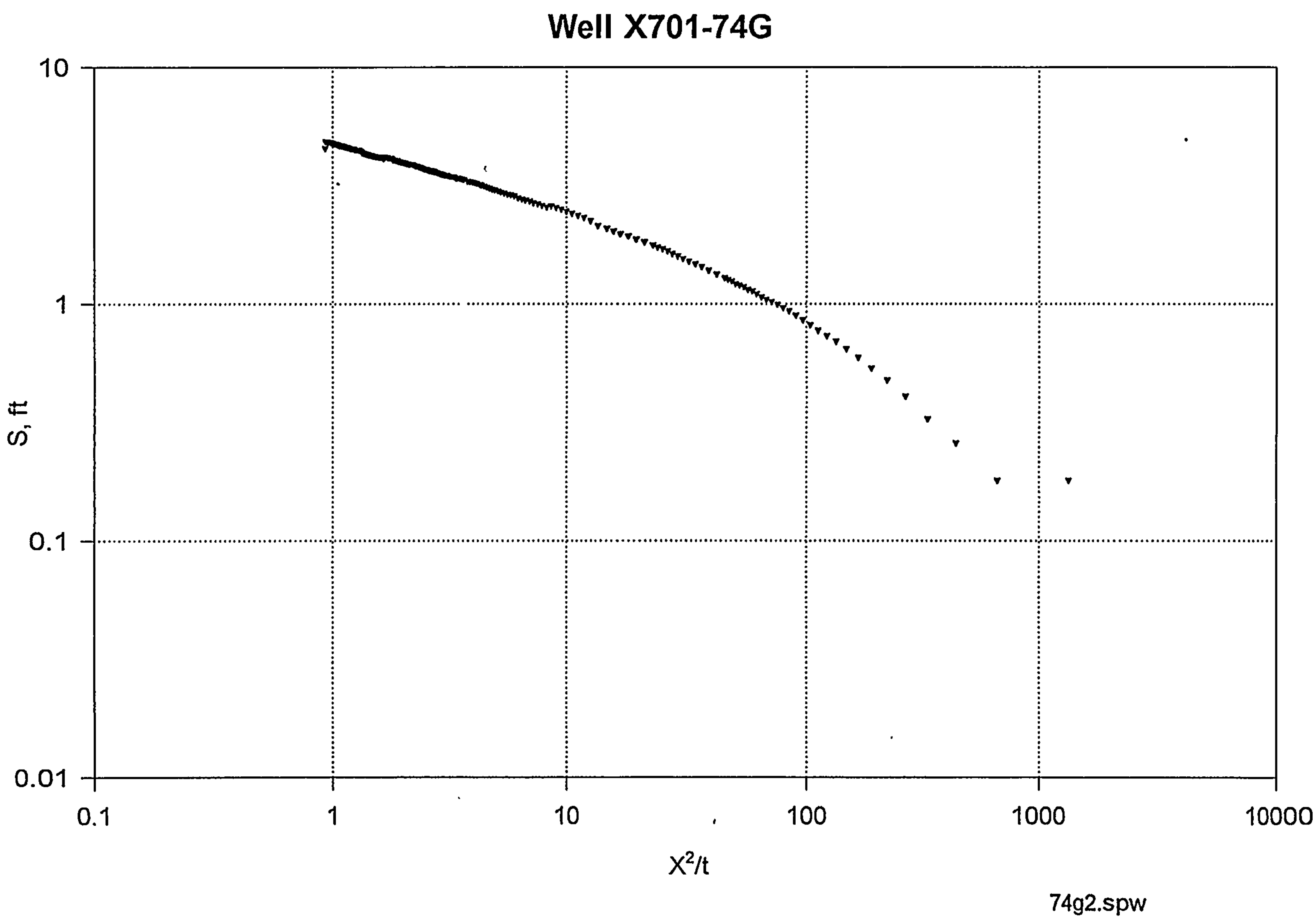

Well X701-71G
S, ft
10
1
0.1
0.01
0.1
1
10
100
1000
10000
X²/t
71g2.spw

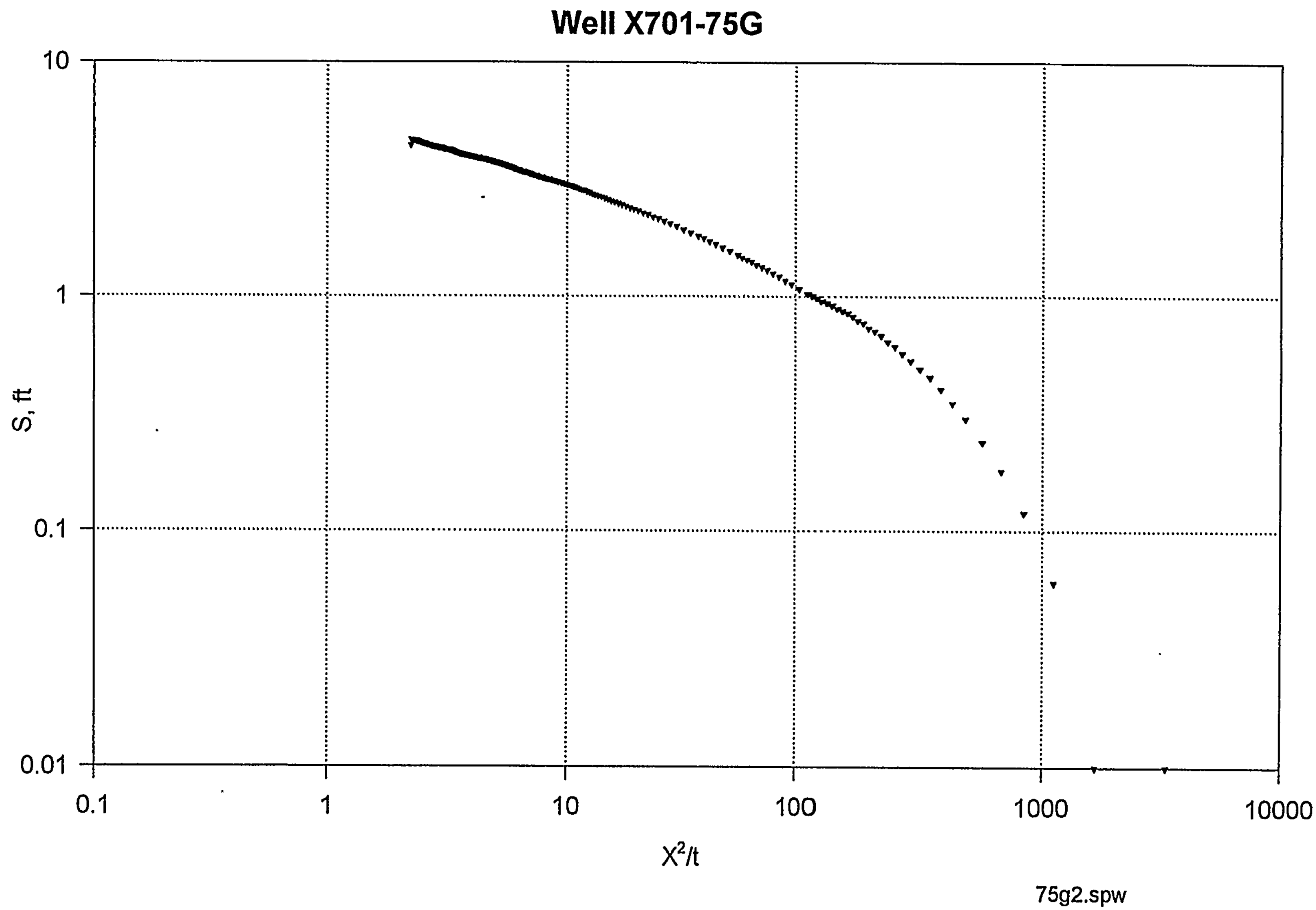

Well X701-72G
10
1
0.1
0.01
S, ft
0.1
1
10
100
1000
10000
X²/t
72g2.spw

# Well X701-73G

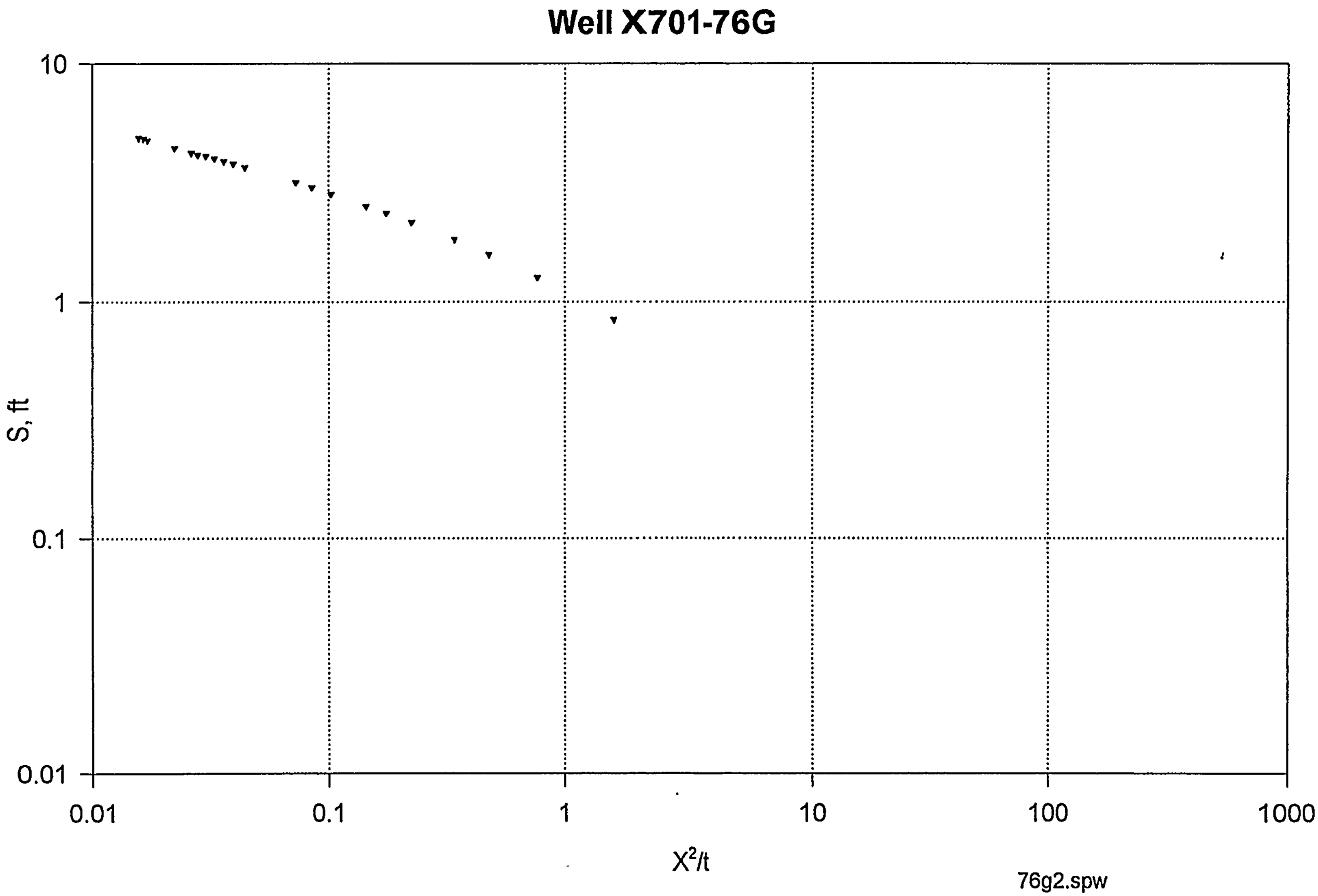


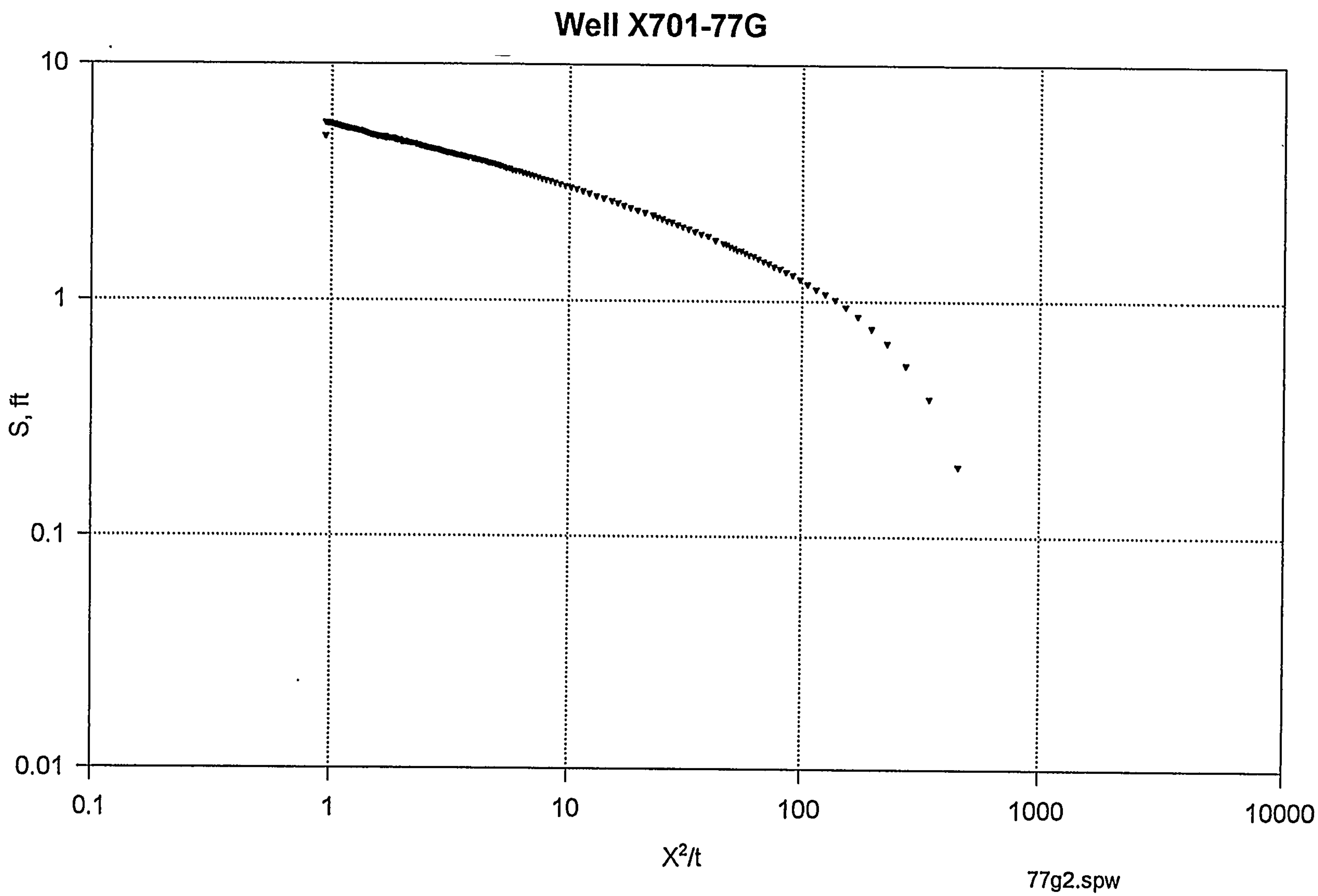

73g2.spw

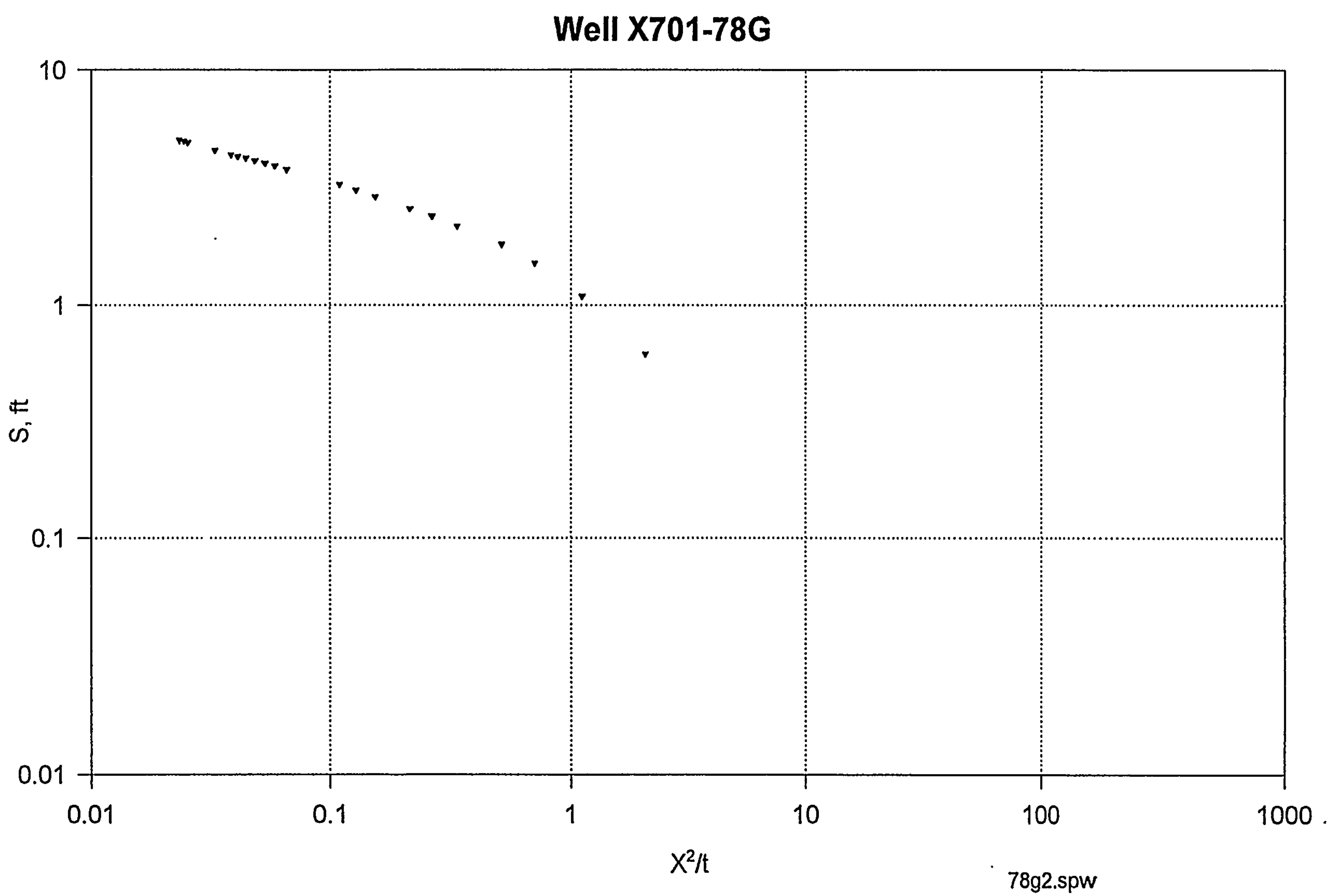

Well X701-74G
S, ft
10
1
0.1
0.01
0.1
1
10
100
1000
10000
$X^2/t$
74g2.spw

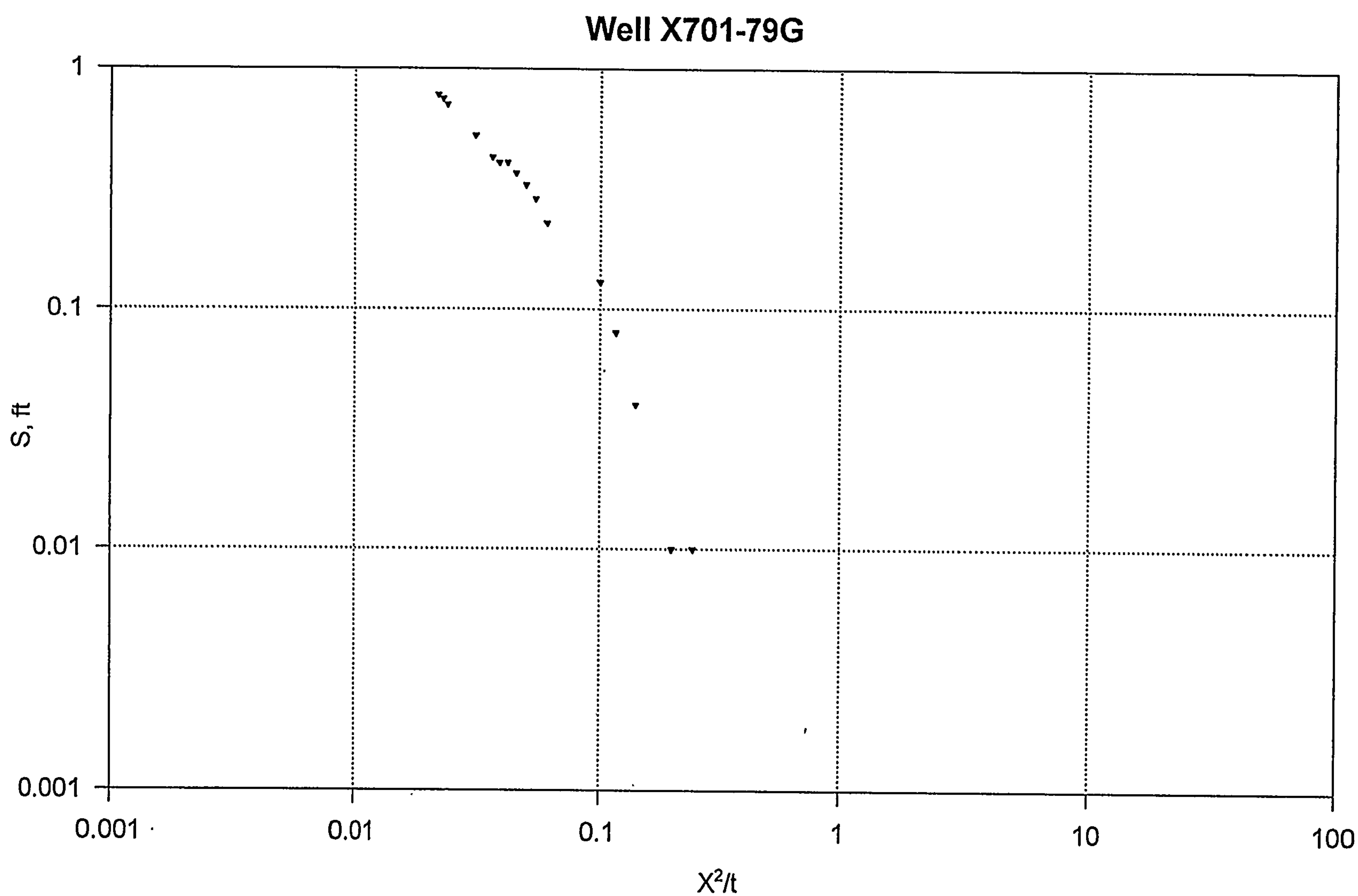


Well X701-75G
10
1
0.1
0.01
S, ft
0.1
1
10
100
1000
10000
X²/t
75g2.spw

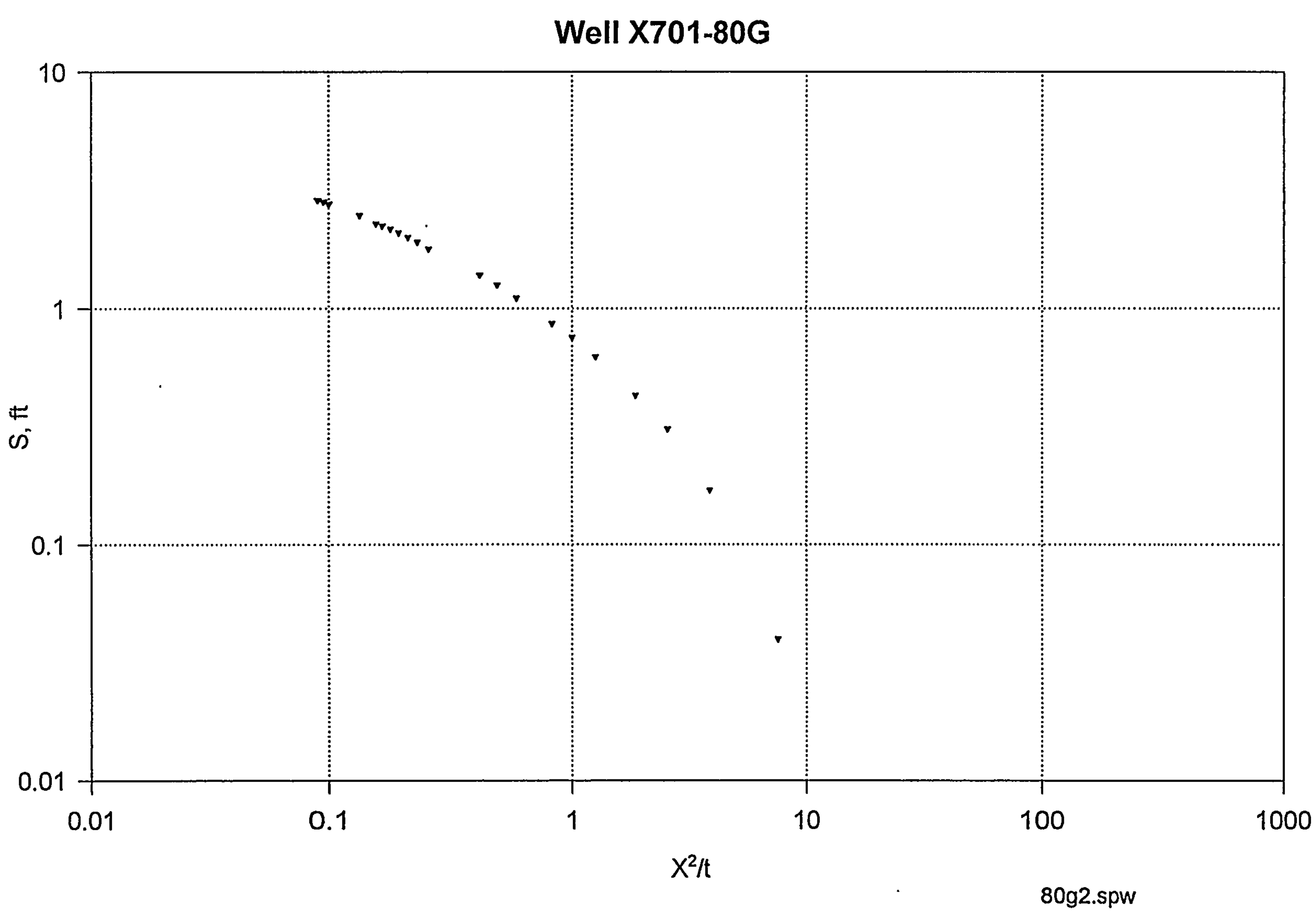

Well X701-76G
10
1
0.1
0.01
S, ft
0.01
0.1
1
10
100
1000
X²/t
76g2.spw


Well X701-77G
S, ft
10
1
0.1
0.01
0.1
1
10
100
1000
10000
X²/t
77g2.spw

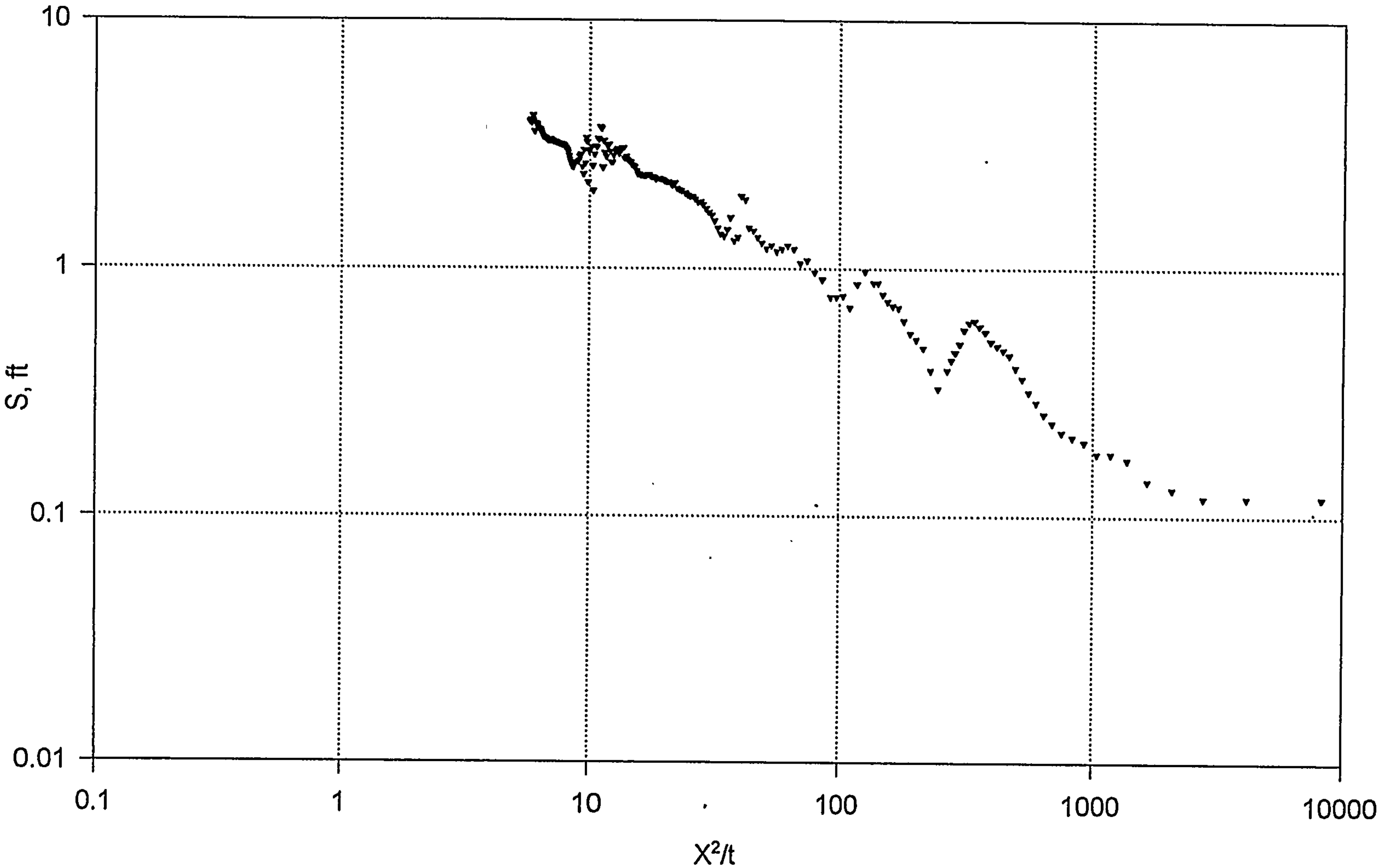

Well X701-78G
10
1
0.1
0.01
S, ft
0.01
0.1
1
10
100
1000
X²/t
78g2.spw




79g2.spw


Well X701-80G
10
1
0.1
0.01
S, ft
0.01
0.1
1
10
100
1000
X²/t
80g2.spw

## Well X701-81G




81g2.spw

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