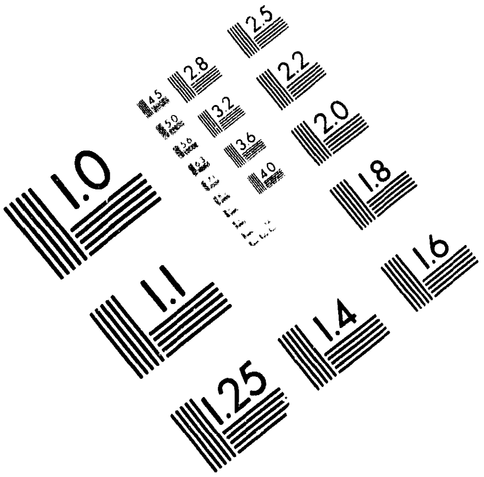
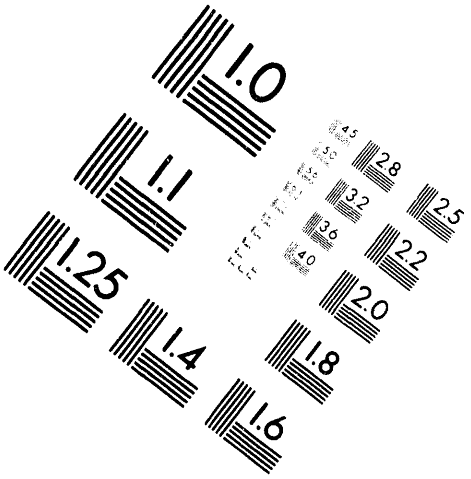
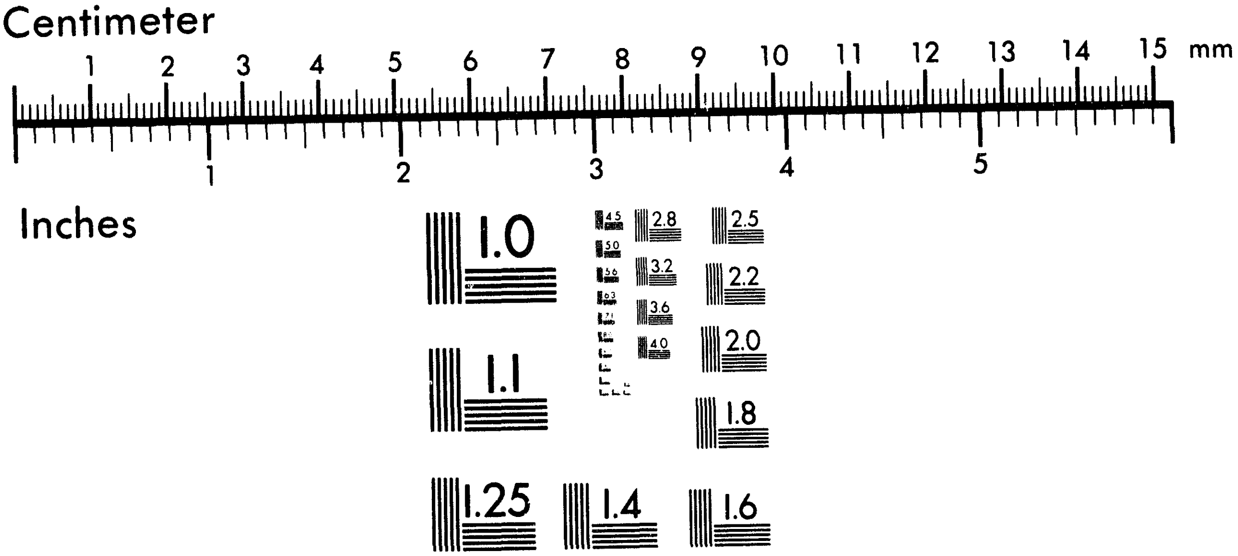


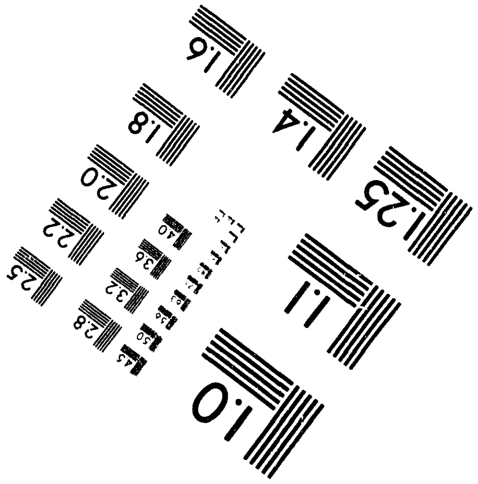


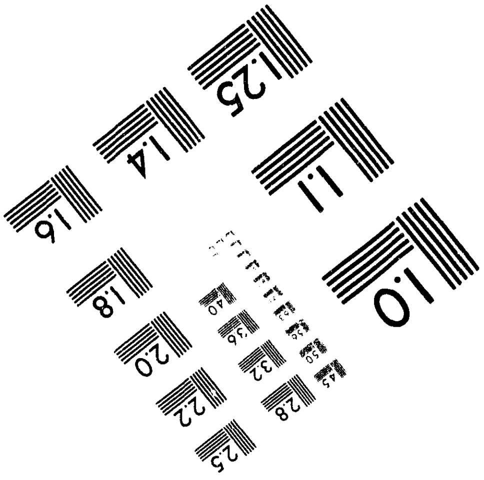
AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202







MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 2

ANL/ESD/TM-69

Pilot-Scale Studies of Soil Vapor Extraction and Bioventing for Remediation of a Gasoline Spill at Cameron Station, Alexandria, Virginia

by W. Harrison, C.J. Joss,* L.E. Martino,* C.V. Pearson, R.W. Peters, D.H. Pope,*
D.M. Dziewulski,* L.A. Raphaelian, L.L. Reed, L.T. Shepard, and T. Sydelko

Energy Systems Division,
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

July 1994

Work sponsored by United States Army Corps of Engineers, Baltimore District

---

**Joss is affiliated with Applied Environmental Sciences, Ltd.; Martino, with Environmental Assessment Division; and Pope and Dziewulski, with Bioindustrial Technologies, Inc.*

Contents

Acknowledgments x

Abstract 1

1 Introduction 1

- 1.1 Background 1
- 1.2 Objectives 3
- 1.3 Approach 5

2 Installation and Testing of Soil-Gas Monitoring Probes and Extraction Wells 6

- 2.1 Phase 1: Installation of Exploratory Borings and Soil-Gas Monitoring Probes 6
- 2.2 Phase 2: Installation of Trench 1 and Horizontal Wells 1, 2, and 3 8
- 2.3 Phase 3: Installation of Trench 2 and Horizontal Wells 4 and 5 and Installation of Vertical Enhancement Wells at Trench 1 8
- 2.4 Summary 9

3 Physical/Chemical Characterization of Fill and Groundwater Samples 10

- 3.1 Soil Characterization 10
  - 3.1.1 Sample Collection 10
  - 3.1.2 Analytical Procedures 10
  - 3.1.3 Characterization of Fill Material 10
- 3.2 Groundwater Characterization 17
  - 3.2.1 Sample Collection 17
  - 3.2.2 Analytical Procedures 17
  - 3.2.3 Groundwater Characterization Results 18
- 3.3 Summary 20

4 Studies of Microbial Populations Contained in the Soil of Cameron Station and their Potential to Degrade Components of Gasoline 21

- 4.1 Objectives and Approach 21
  - 4.1.1 Objectives of the Study 21
  - 4.1.2 Approach Used during the Study 21
- 4.2 Methods, Field Observations, and Additional Data 23
  - 4.2.1 Methods 23
  - 4.2.2 Field Observations 26
  - 4.2.3 Additional Data 29
- 4.3 Summary of Results 37
  - 4.3.1 Bacteria Recovered from Soil Cores 37
  - 4.3.2 Possible Relationships between Bacterial Levels and Concentration of Hydrocarbons 38
  - 4.3.3 Possible Nutrient Limitations 49
  - 4.3.4 Biometer-Flask Studies 50
- 4.4 References 52

Contents (Cont.)

5 Determination of Soil Vapor Properties and the Permeability of Fill Material to Air 53

5.1 Air-Phase Permeability 53
5.2 Full-Scale Permeability Field Tests 55
5.2.1 Equipment and Measurements 55
5.2.2 Site Classification and Geometry 56
5.3 Small-Scale Permeability Field Tests 56
5.4 Equipment and Procedures Used 57
5.4.1 Description of Equipment 57
5.4.2 Field Procedures 64
5.5 Description of Field Experiments 66
5.5.1 Vapor-Flow and Vapor-Property Measurements of Vapor Extracted by V4, April 5, 1993 66
5.5.2 Intermediate-Scale Soil Permeability-to-Air Tests 66
5.5.3 Measurement of Vapor Properties during Evacuation 68
5.6 Results of AIRTEST Modeling 68
5.7 Summary 68

6 Implementation of SVE Program 73

6.1 Equipment Description 73
6.1.1 Overview of Vapor Extraction Equipment 73
6.1.2 Background on the Equipment 73
6.1.3 Summary of the Equipment Operations 74
6.2 Equipment Operation and Upgrades 74
6.2.1 V2B Vapor Extraction Equipment 74
6.2.2 V2B Components 75
6.2.3 V2B Start-Up 75
6.2.4 V2B Operational Upgrades 76
6.2.5 V2B Operation on Vertical Wells 76
6.2.6 V4 Vapor Extraction Equipment 77
6.3 Measurement of Equipment-Operational and Related Environmental Variables 77
6.3.1 Capacities of the V2B Extraction Equipment 77
6.3.2 Capacities of the V4 Extraction Equipment 78
6.3.3 Weather Conditions Related to the V2B and V4 Vapor Extraction Equipment and Horizontal Wells 78
6.3.4 Monitoring of Free-Product Thickness and Groundwater Elevations 81

7 Conclusions and Recommendations 88

7.1 Conclusions 88
7.2 Recommendations for Further Study 89

Appendix A: Wells 1, 2, and 3 — Installation Description for Horizontal-Well SVE 91

Appendix B: Wells 4 and 5 — Installation Description for Horizontal-Well SVE 105

Contents (Cont.)

Appendix C: Size Gradation Curves for Fill Samples 117

Appendix D: Database for Laboratory Samples 129

Appendix E: Description of the Degradation of Straight-Chain and Cyclic Petroleum Products 133

Appendix F: Basic Data for Groundwater Monitoring Wells, Individual Probes, Probe Clusters, and Flow-Enhancement Borings Installed by Argonne at Cameron Station 139

Appendix G: Results of April 5–8, 1993, Field Tests 143

Figures

1.1 Location of Cameron Station Military Reservation 2

1.2 Map Showing Location of Trenches 1 and 2, Horizontal Wells 1–5, Sand-Filled Borings (B1–B4), Monitoring Wells (PX-4, 5, 6, 8, 9, 10, 11 and MWS-7), Probes A–E and N–Q, and Probe Clusters F–M 4

2.1 Locations of Soil-Gas Monitoring Probes and Extraction Wells 7

3.1 Moisture Content as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia 14

3.2 Cation-Exchange Capacity as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia 15

3.3 Soil pH as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia 16

3.4 pH, Nitrate, and Phosphate Concentrations for Various Groundwater Samples Collected at Cameron Station, Virginia 19

4.1 Biometer Flask 25

4.2 Relationship between Product Vapor and Viable Bacteria 30

4.3 Relationship between Product Vapor and FITC Total Count 31

4.4 Concentration of Product Vapor and TPH along the Trench 32

4.5 Incidence of BTEX and Viable Bacteria 33

4.6 Incidence of Xylene and Viable Bacteria 34

4.7 Trended Relationship between Viable Bacteria and Toluene Concentration 35

Figures (Cont.)

4.8 Nonlinear Trend for Viable Anaerobic Bacteria 36

4.9 Nonlinear Trend for Manganese Concentration 37

4.10 Nonlinear Trend for Chloride Concentration and Pearson Correlation for Linearity of Chloride Data 38

4.11 Relationship between Aerobic APB and Formic Acid 39

4.12 Carbon Dioxide Production: Sample 100-9 43

4.13 Carbon Dioxide Production: Sample 100-9, as collected 43

4.14 Carbon Dioxide Production: Sample 140-8 44

4.15 Carbon Dioxide Production: Sample 140-8, as collected 44

4.16 Carbon Dioxide Production: Sample 50-5 45

4.17 Carbon Dioxide Production: Sample 50-5, as collected 45

4.18 Carbon Dioxide Production: Sample 205-8 46

4.19 Carbon Dioxide Production: Sample 205-8, as collected 46

4.20 Relationship of TPH and Viable Bacteria with Linear Distance of the Trench 48

4.21 Relationship between Viable Bacteria on TPH Concentration 49

4.22 Occurrence of Iron and Sulfate 51

5.1 Schematic of Test Setup 54

5.2 Schematic of Test Setup Equipment 58

5.3 Plot of Flow Versus Flowmeter Reading 63

6.1 Fuel Rate Curve — V2 and V4 80

6.2 Hydrograph MWS-7 82

6.3 Hydrograph PX-4 83

6.4 Hydrograph PX-5 84

6.5 Hydrograph PX-8 85

6.6 Hydrograph PX-9 86

6.7 Hydrograph PX-11 87

Figures (Cont.)

A.1 Lateral Well System Layout.. 94

A.2 Lateral Well System As-Built Elevation... 95

A.3 Lateral Well System Elevation — Design.. 97

A.4 Typical Cross Section 98

A.5 Screen Pipe Detail.. 100

A.6 Layout of Well Header System 102

B.1 Well Locations and Free Product Levels.. 108

B.2 As-Built Trench/Well Layout.. 109

B.3 As-Built Cross Section of Augmented Trench System for Wells 4 and 5......... 110

B.4 Well 4 — Trench Detail.. 114

B.5 Well Header Configuration 115

C.1 Gradation Curve — Cameron Station, Sample CA-12, Argonne National Laboratory.. 119

C.2 Gradation Curve — Cameron Station, Sample CA-25, Argonne National Laboratory.. 120

C.3 Gradation Curve — Cameron Station, Sample CA-50, Argonne National Laboratory.. 121

C.4 Gradation Curve — Cameron Station, Sample CA-75A&B, Argonne National Laboratory.. 122

C.5 Gradation Curve — Cameron Station, Sample CA-100, Argonne National Laboratory.. 123

C.6 Gradation Curve — Cameron Station, Sample CA-125, Argonne National Laboratory.. 124

C.7 Gradation Curve — Cameron Station, Sample CA-140, Argonne National Laboratory.. 125

C.8 Gradation Curve — Cameron Station, Sample CA-160A&B, Argonne National Laboratory.. 126

C.9 Gradation Curve — Cameron Station, Sample CA-205, Argonne National Laboratory.. 127

C.10 Gradation Curve — Cameron Station, Sample CA-225A&B, Argonne National Laboratory.. 128

Figures (Cont.)

E.1 Proposed Pathways for the Degradation of Toluene 137

G.1 Horizontal Distances (ft) between Probe A and Probe Clusters F and G 152

G.2 Horizontal Distances (ft) between Probe Clusters, L and M, and Probes E and Q 153

Tables

3.1 Samples of Fill Material Collected at Cameron Station, Virginia 11

3.2 Analytical Procedures or Methods for Determining Physical/Chemical Characteristics of Fill Samples 11

3.3 BTEX and TPH Concentrations of Selected Cameron Station Fill Samples 12

3.4 Summary of Fill Characterization Data 13

3.5 Parameters for Grain Size Analysis of Fill Samples from Cameron Station, Virginia 18

3.6 pH, Nitrate, and Phosphate Concentrations for Groundwater Samples 20

4.1 Viable Bacteria Recovered from Soil Cores 29

4.2 Location of Dominant Bacteria Identified or Suspected in Soil Samples and Concentration of Associated Gasoline Components 40

4.3 Identification of Dominant Aerobic Bacteria Recovered from ADS 41

4.4 TPH Detected in Soil after Use in Biometer Flasks 47

4.5 Toluene Detected in Soil after Use in Biometer Flasks 47

4.6 Ethylbenzene Detected in Soil after Use in Biometer Flasks 48

4.7 Soluble Anions Recovered from Soil Cores 50

4.8 Nitrogen Detected as NH_3 in Soil Cores 52

5.1 Vapor Flow, Temperature, and Pressure Measurements Determined by Using Precision Pipe Sensors 59

5.2 Data Summary for Test Run 1 69

5.3 Data Summary for Test Run 2 70

Tables (Cont.)

5.4 Data Summary for Test Run 4 71

5.5 Data Summary for Test Run 5 72

6.1 Estimated Removal of Volatilized Free Product at Cameron Station, Virginia 79

A.1 Physical Characteristics of Wells 1, 2, 3, and Manifold A 99

A.2 Construction Materials List 103

B.1 Physical Characteristics of Wells Number 4 and 5 and Manifold B 112

D.1 Database for Laboratory Samples 131

G.1 Vapor Flow and Vapor Property Measurements for Vapor Extracted by V4 on April 5, 1993 145

G.2 Results of Test Run 1, Pumping on Probe A and Monitoring Vacuums on Intermediate and Deep Probes at Probe Clusters F and G on April 6, 1993 146

G.3 Results of Test Run 2, Pumping on the Intermediate Depth Probe of Probe Cluster A and Monitoring Vacuums at the Intermediate and Deep Probes at Probe Clusters F and G on April 6, 1993 147

G.4 Results of Test Run 3, Monitoring Vacuums at the Intermediate and Deep Probes at Probe Clusters F and G after Pumping on the Intermediate Depth Probe of Probe Cluster L was Stopped on April 6, 1993 148

G.5 Results of Test Run 4, Pumping on Probe E and Monitoring Vacuums on Intermediate and Deep Probes at Probe Clusters L and M and Well 5 Probes P and Q, April 7, 1993 149

G.6 Results of Test Run 5, Pumping on the Intermediate-Depth Probe of Probe Cluster L and Monitoring Vacuums at the Shallow and Deep Probes at Probe Cluster L and the Shallow, Intermediate, and Deep Probes at Probe Cluster M on on April 7, 1993 151

G.7 Measurement of Total Petroleum Hydrocarbons, Oxygen, and Carbon Dioxide in Vapor Extracted by V4 from Horizontal Wells 1-5 on April 8, 1993 154

Acknowledgments

The authors wish to thank the many staff of Cameron Station without whose cooperation and help this study would not have been possible. Among the U.S. Army personnel are Col. George Eicke, Base Commander, and his assistant, Lt. Col. Lee Reeves. Civilian staff of Cameron Station include Robert Long, Weldon Keyton, and Keith Lockhart. Our managers at the U.S. Army Corps of Engineers, who were highly supportive, were David Drucker and Tim Alexander of the Baltimore District. John Bowman, of the Directorate of Public Works, Fort Myer, provided management backup at critical times during the study.

We wish to mention the excellent soil vapor extraction counsel and (two-dimensional) air-flow modeling assistance provided in the early stages of Argonne National Laboratory's study by Joel Massmann, University of Washington. Robert Schneider, consultant, assisted in the characterization and analysis of the local geohydrological regime.

The authors would also like to thank the staff of Argonne's Information and Publishing Division, Document Processing Center, for word processing support. Finally, Audrey Arns, of Argonne, is gratefully acknowledged for records management and procurement.

Pilot-Scale Studies of Soil Vapor Extraction and Bioventing for Remediation of a Gasoline Spill at Cameron Station, Alexandria, Virginia

by

W. Harrison, C.J. Joss, L.E. Martino, C.V. Pearson, R.W. Peters, D.H. Pope,
D.M. Dziewulski, L.A. Raphaelian, L.L. Reed, L.T. Shepard, and T. Sydelko

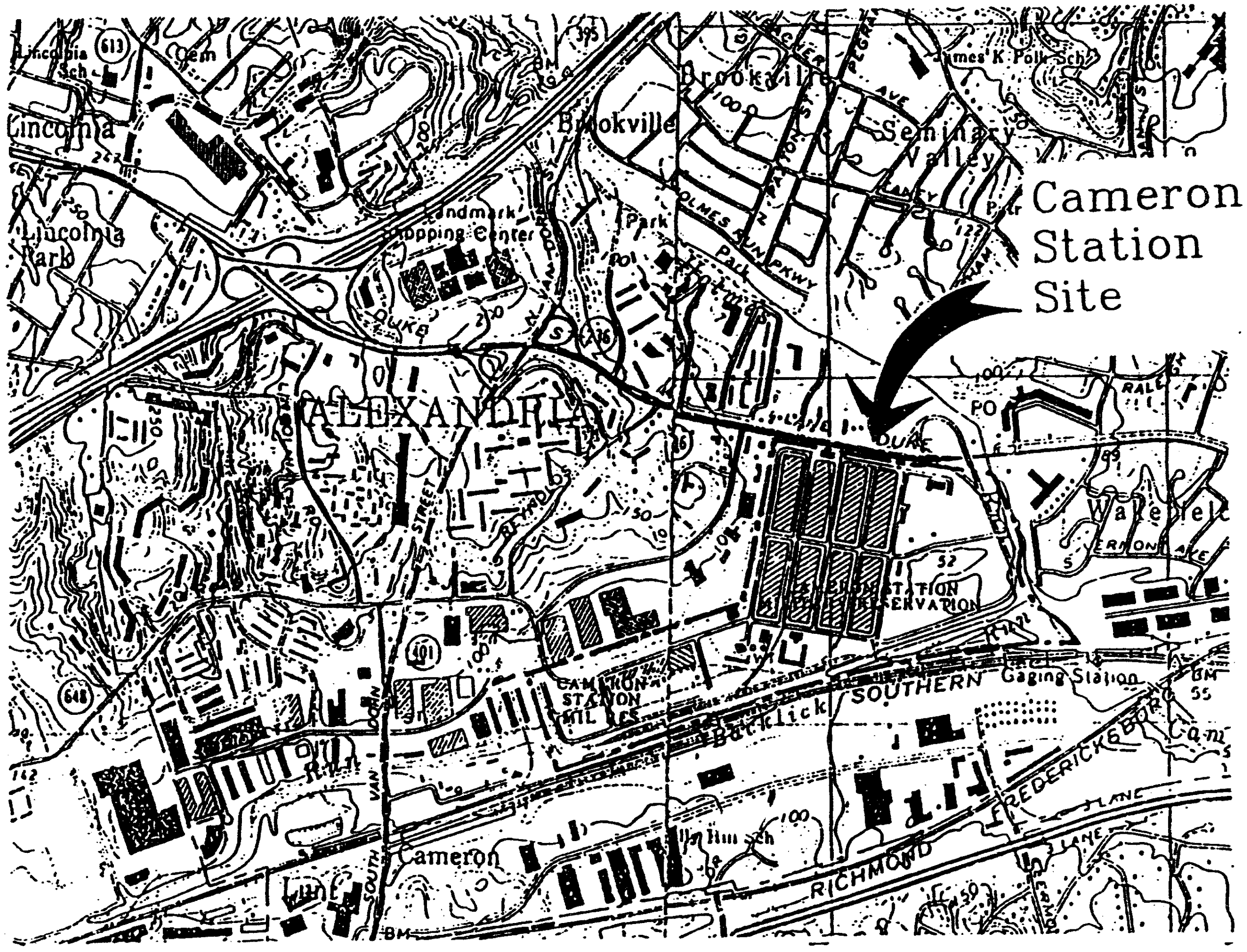
Abstract

Approximately 10,000 gal of spilled gasoline and unknown amounts of trichloroethylene and benzene were discovered at the U.S. Army's Cameron Station facility (Alexandria, Virginia). Because the base is to be closed and turned over to the city of Alexandria in 1995, the Army sought the most rapid and cost-effective means of spill remediation. At the request of the Baltimore District of the U.S. Army Corps of Engineers, Argonne conducted a pilot-scale study to determine the feasibility of vapor extraction and bioventing for resolving remediation problems and to critique a private firm's vapor-extraction design. Argonne staff, working with academic and private-sector participants, designed and implemented a new systems approach to sampling, analysis, and risk assessment. The U.S. Geological Survey's AIRFLOW model was adapted for the study to simulate the performance of possible remediation designs. A commercial vapor-extraction machine was used to remove nearly 500 gal of gasoline from Argonne-installed horizontal wells. By incorporating numerous design comments from the Argonne project team, field personnel improved the system's performance. Argonne staff also determined that bioventing stimulated indigenous bacteria to bioremediate the gasoline spill. The Corps of Engineers will use Argonne's pilot-study approach to evaluate remediation systems at field operation sites in several states.

1 Introduction

1.1 Background

Cameron Station Military Reservation lies on a 164-acre site located about two miles west of downtown Alexandria, Virginia (see Figure 1.1). According to the requirements of the Base Closure and Realignment Act of 1988, the Army base is to be closed by 1995. In support of this closure requirement, Woodward-Clyde Federal Services (WCFS) conducted a Base Closure Remedial Investigation and Feasibility Study (RI/FS), the details of which were given in two reports. The "Site Characterization Report" (SCR) was completed in November 1991, and the



NOTE: FIGURE TAKEN FROM USGS 7.5 MINUTE SERIES
ANNANDALE AND ALEXANDRIA VIRGINIA QUADRANGLES.

FIGURE 1.1 Location of Cameron Station Military Reservation

"Draft Corrective Action Plan" (CAP) was completed in January 1992. The SCR presents results of studies indicating that there had been a subsurface release of gasoline at the PX service station and that the gasoline ("product") had formed a plume that had moved (in the direction of groundwater flow) away from the service station and out under the adjacent parking lot (see Figure 1.2). The Army forwarded the results of these studies to the Virginia State Water Control Board in the form of an Initial Abatement Action Report.

Prompted by the findings in the WCFS's Site Characterization Report, an interim remedial action (IRA) was initiated in June 1991 to comply with Virginia Regulation 680-13-02, Sections 6.4 and 6.5. The IRA includes additional site characterization studies and initial efforts to remove "free product" from the subsurface. IRA activities are being performed in concert with the RI/FS activities; coincidentally, Argonne National Laboratory (ANL) is conducting pilot-scale studies of methods for remediating gasoline contamination in the fill material beneath the parking lot next to the PX service station. Results of the IRA and continuing RI/FS activities and the Argonne pilot-scale studies will be incorporated into the Corrective Action Plan, pursuant to Virginia Regulation 680-13-92 and the Base Closure Record of Decision (ROD). The Remedial Investigation/Feasibility Study process will culminate with the Commonwealth of Virginia and the U.S. Environmental Protection Agency indicating acceptance of the results of the RI/FS and their concurrence with the CAP and ROD.

1.2 Objectives

The objectives of the Argonne work are listed below.

1. Evaluate the feasibility of using soil vapor extraction (SVE) to remediate the lighter fractions of the gasoline on the water table and in the vadose zone at Cameron Station by using either vertical or horizontal vapor-extraction wells (or a combination of both).

2. Investigate the suitability of using computer-controlled, internal-combustion (IC) engines for volatilizing and evacuating in-situ products from the wells and, simultaneously, powering the engines and combusting the hazardous vapors.

3. Determine the suitability of indigenous bacteria for in-situ bioremediation of product.

4. Assess the efficacy of bioventing for enhanced remediation of residual, heavier gasoline fractions upon the termination of SVE activities.

5. Develop a conceptual design for the full-scale SVE and bioremediation work.

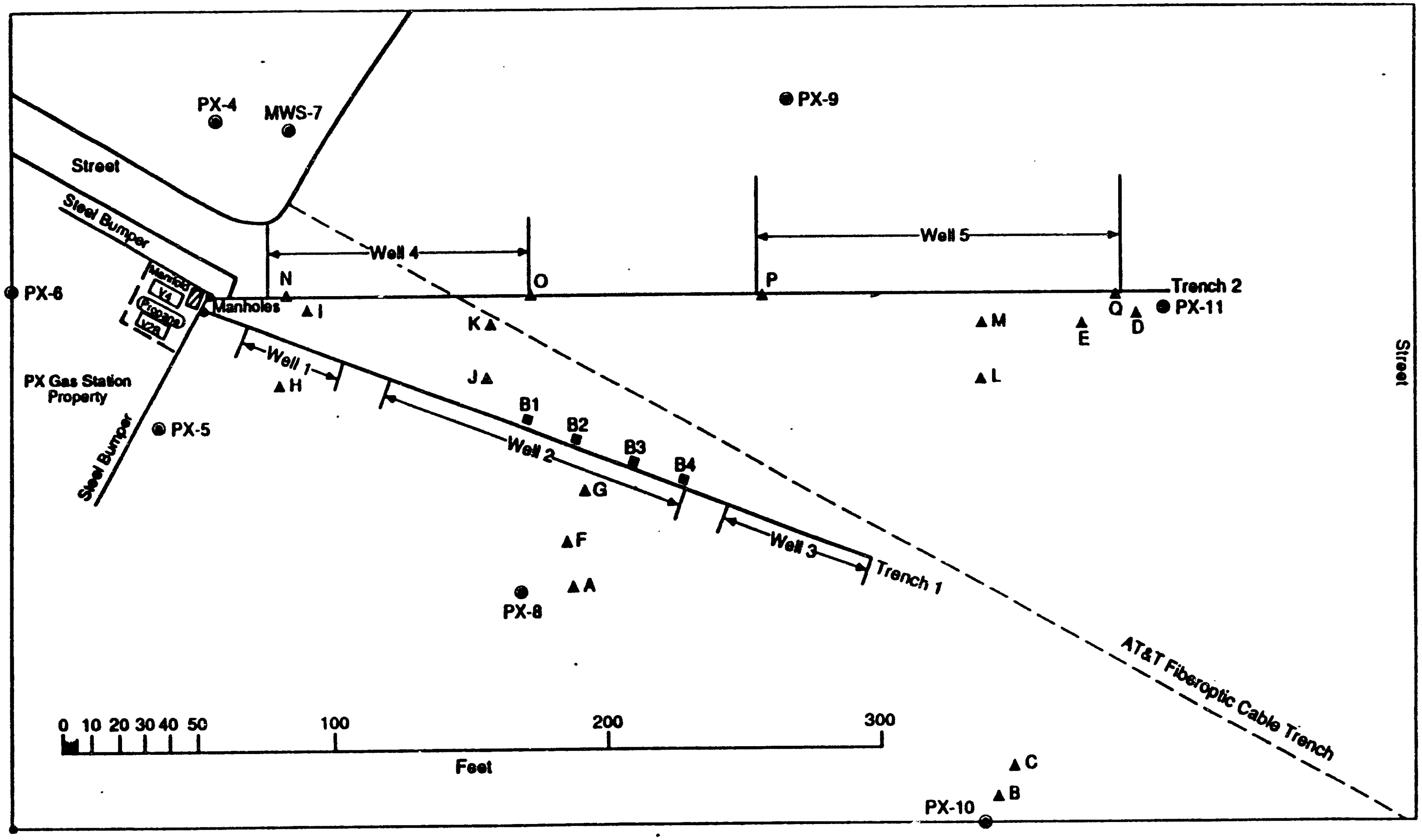


FIGURE 1.2 Map Showing Location of Trenches 1 and 2, Horizontal Wells 1–5, Sand-Filled Borings (B1–B4), Monitoring Wells (PX-4, 5, 6, 8, 9, 10, 11 and MWS-7), Probes A–E and N–Q, and Probe Clusters F–M

1.3 Approach

Although the draft CAP had recommended a horizontal-well and blower system for soil vapor extraction, Argonne's sponsor for this study, the U.S. Army Corps of Engineers (Baltimore District), suggested that Argonne's pilot-scale study begin with an examination of the capability of horizontal wells to operate effectively in the particular geohydrological system beneath the parking lot. It was then decided, in consultation with Argonne's sponsor and WCFS, that three horizontal wells (wells 1, 2, and 3) would be installed in one long trench and that the depth of the trench would be a "uniform eight feet" (see WCFS's "Draft Corrective Action Plan," 1992, p. 8). This trench is referred to throughout the document as Trench 1. Argonne subsequently installed an additional trench (referred to as Trench 2), which was constructed with two horizontal wells (wells 4 and 5). (See Figure 1.2 for the general locations of Trenches 1 and 2.) Finally, at Argonne's suggestion, it was decided that computer-controlled IC engines would be used instead of a blower and air-purification system to effect soil vapor extraction. The IC engines used for the study are manufactured by VR Systems, Anaheim, California, and are known as the V4 and the V2B (see Section 6).

It was decided that analysis of the results of this first SVE experiment, together with a review of ancillary measurements on the subsurface biophysical system (including an evaluation of both groundwater and subsurface soil), would form the basis of further work toward designing an optimum system for remediating the gasoline spill.

2 Installation and Testing of Soil-Gas Monitoring Probes and Extraction Wells

Argonne's pilot-scale effort involved several construction/testing phases, as summarized below. Argonne installed product-extraction wells of varying design and configuration throughout the course of the pilot-scale study at Cameron Station (see Figure 2.1). The design and installation of the extraction wells was varied to reflect the additional information gathered in each of the three construction/test phases of work. In general, our work involved three discrete phases:

- In Phase 1, several vertical soil-gas monitoring probes and exploratory borings were installed and field permeability tests were performed to provide information for the construction of the first horizontal trench.
- In Phase 2, Trench 1 (consisting of horizontal wells 1, 2, and 3) was installed and additional soil-gas permeability tests were performed to develop input parameters for a two-dimensional air-flow model. The modeling results were subsequently used to design and install an additional horizontal trench, Trench 2.
- In Phase 3, Trench 2 (consisting of horizontal wells 4 and 5) was installed, several vertical enhancement wells adjacent to Trench 1 were installed, and aboveground piping was installed to extract vapors from existing groundwater wells PX-4, MWS-7, PX-6, and PX-17 in the vicinity of the source of the UST release.

2.1 Phase 1: Installation of Exploratory Borings and Soil-Gas Monitoring Probes

Argonne's initial efforts included the installation of several exploratory borings and soil-gas monitoring probes (designated Probes A, B, C, D, and E). Probe A was positioned 20 ft from well PX-8. Probes B and C were positioned 10 ft and 30 ft, respectively, from well PX-10. Probes D and E were positioned 10 ft and 30 ft, respectively, from well PX-11. Each probe was screened from 5 to 7 ft below grade. As a result of this effort, Argonne informed the U.S. Army Corps of Engineers (COE) that the stratigraphy of the site was not optimal for the use of soil-vapor-extraction methods. More specifically, a clayey silt layer between the bottom of the parking lot subbase and the water table did not appear to be a favorable stratum for positioning a horizontal vapor-extraction trench. However, Argonne performed several field permeability studies by using an explosion-proof blower; existing monitoring wells PX-8, PX-10, and PX-11; and the newly installed gas-monitoring probes. These tests resulted in the conceptual horizontal well-cluster design that eventually became known as Trench 1.

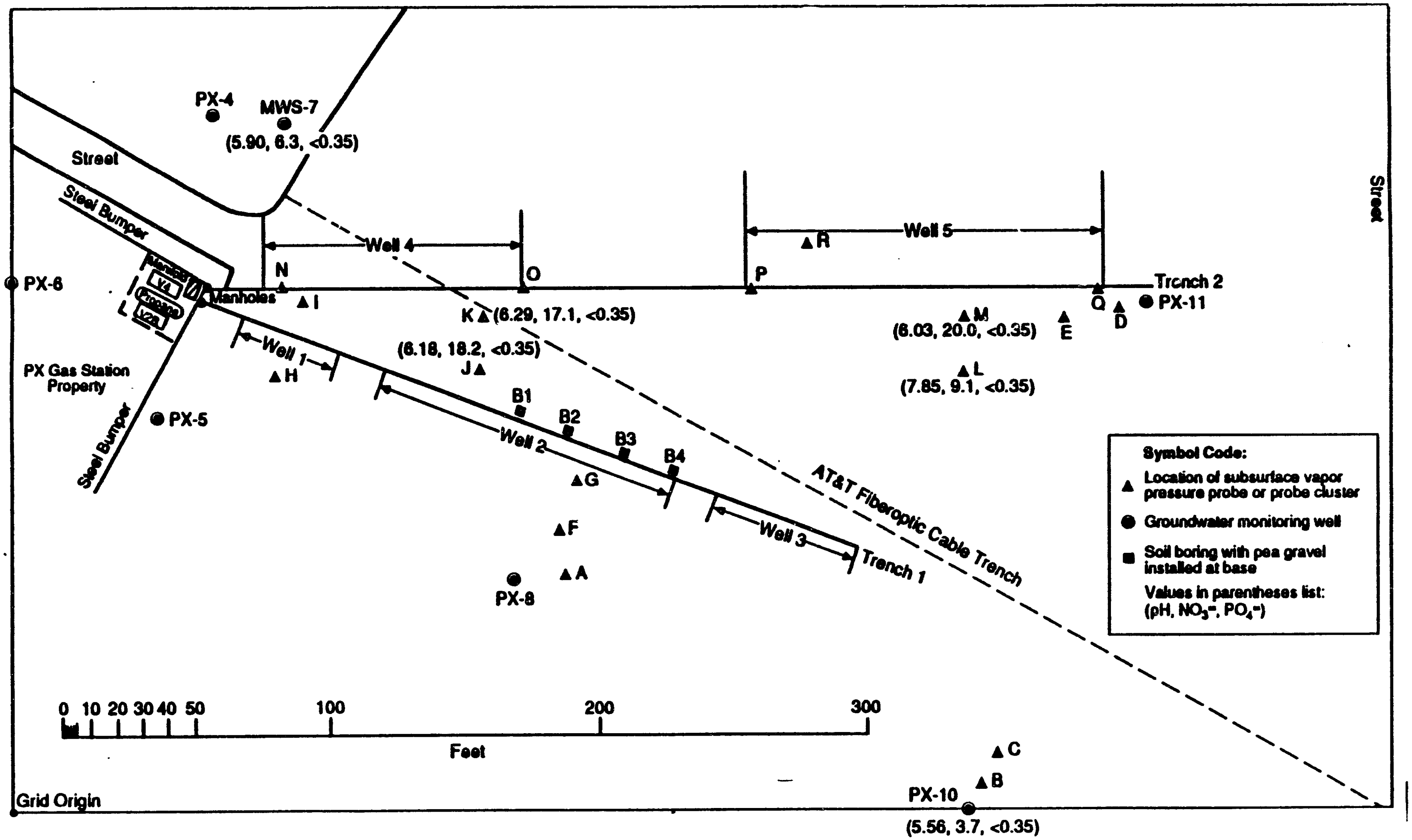


FIGURE 2.1 Locations of Soil-Gas Monitoring Probes and Extraction Wells

2.2 Phase 2: Installation of Trench 1 and Horizontal Wells 1, 2, and 3

To minimize the disruption of parking at the Cameron Station facility, Trench 1 was constructed over two weekend periods. Preliminary phases of the work occurred on July 25–26, 1992, and the trench was completed the following weekend, August 1–2, 1992. In general, Trench 1 consisted of a cluster of three horizontal wells screened at proximal, intermediate, and distal intervals from the SVE IC engine. The wells were isolated from each other by solid piping and soil/bentonite plugs. Each well was positioned 6 in. below the top of gravel-filled cells that are 6 ft in height and located 2 to 8 ft below grade. A detailed installation description for horizontal wells 1, 2, and 3 is given in Appendix A.

During Phase 2, wells 1, 2, and 3 were tested by using the V2B VES IC engine as described in Section 6. Concurrent with the experimentation with the V2B IC engine, Argonne performed additional field permeability tests by using wells 1, 2, and 3; an explosion-proof blower; and four newly installed soil-gas monitoring probe clusters, probes F, G, H, and I. Probes F, G, H, and I contained three gas probes installed in a single boring. The screen for the shallow probe was located from 1 to 3 ft below grade. The screen for the intermediate probe was located from 5 to 7 ft below the ground surface. The deep gas probe was constructed with a 5-ft-long screen that straddled the water table. Probe clusters F and G are located 30 and 10 ft, respectively, from Trench 1. Probe clusters H and I are located 15 ft from either side of Trench 1. The probes were installed so that Argonne could evaluate the vertical profile of the vacuum that results from the trench. The probe clusters were used to determine if significant airflow is being achieved near the water table or if most of the airflow is in the upper part of the unsaturated zone.

The results of the field permeability study using horizontal wells 1, 2, and 3 and probes F, G, H, and I were used as input parameters into a two-dimensional airflow model. The results of the modeling effort highlighted the fact that the design of Trench 1 caused extracted vapors to originate primarily from the subbase of the parking lot and that less than one-third of the extracted vapors were originating from the deeper, and assumedly more contaminated, layer of the vadose zone. These results led Argonne to the third and final phase of the pilot-scale study.

2.3 Phase 3: Installation of Trench 2 and Horizontal Wells 4 and 5 and Installation of Vertical Enhancement Wells at Trench 1

Trench 2 was constructed during a period of minimum activity in the parking lot area. Argonne and contractor staff constructed Trench 2 on Friday and Saturday, October 30–31, 1992. The aboveground piping used to connect the monitoring wells PX-4, MWS-7, PX-6, and PX-17 to the VES IC engine was constructed during the same period.

The efforts in Phases 1 and 2 suggested that vapor extraction is a viable remedial alternative for the Cameron Station contamination scenario. At the time, research activities indicated that horizontal extraction trenches might be successful and that the vacuum/treatment engine could be a reliable and easy to operate "prime mover" for the system. However, as described in Section 2.2, empirical and modeling information from Phase 1 suggested that the design of Trench 1 did not optimize the potential for extracting contaminated soil vapor because the configuration results in the extraction of more vapors from the upper subsurface than from the lower subsurface. Argonne remedied this problem (and simultaneously experimented with the existing horizontal well) by locating several "vertical enhancement wells" to intercept the more conductive subsurface strata and to facilitate the movement of the more contaminated subsurface soil vapor into Trench 1. Argonne also installed an additional horizontal well cluster (Trench 2) that intercepted the more conductive subsurface strata without the use of enhancement wells.

In contrast to Trench 1, Trench 2 involved the placement of a deeper gravel layer to ensure that the more conductive subsurface strata, inferred to be at or near the water table, was intercepted. In addition, Argonne installed an aboveground piping manifold to facilitate the extraction of volatilized free product from several existing vertical monitoring wells that were close to the pump islands at the PX gas station. This aspect of the program was integrated into the pumping/treatment operation on the horizontal wells so that we could evaluate the control features necessary to maximize the extraction of volatilized free product from a vertical well and simultaneously preclude the elevation of the water table above the screened interval, thus blocking entry of vapors into the well. In addition, this aspect of the program allowed us to evaluate how effectively the more "aged" free product that was close to the PX station supports combustion in the VES IC.

In general, Trench 2 consisted of a cluster of two horizontal wells screened at a proximal and distal interval from the SVE IC engine. Each well was positioned 6 in. below the top of gravel-filled cells that were 6 ft in height and located from 5 to 11 ft below grade. The installation of horizontal wells 4 and 5 is described in detail in Appendix B.

2.4 Summary

As noted above, the design, installation, and testing of the SVE concept was an iterative process. Construction/testing in each phase was determined by the experience and knowledge gained from the previous phases of work. As noted in the introduction, work on the construction and operation of the SVE system proceeded in tandem with research on the feasibility of using bioremediation techniques at the site. Sections 3 and 4 detail the efforts to evaluate the physical/chemical/biological characteristics of soil and groundwater at the site. Section 5 describes the field measurements and AIRTEST calculations used to evaluate soil vapor properties and permeability to air of the subsurface fill material. Section 6 describes the SVE equipment and presents information related to the removal of volatilized free product and the history of free-product levels in various monitoring wells.

3 Physical/Chemical Characterization of Fill and Groundwater Samples

Physical/chemical aspects of fill and groundwater at the site were evaluated to determine whether the contamination was amenable to bioremediation techniques.

3.1 Soil Characterization

3.1.1 Sample Collection

Ten samples of the fill material were collected while excavating Trench 1 (see Figure 2.1) during the period July 31 to August 1, 1992. The samples were collected over a distance of approximately 200 ft (linear), from the origin of Trench 1 near the PX gasoline station (Bldg. 23) to a point 225 ft into the parking lot. A steel soil-sampling hand-auger was used for sample retrieval. The auger was cleaned with distilled water and rinsed with hexane prior to each use. Samples were immediately placed in plastic containers (each approximately 2.0 L in volume) and then in a cooler with a blue-ice pack for overnight shipment to Argonne. Further information relevant to sample collection is summarized in Table 3.1.

3.1.2 Analytical Procedures

Physical and chemical analyses were performed at Argonne National Laboratory by using the analytical procedures summarized in Table 3.2. Additional analyses for total petroleum hydrocarbons (TPH) and benzene, toluene, ethylbenzene, and xylenes (BTEX) were performed by an outside laboratory (Data Chem Laboratories) on duplicate samples collected at the time the 10 soil samples were collected. The TPH and BTEX analyses were performed in accordance with EPA Methods 418.1 and 8020, respectively.

3.1.3 Characterization of Fill Material

3.1.3.1 Total Petroleum Hydrocarbons and Benzene, Toluene, Ethylbenzene, and Xylene

The TPH and BTEX results are summarized in Table 3.3. No benzene was detected in any of the samples collected. Generally, the concentrations of toluene, ethylbenzene, and xylene were below 580, 690, and 7,700 ppb, respectively, although appreciable BTEX concentrations were observed at 140 ft from the center of the PX station. The maximum TPH concentration was 320 ppm.

TABLE 3.1 Samples of Fill Material Collected at Cameron Station, Virginia

Sample Code	Sample Depth (ft)	Sample Date	Collection Time	Additional Information
CA-12	6	7/31/92	—	0 ppm[a]
CA-25	8	7/31/92	2:00 p.m.	0 ppm
CA-50	5	7/31/92	2:52 p.m.	0 ppm
CA-75	8	7/31/92	4:16 p.m.	ND
CA-100	9	7/31/92	4:50 p.m.	liquid gas in sample
CA-125	8	8/01/92	7:00 a.m.	465 ppm
CA-140	8	8/01/92	7:40 a.m.	330–350 ppm
CA-160	8	8/01/92	8:15 a.m.	80 ppm
CA-205	8	8/01/92	9:50 a.m.	5.3 ppm
CA-225	8	8/01/92	10:00 a.m.	0 ppm

[a] Concentration determined at time of sample collection by using an organic vapor meter (OVM).

ND: Not determined.

TABLE 3.2 Analytical Procedures or Methods for Determining Physical/Chemical Characteristics of Fill Samples

Soil Parameter	Method
Percent moisture (total residue)	Standard Methods 209A
Cation-exchange capacity	EPA 9081
Particle size characterization:	
Size gradation — sieving	ASTM D2487-85
Particle size analysis — hydrometer	ASTM D422-63
Particle size analysis	U.S.C.S.[a]
Soil pH	EPA 9045

[a] Particle size classification is in accordance with the Unified Soil Classification System.

TABLE 3.3 BTEX and TPH Concentrations of Selected Cameron Station Fill Samples[a]

Sample Code	Aromatic Hydrocarbon Concentration (ppb)[b]				Total Petroleum Hydrocarbon Concentration, (ppm)[c]
	Benzene	Toluene	Ethylbenzene	Xylene	
CA-12	ND[d]	84	28	180	—
CA-25	—	—	—	—	26
CA-50	ND	580	690	7700	—
CA-75	—	—	—	—	180
CA-100	ND	180	81	750	—
CA-125	—	—	—	—	320
CA-140	ND	53,000	57,000	480,000	—
CA-160	—	—	—	—	27
CA-205	ND	2	4	4	—
CA-225	—	—	—	—	ND

[a] Analyses performed by Data Chem Laboratories.

[b] Limit of detection = 2 ppb.

[c] Limit of detection = 10 ppm.

[d] ND = Not Detected.

3.1.3.2 Moisture Content

The moisture content for the 10 fill samples (plus three replicate samples) ranged from 14.8 to 24.9%. Results are summarized in Table 3.4. Figure 3.1 shows the moisture content profile as a function of distance from the origin of Trench 1, near the PX gasoline station. Replicate samples were analyzed for samples collected at 125- and 140-ft distances. The results were fairly reproducible, although there was greater disparity in the values for the samples collected at the 140-ft distance. The figure suggests that the moisture content remains reasonably constant over the entire trench system. These results indicate that the fill material is fairly moist and should support bioremediation schemes (such as bioventing).

3.1.3.3 Cation-Exchange Capacity

The cation-exchange capacity (CEC) for the 10 fill samples (plus replicates) ranged from 11.45 to 34.41 meq/100 g. Analytical results are summarized in Table 3.4, and the CEC profile is plotted as a function of distance in Figure 3.2. Replicate CEC analyses were performed for

TABLE 3.4 Summary of Fill Characterization Data

Sample Code No.	Sample Depth (ft)	Moisture Content (%)	CEC[a] (meq/100 g)	Soil pH
CA-12a	6	21.48	14.09	7.97
CA-12b	6	—	12.54	—
CA-25a	8	14.77	18.71	6.16
CA-25b	8	—	21.26	—
CA-50a	5	16.05	15.35	5.42
CA-50b	5	—	15.67	—
CA-75a	8	19.22	20.35	4.07
CA-75b	8	—	—	—
CA-100	9	17.32	11.45	5.01
CA-125a	8	22.33	15.67	4.89
CA-125b	8	21.96	—	5.00
CA-140a	8	26.27	18.36	5.47
CA-140b	8	21.85	—	5.64
CA-140c	8	19.28	—	—
CA-160a	8	19.73	34.41	4.60
CA-160b	8	—	—	4.57
CA-205	8	21.15	19.42	4.36
CA-225a	8	24.90	24.90	4.59
CA-225b	8	—	—	—

[a] Cation-exchange capacity.

samples collected at 12-, 25-, and 50-ft distances along the experimental trench. As shown in Figure 3.2, the results were fairly reproducible; the resulting CEC values generally did not differ by more than 1.5 meq/100 g. With the exception of the CEC value at 160 ft (linear), CEC remained relatively constant, ranging from 15 to 20 meq/100 g, with a mean value of 18.1 meq/100 g. This finding indicates that a small amount of gasoline may be sorbed onto the fill material. The values of CEC are relatively small, indicating that there should not be an appreciable clay content in the soil, which is confirmed by the particle size analyses described in Section 3.1.3.5.

3.1.3.4 Soil pH of Fill Material

The soil pH of samples of fill material ranged from 7.97 to 4.07; results are summarized in Table 3.4 and Figure 3.3. Replicate analyses were performed for samples collected at 125, 140, and 160 ft along Trench 1. As shown in Figure 3.3, the results were quite reproducible; the maximum difference between the replicate soil pH analyses was 0.14 pH units. The soil pH results also indicate that the fill material ranges between a slightly basic condition to an acidic

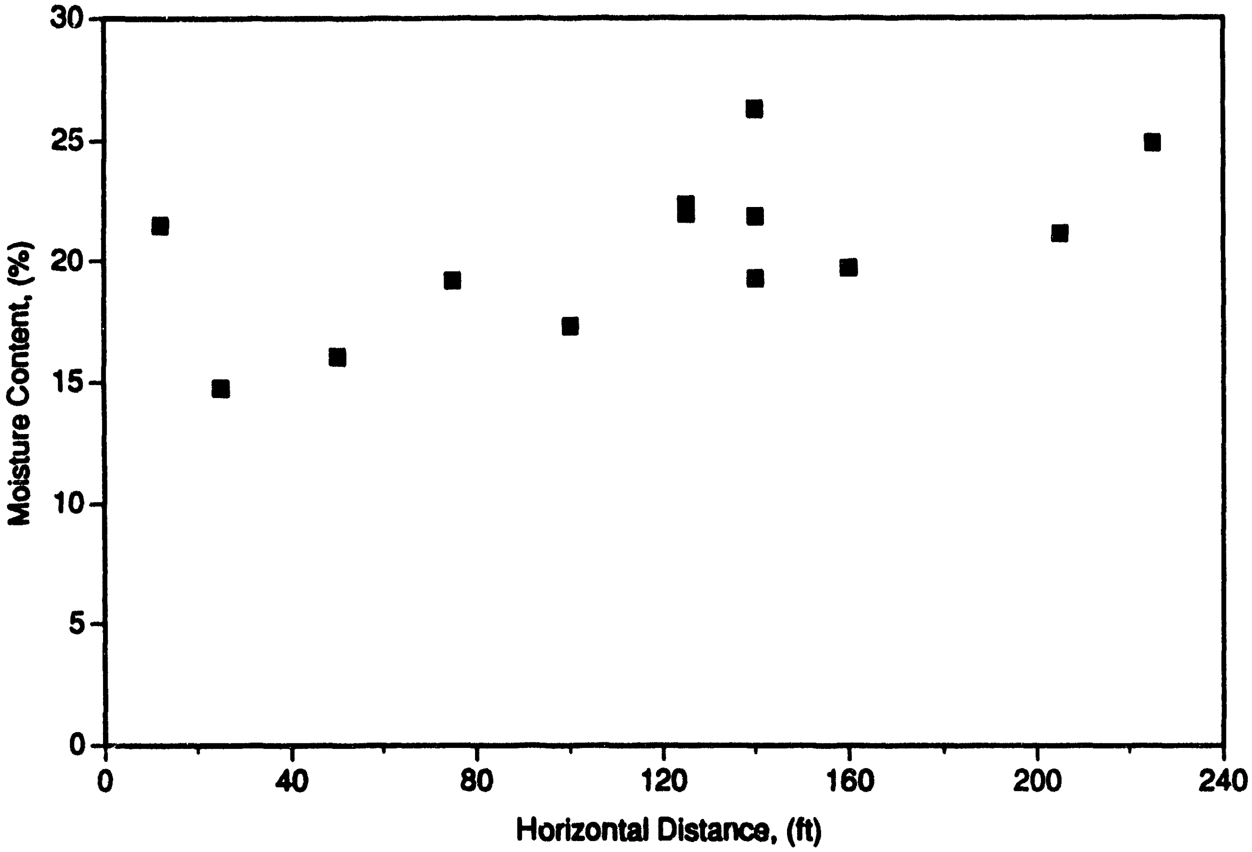


FIGURE 3.1 Moisture Content as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia

condition. Further, the soil pH of the fill material generally becomes more acidic with increasing distance from the trench origin to a distance of approximately 80 ft and then remains relatively constant, in the range of pH 4.6 to 5.0.

3.1.3.5 Grain Size Analysis of Fill Material

The fill samples were analyzed to determine their size distribution and to classify the samples according to the Unified Soil Classification System. The analyses generally followed the American Society Testing and Materials (ASTM) procedures outlined for combined hydrometer analysis (ASTM 1987). Samples were air-dried before they were weighed and were then screened through a number 10 mesh (2.0-mm) sieve. Particles retained on the number 10 sieve were then screened through a 1-in., 3/4-in., 3/8-in., number 4 mesh (4.75-mm) and number 10 mesh (2.0-mm) sieve. The percentage of the original sample retained on each sieve was calculated on the basis of total sample weight.

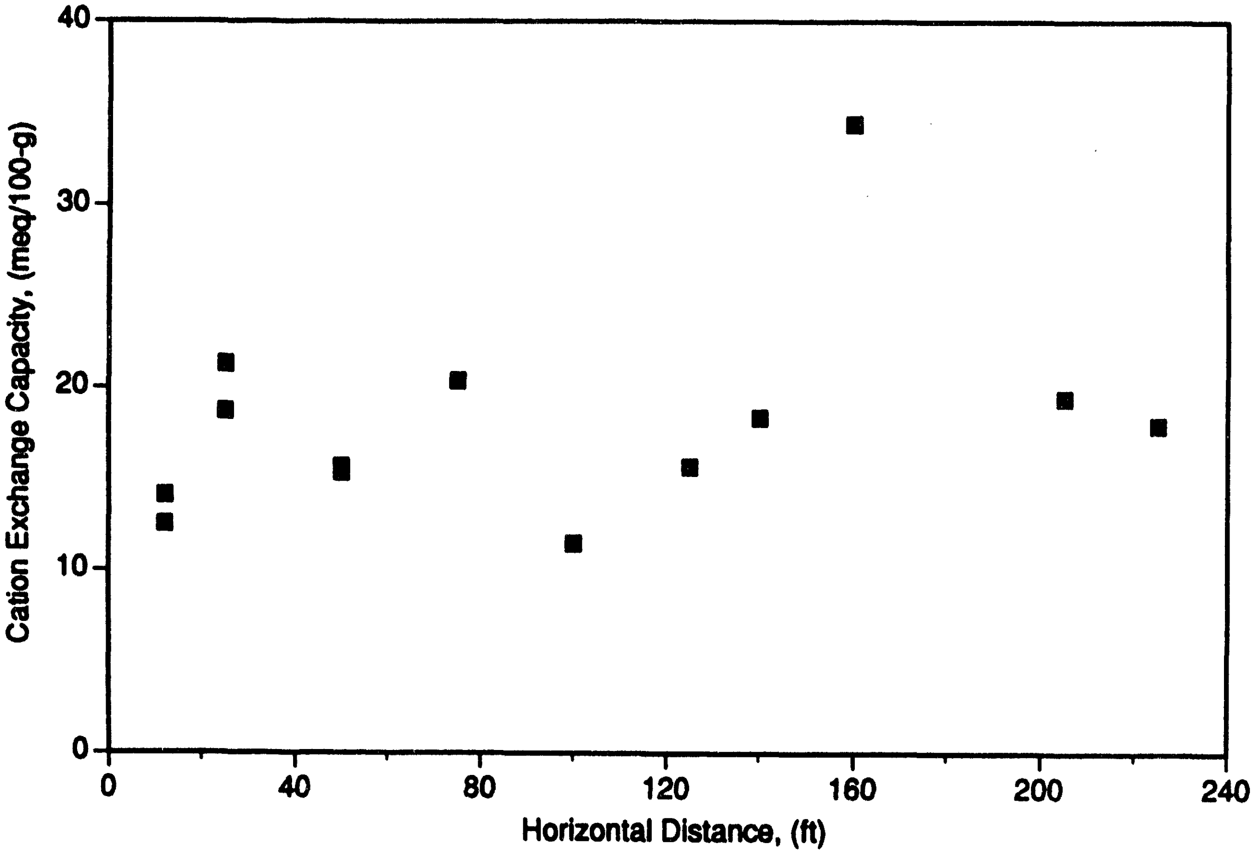


FIGURE 3.2 Cation-Exchange Capacity as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia

About 50 g of sediment passing through the number 10 mesh sieve was weighed out and mixed with a dispersing agent. After soaking for at least 12 h, the sediment slurry was mixed in a high-speed blender and transferred to a 1,000-mL cylinder. Slurry volume was increased to 1.0 L by adding distilled water, and the cylinders were transferred to a water bath, which was maintained at a constant temperature of 20°C.

A control sample of distilled water and dispersing agent solution was set up to determine the dispersing agent correction required for each batch of samples. An ASTM Model 152H soil hydrometer was used for all readings, and the meniscus correction was determined to be +1.0 in all cases. Once in the water bath, samples were vigorously agitated by using a stainless-steel plunger. Hydrometer readings were taken at intervals of 5 and 120 min after sedimentation began. Following the final reading, the sediment slurry was emptied into a number 230 mesh (63-µm) sieve. The slurry was wet-sieved, and the material retained on this sieve was transferred to a Pyrex™ beaker. After oven-drying, this material was dry-sieved through number 18 (1.0-mm), 35 (500-µm), 60 (250-µm), 120 (125-µm), and 230 (63-µm) mesh sieves.

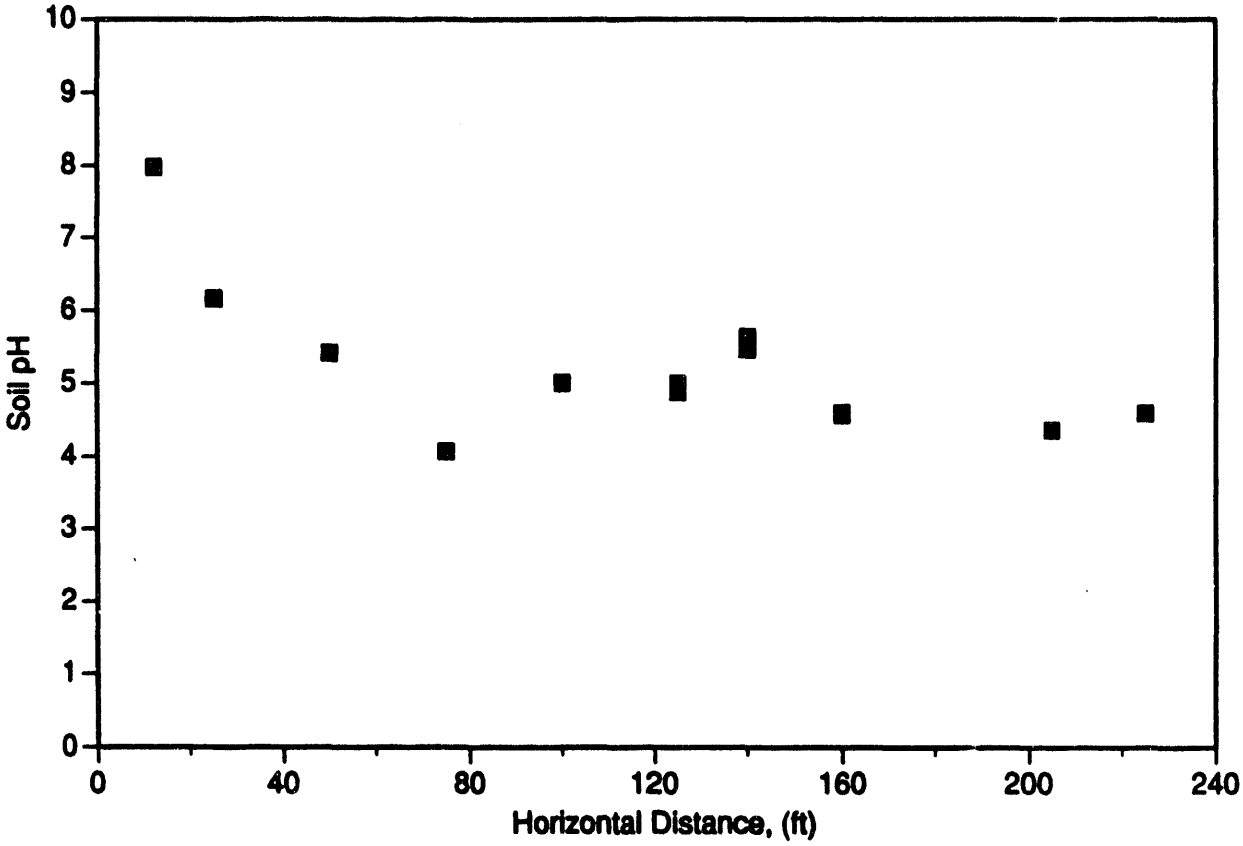


FIGURE 3.3 Soil pH as a Function of Distance along the Experimental Trench System at Cameron Station, Virginia

The weights of sediment retained on these sieves were used to calculate the particle size distribution of the portion finer than the number 10 mesh (2.0-mm) sieve, as were the hydrometer readings. These calculations were completed according to procedures (ASTM D2487-85 and ASTM D422-63) outlined in ASTM (1987). The specific gravity for sediment particles in all samples was assumed to be 2.65.

Grain size distributions calculated for each sample (and replicate samples) were plotted on USACE Form 2087 (gradation curves). On the basis of these curves (shown in Appendix C), the average particle size (M_Z) for each sample was calculated by using the formula listed below:

$$M_Z = \frac{84\phi + 50\phi + 16\phi}{3} \quad (1)$$

Sorting indices (S_0) for each sample were calculated by using the following formula:

$$S_0 = \left[\frac{84\phi - 16\phi}{4.0} + \frac{95\phi - 5\phi}{6.6}\right] \quad (2)$$

Average particle size and sorting index for each fill sample are given in Table 3.5. The gradation curves for each fill sample (and replicate samples) are shown in Appendix C. Replicate samples were analyzed for samples collected at 75-, 160-, and 225-ft distances along the experimental trench. The results for the replicate samples are plotted on the same gradation curve as was used to plot the original sample. These three gradation curves all indicate a high degree of reproducibility. Nominal textural designations for these samples could not be accurately determined by using the soil classification system outlined in ASTM D2487-85 (ASTM 1987), because the samples all contained substantial fine fractions that passed the 230 mesh sieve. According to the method (ASTM D2487-85), these fine-grained soils can only be classified after their Atterberg limits have been determined. Because testing these soils for Atterberg limits is beyond the scope of this project, only approximate nominal designations could be applied (refer to Table 3.5).

The high degree of reproducibility is shown with the replicate samples (marked as "a" and "b" in Table 3.5); the sorting factor differed by less than 1.8%. The mean particle size generally agreed within 0.002 mm (with the exception of sample CA-225, which differed by 0.005 mm). One sample (CA-160a and CA-160b) is classified as silt or clay, and it contains 15.29% sand and can be classified as "with sand." Four samples (including replicates) are classified as sandy silts or sandy clays (CA-75a and CA-75b, CA-140, CA-205, and CA-225a and CA-225b). The other five samples (CA-12, CA-25, CA-50, CA-100, and CA-125) are classified as silty sands.

3.2 Groundwater Characterization

3.2.1 Sample Collection

Six groundwater samples were collected on October 29, 1992, from monitoring wells MWS-7 and PX-10, along with groundwater from probes J, K, L, and M that correspond to 2.0-in. I.D. PVC probes screened across the water table (see Figure 3.4 for sampling locations). Groundwater samples were collected with new Teflon™ bailers at each sampling point and introduced into plastic sampling bottles (each approximately 0.5 L in volume). The bottles were placed in a cooler and shipped by overnight express to Argonne.

3.2.2 Analytical Procedures

The groundwater was analyzed for pH, nitrate, and phosphate by using the procedures described in Standard Methods (1992). The procedures were as follows:

- pH value — standard methods procedure 4500-H^+.

TABLE 3.5 Parameters for Grain Size Analysis of Fill Samples from Cameron Station, Virginia

Sample No.	Sample Depth (ft)	Sorting Factor (S_o)	Average Grain Size (M_z)		Nominal Textural Classification
			ϕ	mm	
CA-12	6.0	0.60 ϕ	4.05	0.060	silty sand
CA-25	8.0	4.97 ϕ	3.10	0.120	silty sand
CA-50	5.0	4.89 ϕ	2.80	0.150	silty sand
CA-75a	8.0	3.95 ϕ	5.12	0.030	sandy silt or sandy clay
CA-75b	8.0	3.94 ϕ	5.20	0.028	sandy silt or sandy clay
CA-100	9.0	3.14 ϕ	2.25	0.200	silty sand
CA-125	8.8	5.08 ϕ	2.43	0.180	silty sand
CA-140	8.0	4.05 ϕ	5.25	0.028	sandy silt or sandy clay
CA-160b	8.0	3.60 ϕ	7.05	0.008	silt with sand or clay with sand
CA-160b	8.0	3.64 ϕ	6.97	0.008	silt with sand or clay with sand
CA-205	8.0	4.04 ϕ	4.90	0.035	sandy silt or sandy clay
CA-225a	8.0	3.36 ϕ	6.00	0.017	sandy silt or sandy clay
CA-225b	8.0	3.42 ϕ	5.80	0.022	sandy silt or sandy clay

- Nitrogen (Nitrate) — standard methods procedure 4500-NO_3-B.
- Phosphate — standard methods procedure 4500-P: vanadomolybphosphoric acid colorimetric method.

3.2.3 Groundwater Characterization Results

The results for pH and for nitrate and phosphate concentrations are summarized in Table 3.6; the results are also indicated (values are listed in parentheses) in Figure 3.4 for the six groundwater samples. The results indicate that the groundwater is slightly acidic, has adequate nitrogen concentrations to supply microbial degradation, and has minimal phosphate concentrations. Adequate nitrogen and phosphorus concentrations are required to support biodegradation techniques. The Safe Drinking Water Standard for nitrogen is 10 mg/L, while many effluent discharge limits are 0.5 mg/L (U.S. EPA 1987). The higher nitrate concentrations (ranging from 3.7 to 20.0 mg/L) in the groundwater samples indicate that contamination is present and that the groundwater is conducive to bioremediation techniques. The low phosphorus concentrations (all were below 0.35 mg/L) may indicate that phosphorus may be a limiting nutrient for bioremediation.

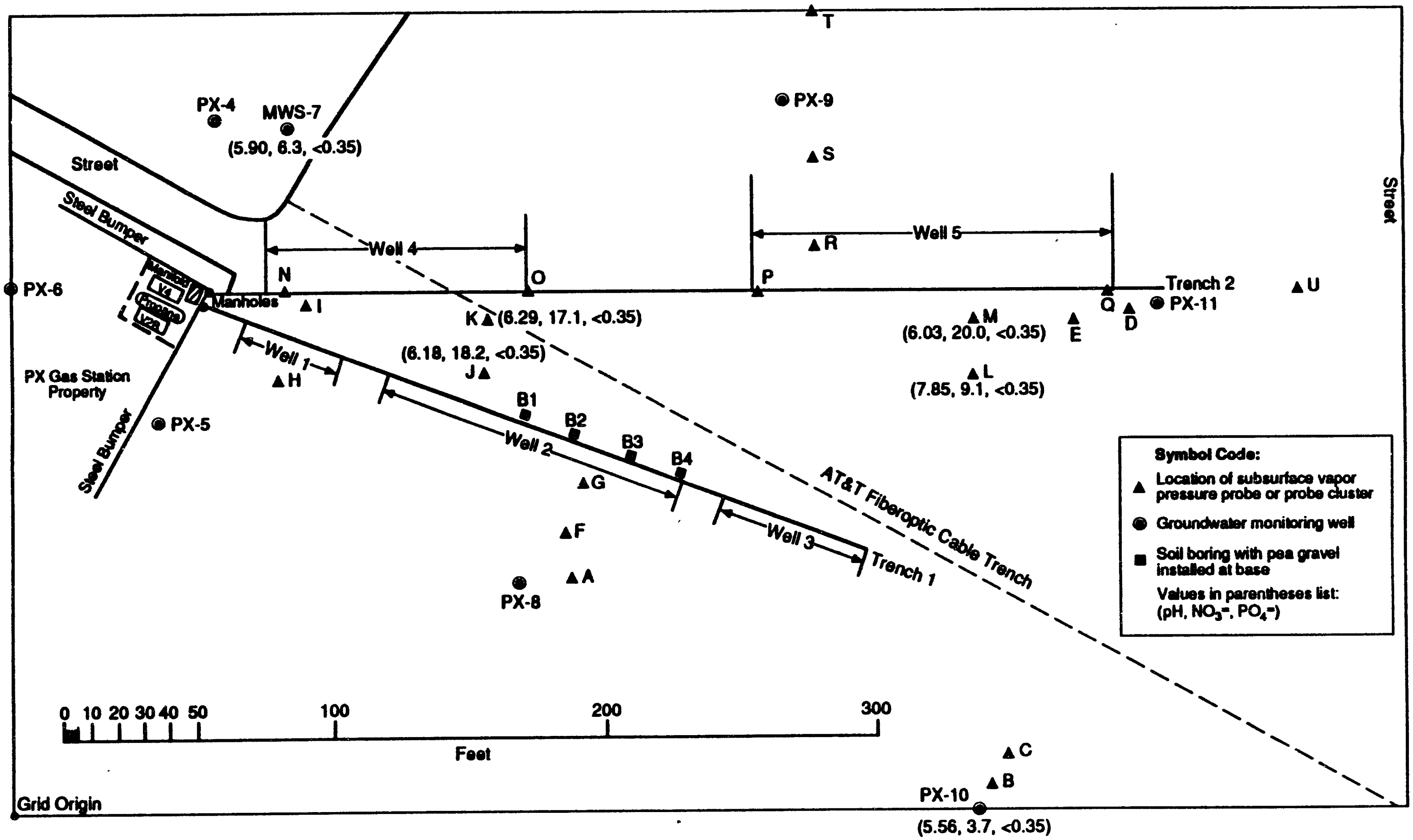


FIGURE 3.4 pH, Nitrate, and Phosphate Concentrations for Various Groundwater Samples Collected at Cameron Station, Virginia

3.3 Summary

On the basis of the reported physical/chemical results, it was determined that the fill and the groundwater would be conducive to bioremediation techniques. Accordingly, Argonne conducted a more detailed evaluation of the site. These results are summarized in Section 4.

TABLE 3.6 pH, Nitrate, and Phosphate Concentrations for Groundwater Samples

Sample Identification	pH	Concentration (mg/L)	
		NO_3^-	PO_4^{-3}
Well MWS-7	5.90	6.332	<0.35
Well PX-10	5.56	3.716	<0.35
Hole J	6.18	18.196	<0.35
Hole K	6.29	17.050	<0.35
Hole L	7.85	9.084	<0.35
Hole M	6.03	20.040	<0.35

4 Studies of Microbial Populations Contained in the Soil of Cameron Station and their Potential to Degrade Components of Gasoline

4.1 Objectives and Approach

4.1.1 Objectives of the Study

The original objective of the microbial studies was to evaluate the potential for indigenous microbes to degrade components of gasoline.

The microbiological study was performed to determine:

- the level of bacteria present in the contaminated soil,
- the ability of the indigenous bacteria to degrade the gasoline components in situ, and
- possible nutrient limitations that might reduce or prevent the degradation of gasoline components by the indigenous microbial community.

Microbiological sampling of soils was conducted during the construction of Trench 1. All soil sampling was performed by BTI on August 1, 1992. Biometer-flask tests employing soil samples from the Cameron Station site were used to address some of the important questions regarding the interaction of the microbial communities, soil chemistry, and contaminant degradation (see below).

4.1.2 Approach Used during the Study

4.1.2.1 Characterization of Microbial Populations and Chemical Species Important in Microbial Metabolism

Soil sample collection was done during the construction of the trench for SVES well emplacement. These samples were processed to determine the levels and general types of indigenous bacteria. Categories of bacteria included aerobic bacteria, obligately anaerobic bacteria, sulfate-reducing bacteria, and acid-producing bacteria (APB). Many aerobic bacteria are efficient hydrocarbon degraders; therefore, identification of this general group was emphasized (see Section 4.2.3.3 and Appendix D). Facultatively anaerobic bacteria behave like aerobic bacteria when oxygen is present, but they may use nitrate, iron, or other metals (e.g., Mn) as alternative electron acceptors when oxygen is absent.

Samples were analyzed for sulfate, nitrate, nitrite, ammonia, and organic acids because they are important nutrients in microbial metabolic processes and may aid in identifying certain metabolic processes. For example, if facultative anaerobes were dominant and actively reducing nitrate to nitrite, further reduction of nitrite to ammonia could also occur. Carbon processing (degradation or utilization) under anaerobic conditions will usually result in the production of organic acids; formic and acetic acid are the organic acids most often produced (Riser-Roberts 1992). The presence of sulfide could be an indicator of SRB activity.

4.1.2.2 Use of Biometer Flasks to Determine Potential for Microbial Degradation of Hydrocarbons

Biometer flasks, which are closed, controlled environments, were prepared by using portions of soil cores from each location. These flasks were used to determine the rate (mM/day) of CO_2 evolution and total amount (mM) of CO_2 evolved from the prepared sample under aerobic conditions. Air was regularly introduced into the flask through an ascaute column, which removes CO_2 from the air. The CO_2 absorbent (NaOH) was replaced regularly. A control flask was used to determine baseline CO_2 levels. Refer to Section 4.2 for details on the use of biometer flasks.

Biometer-flask experiments were also used to determine the effects of added nutrients (e.g., carbon sources), nutritional supplements (e.g., trace metals or electron acceptors such as nitrate), and moisture on microbial activities. The decision to add supplements was made on the basis of the results of chemical analyses of soil cores, which demonstrated that certain nutrients (e.g., nitrate and phosphate) were potentially limiting. The levels and types of BTEX and TPH in the biometer flasks were also monitored to determine microbial degradation. It is important to note that carbon dioxide evolution in the biometer flasks could be due to the metabolism of indigenous carbon sources (humic and fulvic acids) and/or gasoline components.

Analyses for TPH and BTEX were performed on extracts of the original soil cores and on soils after they were used in biometer-flask studies. The change in the concentrations of TPH and BTEX, after incubation in the biometer flasks, was used as an indicator of degradation.

4.2 Methods, Field Observations, and Additional Data

4.2.1 Methods

4.2.1.1 On-Site Sample Collection Procedures

Soil cores were collected as digging occurred along the length of the trench. When the backhoe reached the desired sampling depth, a steel soil-sampling hand-auger was lowered into the trench and a sample of the fill was collected. A 1-cm^3 portion of this sample, approximately 2 in. from the bottom of the core, was inoculated in sterile deionized water so that a soil slurry could be prepared. The remainder of this first core was removed from the auger and placed into a sterile 250-mL polypropylene centrifuge bottle. This bottle was then placed in a cooler at 4°C for transport to the laboratory. The first core was also used for biometer-flask studies. Three additional cores were collected from each site adjacent to the initial core. One core was used for the biometer-flask study, one for the preparation of soil extract medium or additional culture (if necessary), and the last served as a backup. Before each use, the auger was cleaned with deionized water and decontaminated by rinsing three times with 70% isopropyl alcohol.

4.2.1.2 On-Site Culture Methods

Soil samples were added to sterile deionized (DI) water to prepare slurries. One milliliter of each slurry was used to inoculate anaerobic dilution solution (ADS; a holding medium), which could be used as an alternative source for subculture in the laboratory. BTI MICKIT™ III[1] media were used to determine the levels of viable bacteria belonging to the following four general categories: (1) acid-producing bacteria (which are facultative and/or obligate anaerobes capable of producing organic acids), (2) sulfate-reducing bacteria (SRB, which are obligate anaerobes capable of reducing sulfate to sulfide), (3) aerobes, and (4) obligate or facultative anaerobes. This method employs a five-bottle serial dilution to estimate the numbers of viable bacteria to the nearest order of magnitude.

4.2.1.3 Microscopic Enumeration

Portions of the samples were spotted, dried, heat-fixed to multiwell slides, and stained with fluorescein isothiocyanate (FITC). The total microbial populations (living and dead cells) were then enumerated by means of epifluorescent microscopy.

---

[1] MICKIT™ III — name given to a self-contained field kit, produced by BTI, containing bacteriological media for enumeration of bacteria by serial decimal dilutions.

4.2.1.4 Laboratory Subculture

Subcultures of MICKIT™ III cultures, or ADS preparations, were prepared on standard plate count agar (PCA). Subcultures for bacterial identifications were prepared by using BIOLOG Universal Growth Medium (BUGM; a tryptic soy-based medium produced by BIOLOG, Hayward, Calif.). Bacterial colonies were evaluated on the basis of morphology (the shape and size), color, and texture. Differential colony counts were performed to determine the dominant organisms, which were then identified by using the BIOLOG Microstation™ System.

4.2.1.5 Bacterial Identification

Gram stains were performed to determine whether organisms were gram positive or gram negative. Slurries of selected colonies were prepared to contain a final concentration of 6.0×10^8 cells/mL. These slurries were then inoculated in the appropriate BIOLOG MicroPlate™ and incubated at 35°C. After 24 h, positive reactions in the 95 cells of each MicroPlate™ were scored and logged in the BIOLOG software program. Identifications were made by generating a numerical metabolic fingerprint. Additional metabolic tests were performed by using American Petroleum Institute (API) identification methods (Analytab Products, Plainview, NY) for Enterobacteriaceae and other gram-negative bacteria (api20E™ method) and/or nonfermenting gram-negative bacteria (Rapid NFT™ method).

4.2.1.6 Biometer Flask Procedures

Fifty-gram portions of the soil samples from each location were added to four biometer flasks. One two-flask set of soil samples (flasks) was adjusted to 70 wt% water, as recommended in the original citation for biometer flask use (Pramer and Bartha 1965; Figure 4.1). One flask in each set received a supplement consisting of nitrate, phosphate, and ammonia at 100, 100, and 10 ppm final concentrations. These flasks were incubated in the dark at room temperature for 21 days. A second two-flask set was used in the "as-collected" condition (water content of these samples ranged from 25 to 30 wt%). One flask received the nitrate, phosphate, and ammonia supplement. The flasks containing "as-collected" soil were incubated in the dark at room temperature for 14 days. Air was introduced into a flask only when the NaOH used to absorb carbon dioxide was removed from the side arm.

Carbon dioxide production was measured by removing sodium hydroxide solutions from the flask and titrating with 0.05 N HCl prepared in CO_2-free water. Indicator solution was metacresol purple prepared according to *Standard Methods* (1989, Section 2310 B. Titration Method).

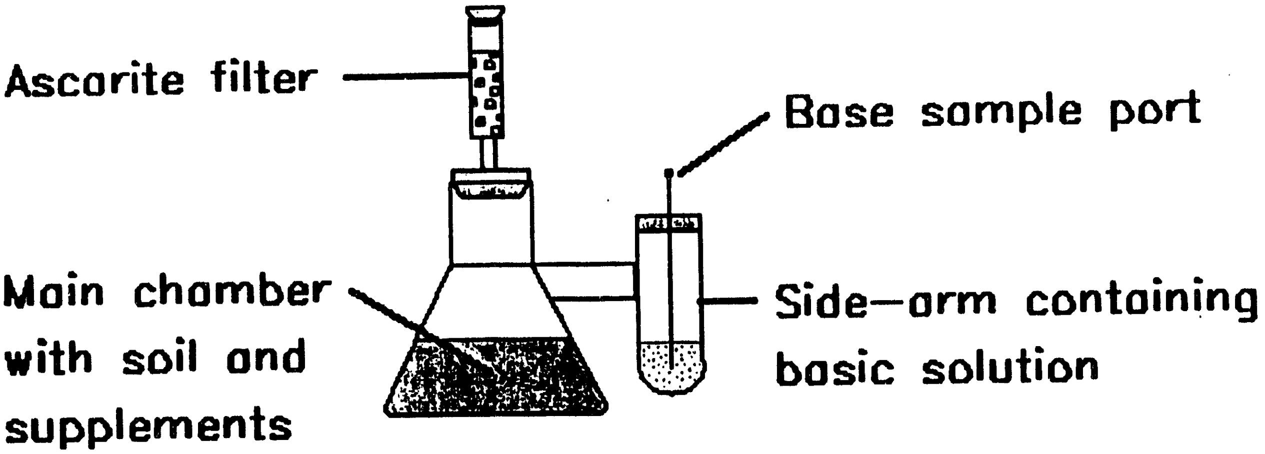


FIGURE 4.1 Biometer Flask

4.2.1.7 Chemical Analyses

To analyze solid samples by using the following analytical methods, it was first necessary to prepare slurries in DI water.

4.2.1.7.1 Total Suspended Solids. Total suspended solids were determined by using Method 2540 D, American Public Health Association, *Standard Methods* (1989).

4.2.1.7.2 Anion Analysis. Soil slurries (5 mL) were filtered through a 0.2-µm (nominal pore size) syringe filter directly into a sealed nitrogen-filled bottle. Analysis of the soluble anions in the filtrates was done by using a Dionex 2000i/SP ion chromatograph with a Dionex 4270 integrator. The column used was a Dionex AS4A Ion Pac® column with a flow rate of 2.0 mL/min. The column eluate was 1.8 mM Na_2CO_3/1.7 mM $NaHCO_3$. The regenerant was 0.025 N H_2SO_4. Components were identified by comparing the results with pre-run standards used to make a three-point linear calibration based on three different concentrations of the anion standard stock solution containing 0.1, 1.0, and 10.0 ppm each of sodium chloride, sodium nitrite, sodium nitrate, potassium phosphate, and potassium sulfate (Method 4110 B., American Public Health Association, *Standard Methods* [1989]).

4.2.1.7.3 Organic Acid Analysis. A portion of the filtrate prepared for anion analysis was acidified, and the organic acids were extracted into petroleum ether. Complete partitioning was accomplished by freezing the sample and decanting the organic portion into a vessel containing anhydrous sodium sulfate (to remove any traces of water). The samples were analyzed by using a gas chromatograph equipped with a packed column and a water- and oxygen-free helium carrier. Concentrations of organic acids were determined by comparison with standards. Formic, acetic, propionic, isobutyric, butyric, isovaleric, valeric, isocaproic, caproic, and heptanoic acids can be detected by using this method. The minimum detection limit for this test is 2.0 ppm.

4.2.2 Field Observations

The following information includes observations made during core sampling. These are qualitative statements regarding the composition of the sample and data on the vapor concentration of product (as noted earlier, the term "product" will be used as a general term for all components in weathered gasoline beneath the parking lot). These vapor data were obtained by Argonne personnel, who used a Thermo Environmental Instrument, Inc., organic vapor monitor, Model 5805 with a 10.6-eV lamp, which was capable of detecting BTEX and other volatile components over a 0–2000-ppm range.

The sample number used in the following list consists of two parts: (1) the first number is the location, in feet, of the core along the length of the trench (sampling originated at the end of the trench nearest to the gas station and extended out into the parking lot), and (2) the second number is the depth, in feet, at which the sample was taken; this value represents the top of the core sample.

Sample Number: 13-6

Concentration of product vapor after stripping off asphalt (at surface): 0.5 ppm

Concentration of product vapor in the trench prior to core collection: 244 ppm

Comments: Soil was compact and muddy. The sample was collected just below a gravel-like fill.

Sample Number: 25-8

Concentration of product vapor after stripping off asphalt (at surface): 1.0 ppm

Concentration of product vapor in the trench prior to core collection: 5.3 ppm

Comments: Dense, very tight, nonporous with sand and oxidized throughout the core. Intermittent patches of gray (clay).

Sample Number: 50-5

Concentration of product vapor after stripping off asphalt (at surface): 15 ppm

Concentration of product in the trench prior to core collection: 260 ppm

Comments: Very sandy sample. Some "black" material in deeper region of the core. Strong odor of product. Black material was organic because it floated in sterile DI water used to make the soil slurry.

Sample Number: 75-8

Concentration of product vapor after stripping asphalt (at surface): 17 ppm

Concentration of product vapor in the trench prior to core collection: 306 ppm

Comments: Sand with interspersed greenish gray clay. Some stratified clay layers. Consistency of portions of the sample was similar to modeling clay.

Sample Number: 100-9

Concentration of product vapor after stripping asphalt (at surface): 8 ppm

Concentration of product vapor in the trench prior to core collection: 416–629 ppm

Comments: Mixture of sand (dominant) and isolated cells of clay. Clay was a bluish-gray with some green tint. The sample contained sufficient product to rapidly stain surfaces of sample bottles, latex gloves, etc.

Sample Number: 123-7

Concentration of product vapor after stripping asphalt (at surface): 9 ppm

Concentration of product vapor in the trench prior to core collection: 465 ppm

Comments: Top portion of the core was sand with progressively higher amounts of clay in the bottom portion of the sample.

Sample Number: 140-8	
Concentration of product vapor after stripping asphalt (at surface):	10 ppm
Concentration of product vapor in the trench prior to core collection:	330–350 ppm

Comments: Sand overlying clay. Some plant debris was contained in the clay layer. The highest product vapor reading, 419 ppm, was obtained from the large sample vessel used for Argonne samples.

Sample Number: 160-8	
Concentration of product vapor after stripping asphalt (at surface):	0 ppm
Concentration of product vapor in the trench prior to core collection:	50 ppm

Comments: Large vessel containing sample for Argonne analysis had product levels of 286 ppm. Core was sand (4–6 in.) overlying clay (12 in.).

Sample Number: 205-8	
Concentration of product vapor after stripping asphalt (at surface):	0 ppm
Concentration of product vapor in the trench prior to core collection:	3.5–5.3 ppm

Comments: Sand overlying clay as for Sample 160-8.

Sample Number: 225-8	
Concentration of product vapor after stripping asphalt (at surface):	not done
Concentration of product vapor in the trench prior to core collection:	0 ppm

Comments: Sand (4–6 in.) overlying clay (6–8 in.).

4.2.3 Additional Data

Laboratory data are presented in Appendix D.

4.2.3.1 Possible Relationships between Chemical and Microbiological Factors

It is important to reiterate here that laboratory TPH values used in this study include all components in the soil samples that are soluble in freon. During extraction, approximately one-half of the low-molecular-weight compounds (e.g., BTEX) will be lost. TPH values do contain, therefore, known amounts of benzene, toluene, ethylbenzene, and xylene.

The number of viable bacteria recovered at each location and depth along the trench is presented in Table 4.1. The relationship between numbers of viable bacteria and the level of product vapor is shown in Figure 4.2. The plot shows that aerobic and APB bacterial levels increased to maximum levels just prior to the location containing the maximum level of product. As product declined with distance, the levels of these bacteria also declined. However, when the level of product diminished to zero, the microbial populations again increased. These data suggest that certain bacterial populations may have become conditioned to the fuel-containing environment between 0 and 150 ft (wells 1 and 2) and that the populations beyond 150 ft from the origin of the trench (wells 2 and 3) were different and possibly not conditioned to the hydrocarbon-containing environment. The anaerobic population was generally at low levels in the presence of

TABLE 4.1 Viable Bacteria Recovered from Soil Cores[a]

Linear Distance of Trench (ft)	Depth of Sample (ft)	Aerobic Bacteria (cells/g)	APB[b] (cells/g)	Anaerobic Bacteria (cells/g)
13	6	2.6×10^4	2.6×10^4	2.6×10^4
25	8	2.8×10^4	2.8×10^3	2.8×10^4
50	5	$>2.5 \times 10^6$	$>2.5 \times 10^6$	2.5×10^4
75	8	$>4.7 \times 10^6$	$>4.7 \times 10^6$	$>4.7 \times 10^6$
100	9	$>4.0 \times 10^6$	4.0×10^4	4.0×10^4
123	7	4.0×10^4	4.0×10^4	4.0×10^4
140	8	4.4×10^3	4.4×10^3	4.4×10^4
160	8	6.5×10^2	6.5×10^2	6.5×10^4
205	8	$>2.8 \times 10^6$	2.8×10^4	$>2.8 \times 10^6$
225	8	$>2.2 \times 10^6$	2.2×10^4	$>7.2 \times 10^6$

[a] Values were determined by using serial decimal dilutions (see Appendix D, Materials and Methods) and adjusted according to the wet weight of the soil sample used for culture.

[b] APB = Acid-Producing Bacteria — bacteria that can produce organic acids.

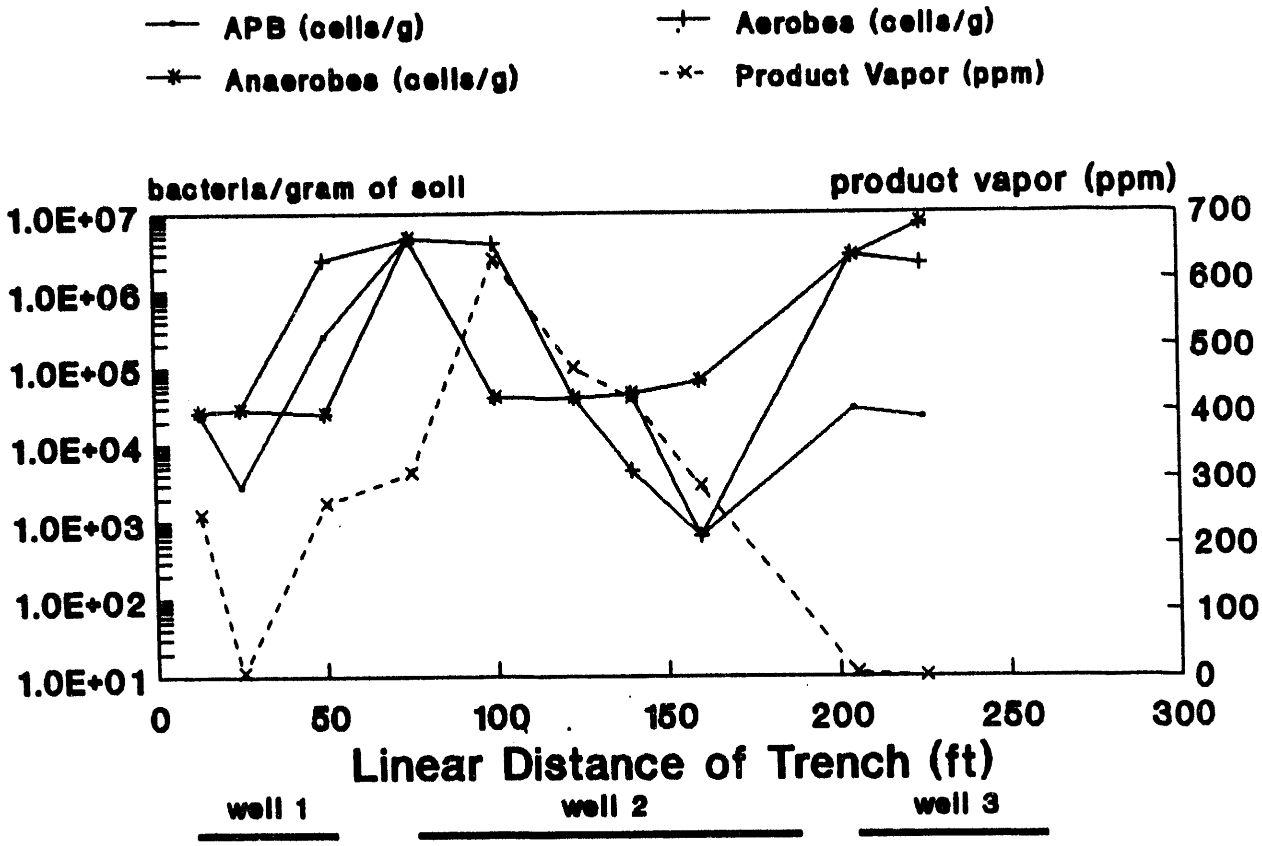


FIGURE 4.2 Relationship between Product Vapor and Viable Bacteria

product and higher at the end of the trench (well 3) where product was absent. Figure 4.3 shows the data for the total bacterial counts (i.e., live and dead; cultivable or noncultivable) in each sample. A trend similar to that for the viable counts can be seen.

The data for product vapor evolved from the trench and total petroleum hydrocarbon (TPH) detected in the soil is presented in Figure 4.4. The results show that the maximum concentration of volatile components and TPH occurred between 100 and 160 ft from trench origin (well 2). A similar relationship was found for toluene, ethylbenzene, and xylene; the highest concentrations of BTEX occurred in well 2 at the 140-ft sample location (see below). However, benzene was not detected in any of the samples.

The effect of TPH on the levels of viable APB and aerobes is presented in Figures 4.2 and 4.3. It appears that some bacterial communities may be stimulated at moderate TPH concentrations, but inhibited at high levels of TPH. This inhibition could be due to the combined toxic effects of the various gasoline components at the higher concentrations. At very low concentrations of gasoline components, the bacterial populations are low (e.g., 25-ft and 160-ft locations). The lack of usable carbon might account for the low bacterial populations.

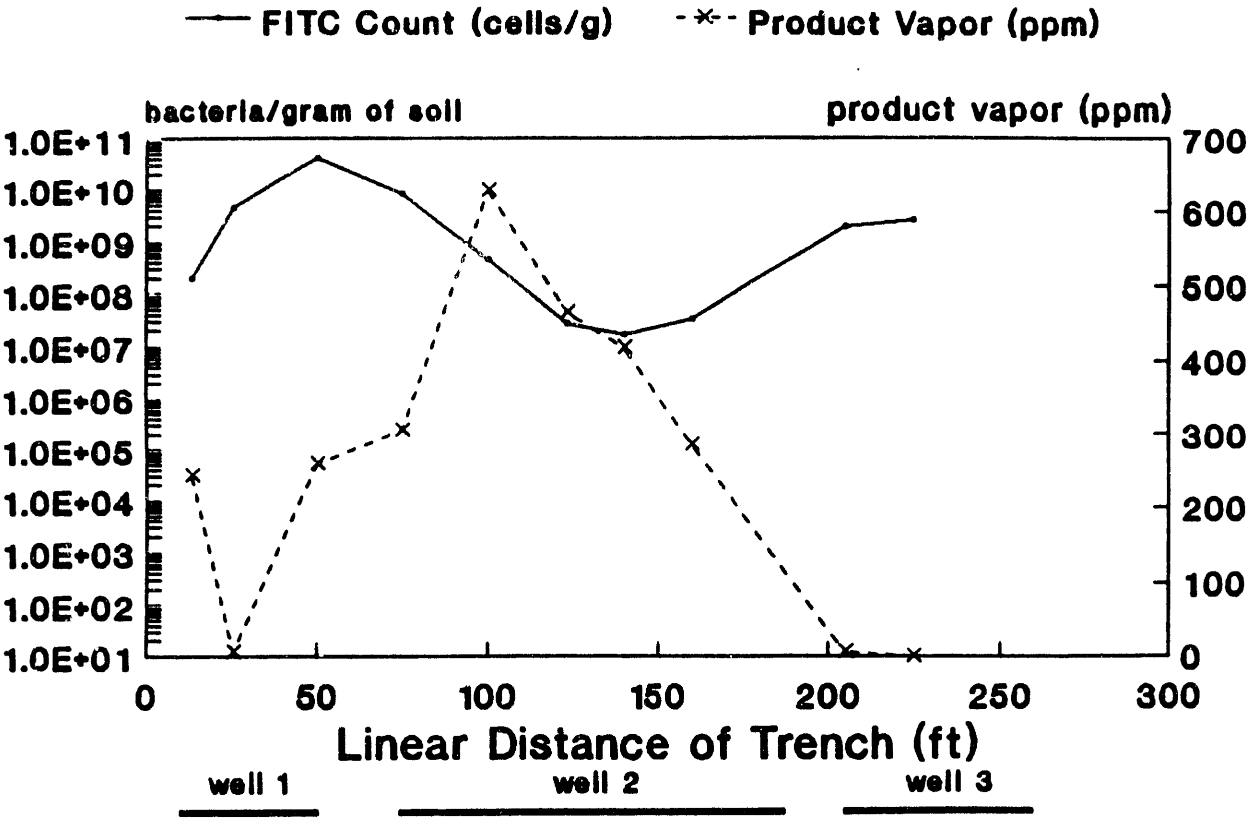


FIGURE 4.3 Relationship between Product Vapor and FITC Total Count

Figures 4.5 and 4.6 show the relationships between ethylbenzene, toluene, xylene, and indigenous APB and aerobic bacteria at various locations along the trench. The relationships were similar to those seen between the bacterial community and TPH.

Figure 4.7 shows that there is no discernible overall trend for toluene concentration versus the level of organisms. The same situation was seen for xylene and ethylbenzene. For comparison, Figure 4.3 shows the relationship between TPH and viable bacteria; the overall "trend" (not shown) was positive for APB and aerobic bacteria but negative for anaerobic bacteria. The maximum concentration of each of the products occurred between 100 and 160 ft. Therefore, it is impossible to determine which of the product components was responsible for the negative effect on the bacterial populations at these locations in well 2.

4.2.3.2 Possible Physical and Chemical Relationships

The above data suggest that gasoline components may have localized in the subsurface environment or possibly in zones of water flow. In particular, the anaerobic bacteria populations showed a nonlinear trend; the bacterial numbers were generally at lower levels (Figure 4.8) when

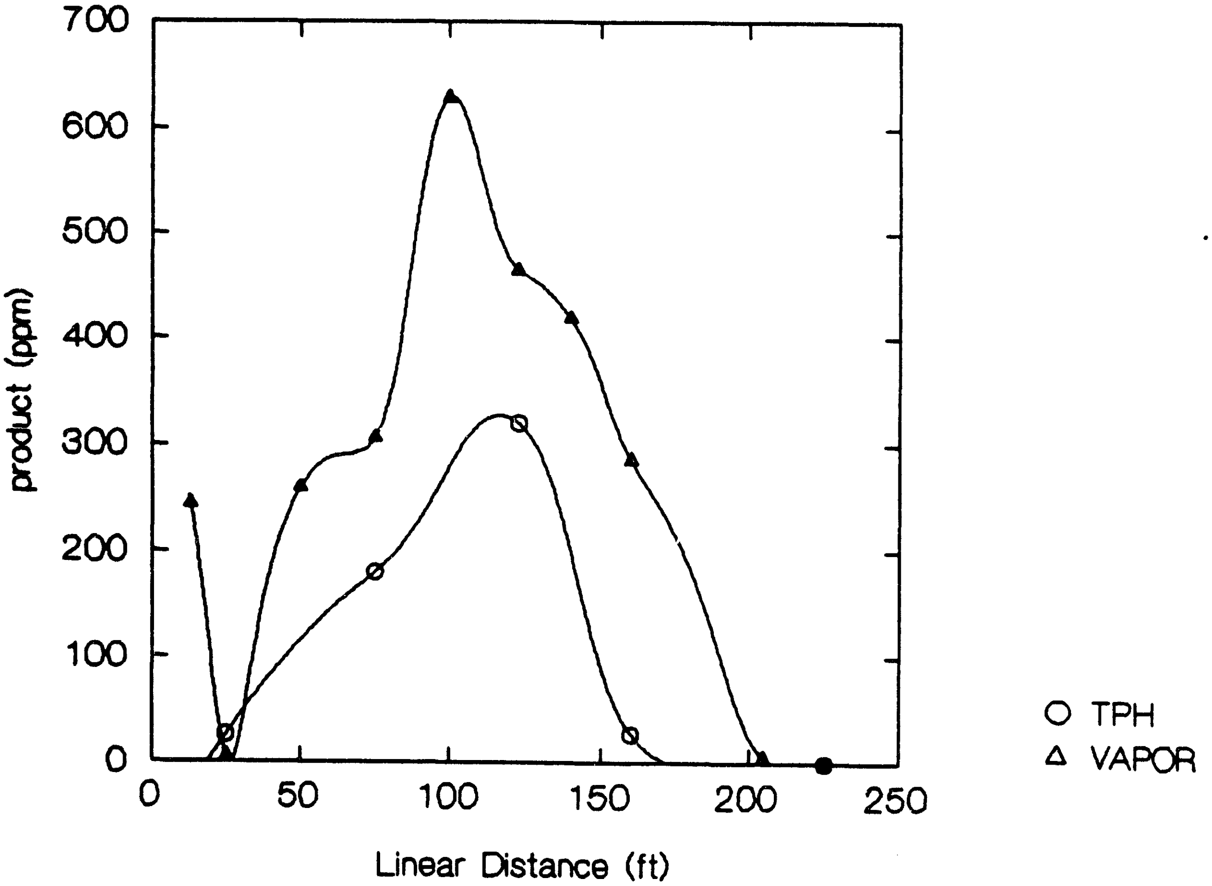


FIGURE 4.4 Concentration of Product Vapor and TPH along the Trench

product was at the highest levels (Figure 4.2). At the most distant portions of well 3 (200–250 ft), the anaerobic population increased again. The same trend was seen with manganese (Figure 4.9) and chloride (curved line in Figure 4.10), suggesting washout of these components. Assuming that water drawn into the area (i.e., between the origin of the trench and 150 ft from the origin) contained a low level of dissolved oxygen, the high level of anaerobes at the end of well 3 could be due to the lack of water flow in that region. The region at the end of well 3 also had soil samples containing the greatest amount of clay. The clay would act as a barrier to water flow.

Descriptive information taken during the sampling process indicated that the areas containing the highest amounts of product were, quite possibly, well aerated, as indicated by the rich orange to reddish-orange color of the soil. As mentioned above, Argonne's chemical analyses of the soil indicated a high level of iron throughout the trench. Percolation (or recharge from exposed soil areas adjacent to the paved parking lot) may have been responsible for introducing oxygen and/or oxygenated rainwater into the area, resulting in the washout of water-soluble components (Fe, Cl, SO_4). As the distance from the gasoline station increased, the degree of recharge with fresh water may have diminished, which may explain the shapes of the curves in Figures 4.8–4.10. Cores collected beyond 200 ft had higher levels of anaerobes, chloride, sulfate, more clay, and were gray, grayish-green, and bluish-gray, indicating less contact with oxygenated waters.

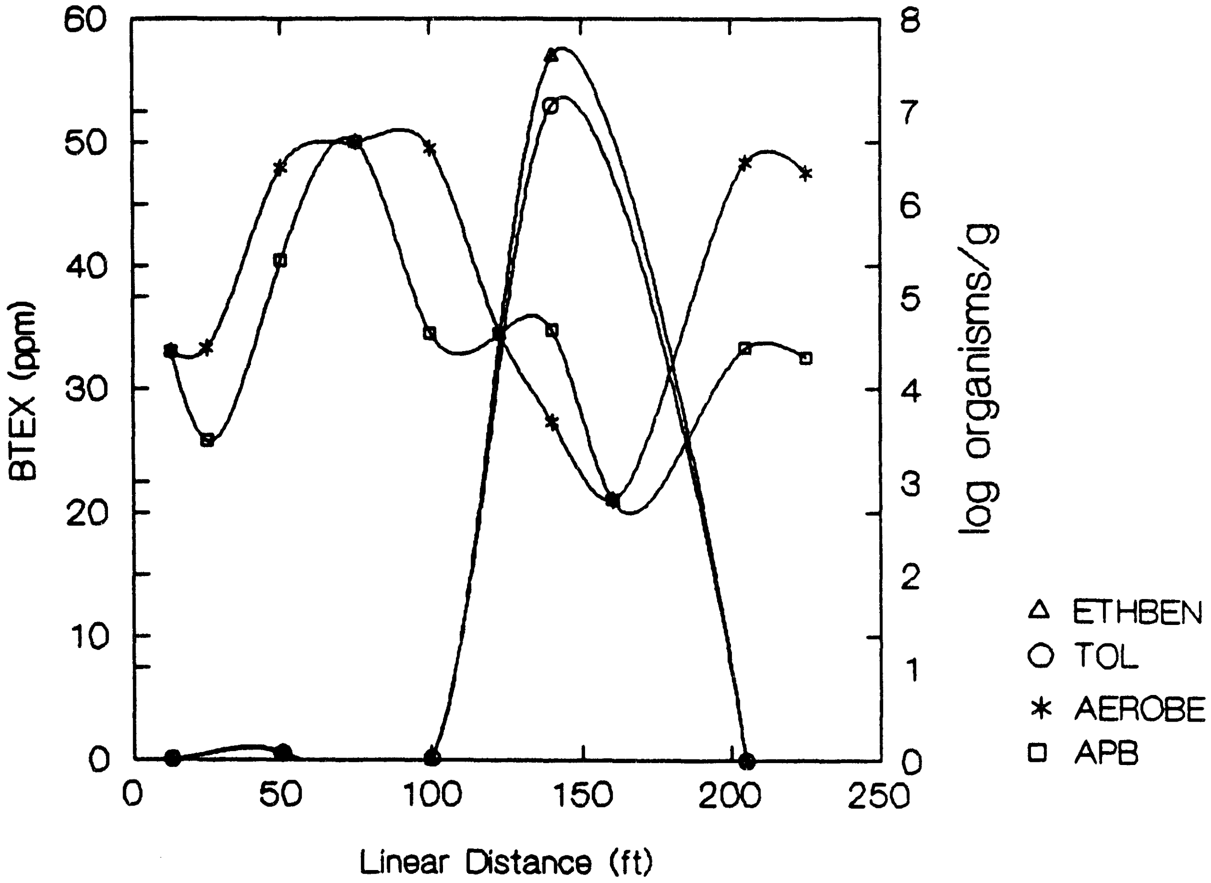


FIGURE 4.5 Incidence of BTEX and Viable Bacteria

Organic acids were at low levels in all subsurface environments sampled. The dominant acids usually found in anaerobic environments include formic and acetic acids (Kobayashi and Rittmann 1982). The maximum level of acid (formic at 40 ppm) was found (Figure 4.11) at the location that had the lowest bacterial populations (well 3, 160 ft). It is possible that this area showed a slight increase in formic acid because it represented a localized zone of increased bacterial activity. The same location, and locations adjacent to it, showed the highest concentrations of ammonia, which could also be indicative of increased metabolic activity.

4.2.3.3 Bacterial Identifications and Possible Functions

Table 4.2 provides information on the dominant aerobic (and some facultatively anaerobic) bacteria that were isolated from each location along the trench. (See Table 4.1 for the levels of aerobic, facultatively anaerobic, and anaerobic bacteria detected at each location along the trench.) Bacteria of the genus *Bacillus* dominated the populations at most locations. Table 4.3 gives additional details and comments on the bacteria isolated. *Bacillus* sp. are widespread in soils and are very versatile with regard to the use of carbon (carbohydrates, carboxylic acids, organic acids, etc.). The genus is known for its ability to produce extracellular enzymes that attack a variety of

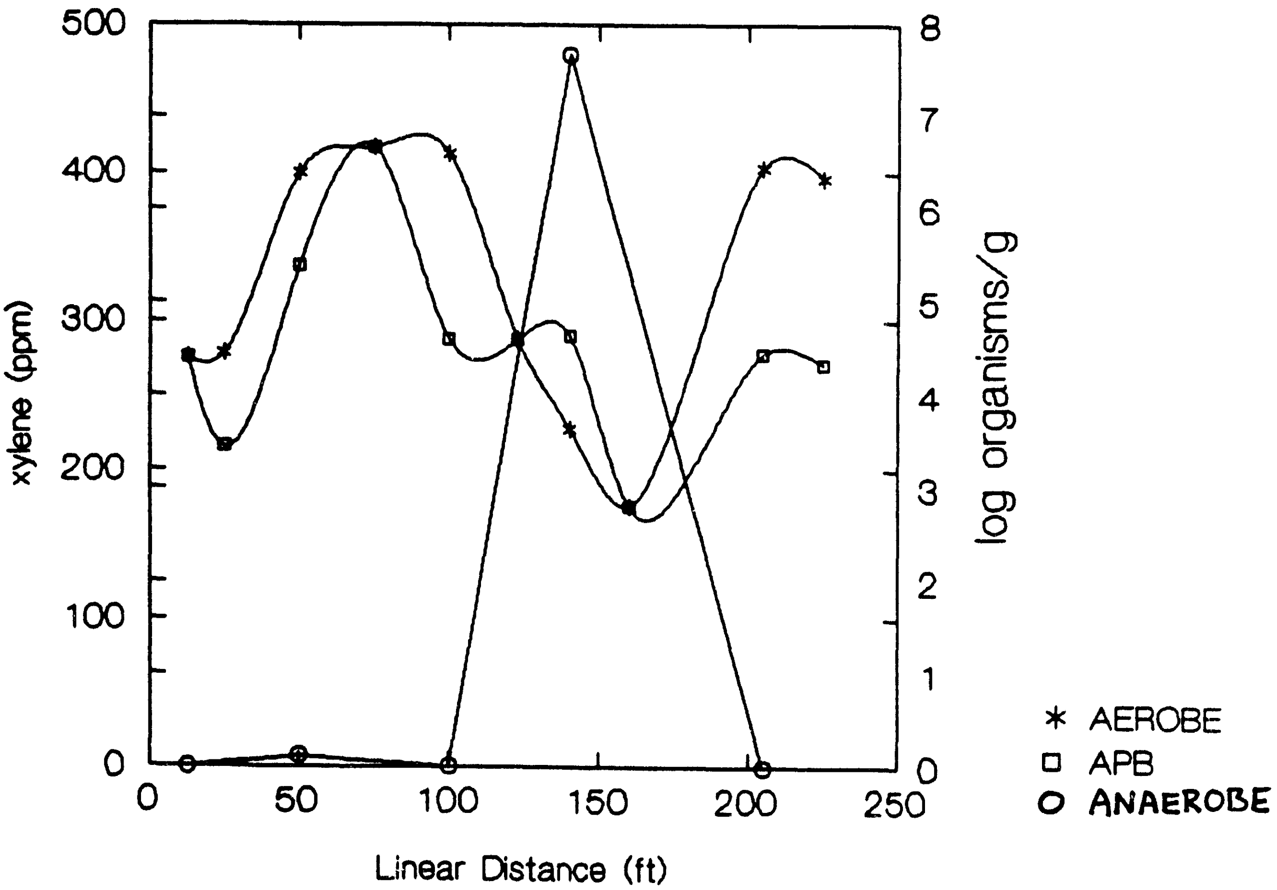


FIGURE 4.6 Incidence of Xylene and Viable Bacteria

natural biopolymers (e.g., gelatin and proteins). In the presence of the proper carbon sources, these bacilli can produce large amounts of carbon dioxide. Most are considered aerobic, but some may grow and use carbon in the presence of electron acceptors other than oxygen (e.g., nitrate yielding nitrogen or ammonia from the reduction, or ferric iron, which is reduced to ferrous iron).

Many *Bacillus* sp. oxidatively transform polycyclic compounds (isoprenoids, steroids). They have the capability of hydroxylating specific ring positions. Oxidation (hydroxylation) of alkyl benzenes is often the first step in ring scission, which can then lead to further degradation (see Appendix D).

A *Pseudomonas* sp. was identified at only one site. The pseudomonads have been shown to be adept at degrading alkanes, alkenes, phenol, toluene, xylene, and other related compounds (see Appendix D). The genus *Alcaligenes*, which is closely related to *Pseudomonas* and is often difficult to differentiate from it, may also have similar capabilities. Corynebacteria have been shown to degrade alkanes of moderate chain length (e.g., octane and decane), as well as heterocyclic compounds (Kobayashi and Rittmann 1982). The genera identified in Table 4.3 have been found associated with hydrocarbon contamination/degradation.

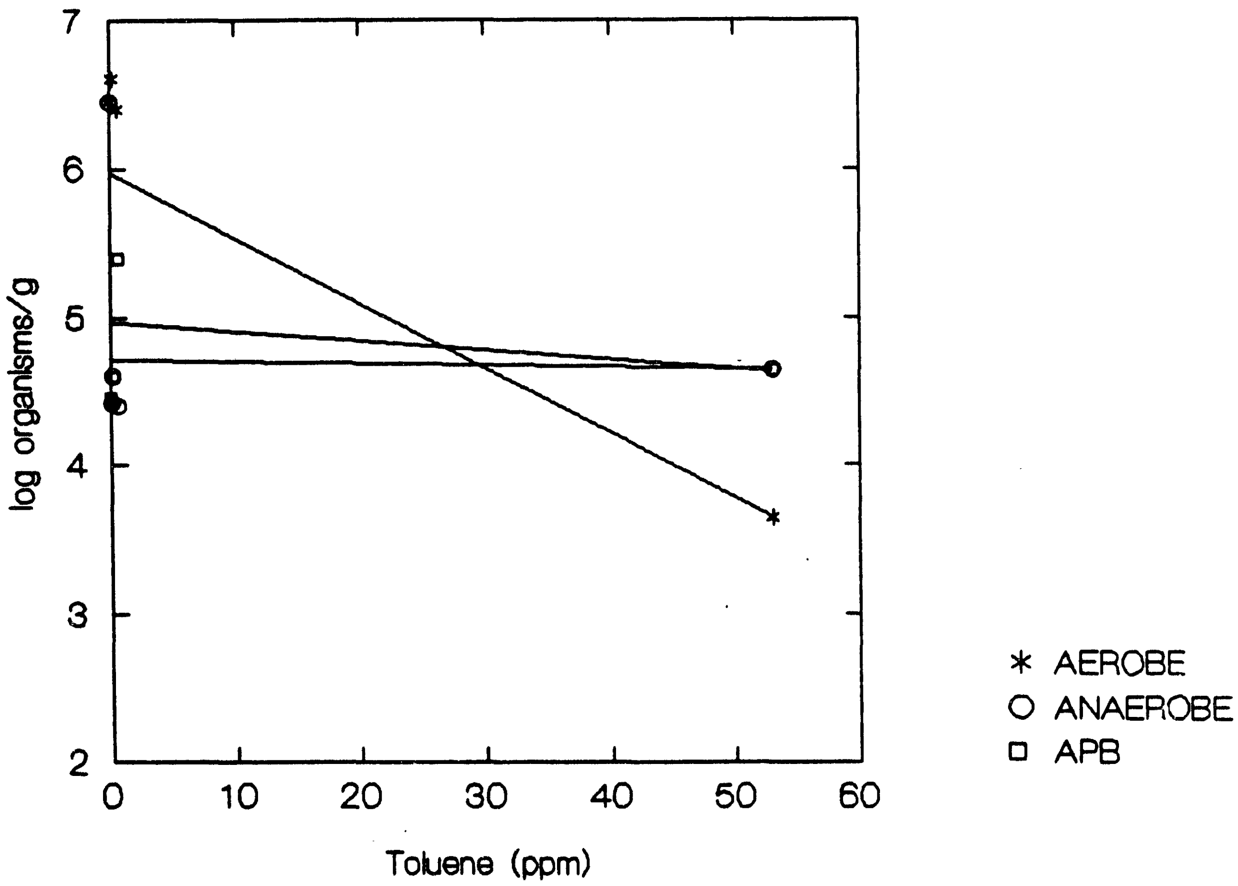


FIGURE 4.7 Trended Relationship between Viable Bacteria and Toluene Concentration

4.2.3.4 Biometer Studies

Figures 4.12 and 4.13 showed that the greatest amount of carbon dioxide evolution from a soil sample was in the presence of high product concentration and moderate numbers of bacteria. High levels of bacteria and moderate levels of product showed relatively low carbon dioxide evolution (Figures 4.14 and 4.15). Figures 4.16 through 4.19 show the data for carbon dioxide evolution from the biometer flasks prepared from other locations.

Some biometer flasks showed a severe decrease in CO_2 production between days six and seven. This decrease may have been an indication that one preferred carbon source had been exhausted and the population was adjusting to a new carbon source, a phenomenon known as diauxic growth. Other flasks showed major increases in CO_2 evolution. Populations in these flasks may have been better adapted. It should be noted that this feasibility study did not discriminate between fuel and indigenous carbon sources (e.g., humic and fulvic acids) as carbon sources. Some carbon dioxide evolution could be attributed to the indigenous carbon sources.

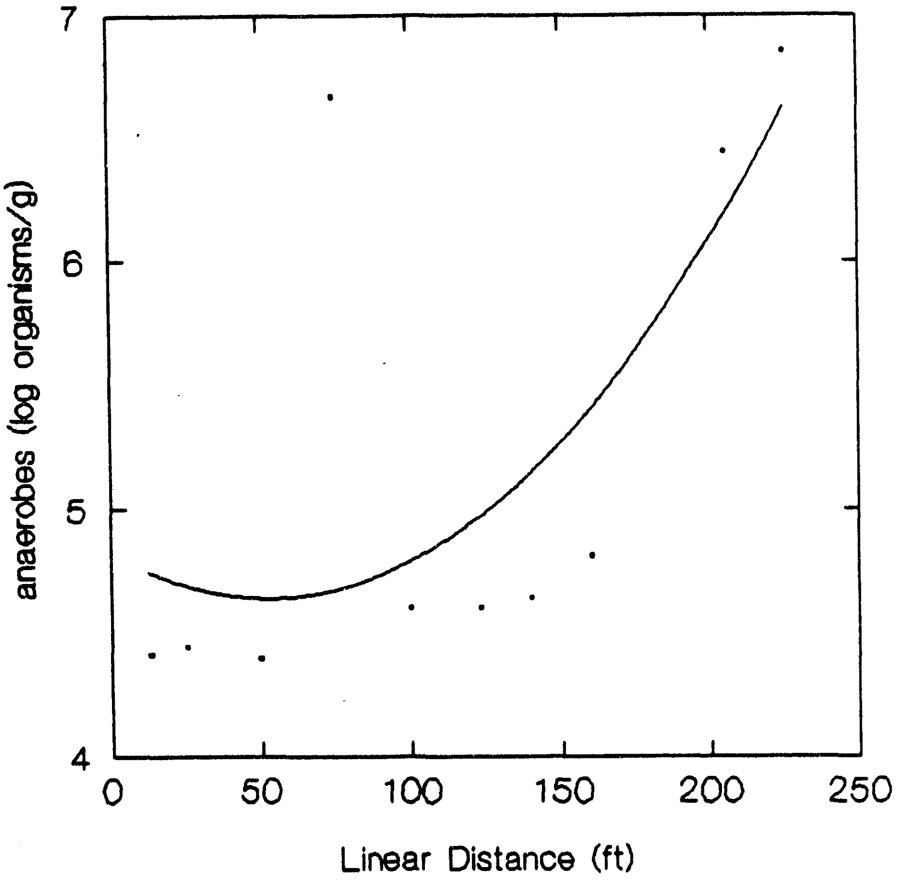


FIGURE 4.8 Nonlinear Trend for Viable Anaerobic Bacteria

Table 4.4 lists the raw data collected for carbon dioxide evolution and TPH remaining in each of the biometer flasks. It can be seen that there is a great degree of variability in both sets of data. No initial TPH data are available for these flasks. The flasks were prepared from the 13-, 50-, 100-, 140-, and 205-ft locations. The other locations (i.e., 25-, 75-, 123-, 160- and 225-ft locations; see Table 3.3) were analyzed by Argonne.

Tables 4.5 and 4.6, respectively, show the amount of carbon dioxide evolved and the initial and final amounts of toluene and ethylbenzene detected in the biometer flasks. The values for the products remaining indicated that some degradation had occurred in the flasks containing soils from the 13-, 50-, and 205-ft locations. However, the data for product remaining in the soil prepared from the 100- and 140-ft locations appear to be reversed in Tables 4.5 and 4.6 (i.e., there is more product remaining in the biometer flasks after exposure to biometer flask conditions than was present before exposure). This finding may indicate a high degree of heterogeneity in the samples or mobilization/solubilization of product by microbes.

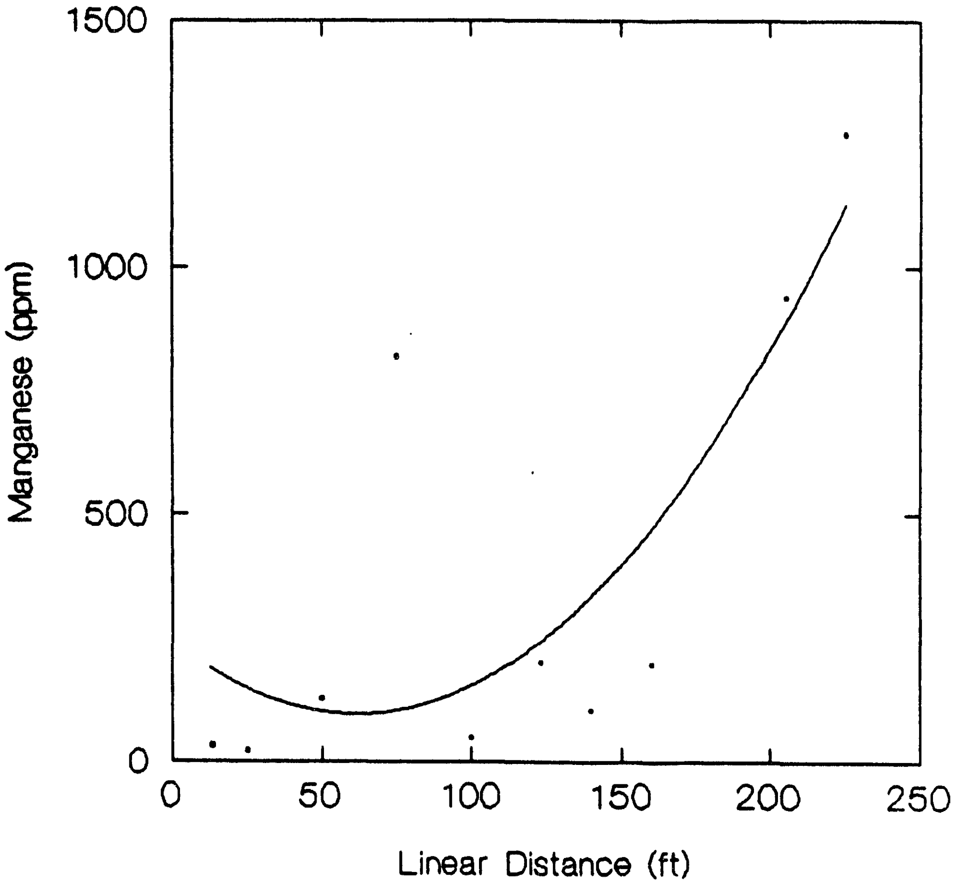


FIGURE 4.9 Nonlinear Trend for Manganese Concentration

4.3 Summary of Results[2]

4.3.1 Bacteria Recovered from Soil Cores

Table 4.2 presents information on the dominant aerobic (or facultatively anaerobic) bacteria isolated at each location along the trench. The genus *Bacillus* dominated the population at most of the locations. *Bacillus* sp. are widespread in soils and use a wide variety of carbon sources (i.e., carbohydrates, carboxylic acids, and organic acids).

The pseudomonads have been shown to degrade alkanes, alkenes, phenol, toluene, xylene, and other related compounds. They were isolated at only one location. However, a probable

---

[2] For proper interpretation of the data presented in this section, it must be kept in mind that total petroleum hydrocarbon (TPH) values include all components in the soil that are soluble in freon. During extraction, approximately one-half of the low-molecular-weight compounds, benzene, toluene, ethylbenzene, and xylenes (BTEX), will be lost. TPH does contain, therefore, a certain amount of BTEX, and the effects of TPH versus BTEX on the various bacterial populations cannot be completely segregated.

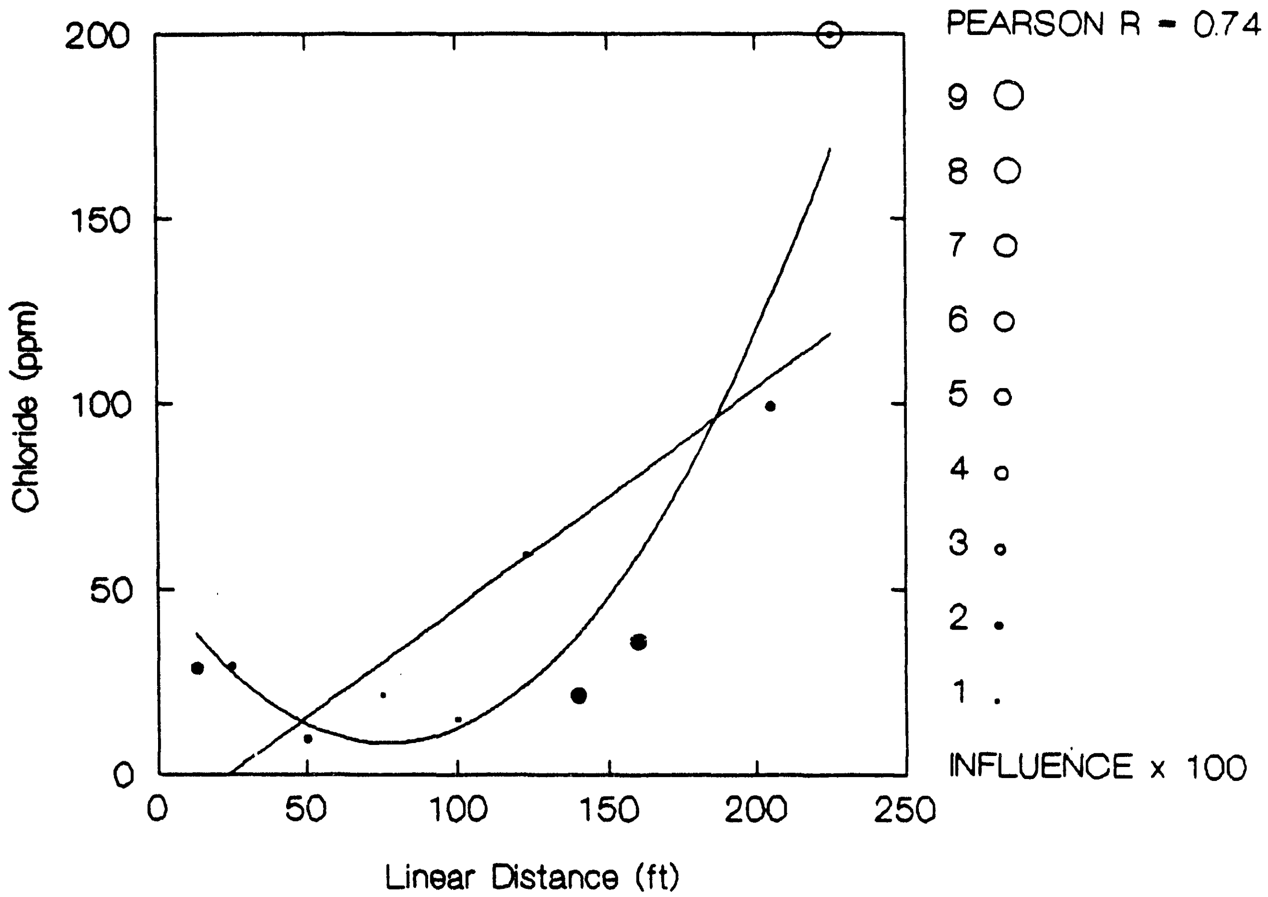


FIGURE 4.10 Nonlinear Trend for Chloride Concentration and Pearson Correlation for Linearity of Chloride Data

Alcaligenes sp., which is closely related to *Pseudomonas* and often difficult to differentiate from them, was also recovered from one sample location. Several samples also contained populations of probable corynebacteria. Corynebacteria are able to degrade alkanes of moderate chain length (e.g., octane and decane), as well as heterocyclic compounds (Kobayashi and Rittmann 1982).

Recovery of bacteria in these genera suggests the presence of bacterial populations with the potential for hydrocarbon degradation. Additional details are presented in Section 4.2.3.3.

4.3.2 Possible Relationships between Bacterial Levels and Concentration of Hydrocarbons

The relationship between total petroleum hydrocarbon (TPH) concentration and the levels of viable APB and aerobes is presented in Figure 4.20. The graph shows the following:

- At the highest TPH concentration (>300 ppm at the 123-ft location), 4.4×10^4 viable organisms/g were detected in the soil.

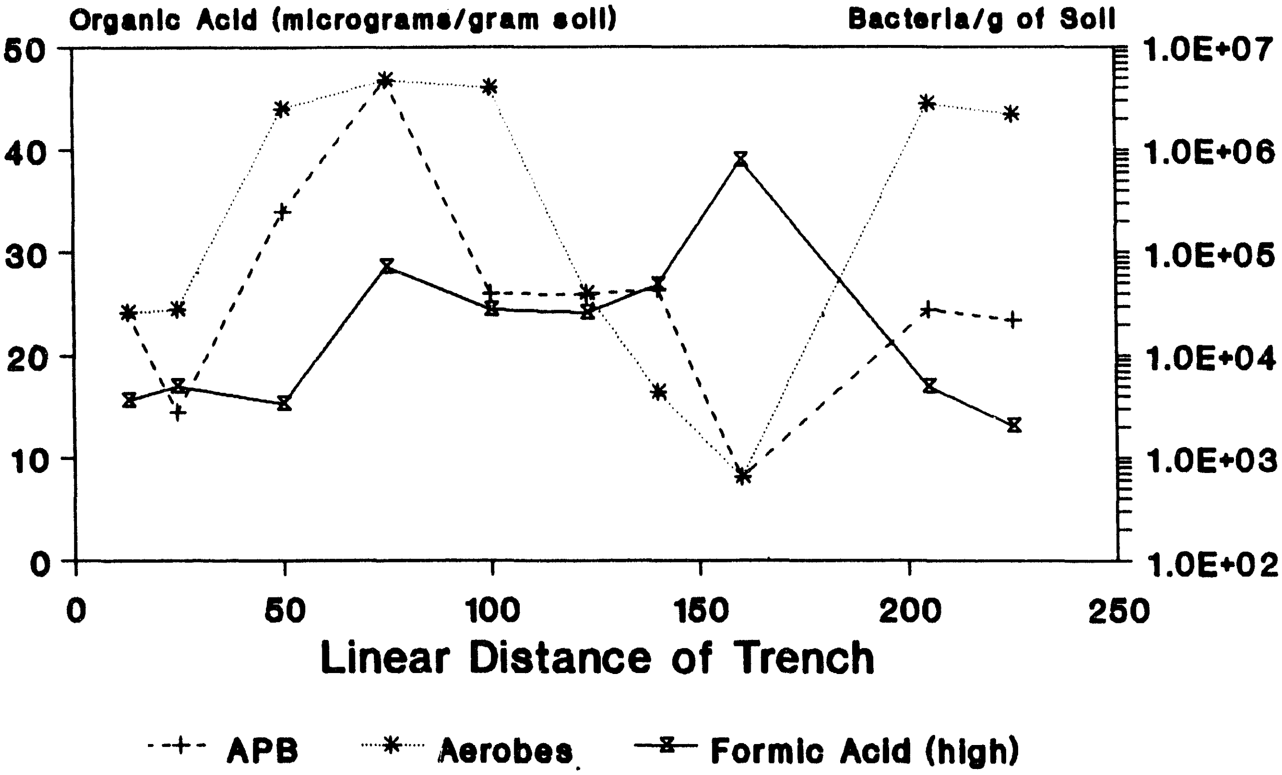


FIGURE 4.11 Relationship between Aerobic APB and Formic Acid

- At low to moderate concentrations of TPH (0-200 ppm), viable APB[3] and aerobic bacterial populations varied from 6.5×10^2 organisms/g at the 160-ft location to >4.7×10^6 organisms/g at the 75-ft location. *Both samples were located within horizontal well 2.*

These data suggest that the bacterial communities *may be* stimulated by moderate TPH concentrations (Figure 4.21). However, if the concentration of TPH becomes too great, the populations decline. As the concentration of TPH increases, the proportion of benzene, toluene, ethylbenzene, and xylene (BTEX) in the sample also could be expected to increase, because the extraction method used to estimate TPH recovers both TPH and BTEX. Therefore, the observed decline in viable bacteria between 123 and 140 ft could be due to the *combined* toxic effects of the various gasoline components that were present. At very low concentrations of gasoline components, the bacterial populations are also smaller (e.g., 25-ft and 160-ft locations; Figure 4.2); however, this decline could be due to a lack of utilizable carbon (see Section 4.3.3 below). Additional data showing these relationships are presented in Section 4.2.3.1.

---

[3] The APB initialism is used for anaerobic and facultatively anaerobic bacteria that are capable of producing short-chain organic acids.

TABLE 4.2 Location of Dominant Bacteria Identified or Suspected in Soil Samples and Concentration of Associated Gasoline Components[a]

Dominant Bacteria Identified or Suspected	Well No.	Linear Distance of Trench 1 (ft)	Gasoline Component, Concentration			
			TPH (ppm)	Toluene (ppb)	Ethyl Benzene (ppb)	Xylene (ppb)
Bacillus coagulans *Bacillus insolitus* *Bacillus polymyxa* *Bacillus* sp. *Micrococcus* sp.	1	12	ND[b]	84	28	180
No identifications	1	25	26	ND	ND	ND
B. insolitus	1	50	ND	580	690	7700
Bacillus subtilis *B. insolitus* *Pseudomonas* sp.	2	75	180	ND	ND	ND
Corynebacterium sp. Suspected *Cellulomonas* *Microbacterium* or *Curtobacterium*	2	100	ND	180	81	750
Corynebacterium sp.	2	125	320	ND	ND	ND
B. insolitus Suspected *Corynebacterium* sp.	2	140	ND	53,000	57,000	480,000
Suspected *Alcaligenes* sp.	2	160	27	ND	ND	ND
B. insolitus *Bacillus megaterium* *Bacillus* sp.	3	205	ND	2	40	4
Bacillus sp. Suspected *Corynebacterium* sp.	3	225	<10	ND	ND	ND

[a] Although expected to be present, benzene was not detected in any of the samples. Review of laboratory results confirmed no detection of benzene in any sample.

[b] ND - Analysis not done.

TABLE 4.3 Identification of Dominant Aerobic Bacteria Recovered from ADS

Identification	Linear Distance of Trench (ft)	Depth of Sample (ft)	Comment
Bacillus sp.	12	6	Possible thermophile (?)
Bacillus polymyxa			Nitrogen fixer; pectin and polysaccharides decomposed; varied carbon sources in the presence of NH_4-N
Bacillus coagulans			Minimal nutritional requirements; prefers pH ≤6.0
Bacillus insolitus			Growth and sporulation at low temperatures
Micrococcus sp.			Tolerant of 5% NaCl; respiratory; produce pigments; members of the genus are capable of degrading aliphatic hydrocarbons
No Identifications	25	8	
Bacillus subtilis (2)	50	5	Pectin and polysaccharides degraded; pigments; simple nutritional requirement when NH_4-N present; nitrate allows anaerobic growth; prefers acidic pH
Bacillus insolitus			See above
Strain A745B Unknown			Aerobic; slow growth; possible CO_2 requirement
Bacillus insolitus	75	8	See above
Pseudomonas sp.			Tentative ID; possible ring cleavage
Corynebacterium sp.	100	9	Often recovered from soil; actually a facultative anaerobe
Strain A747A Unknown			Similar to A745B above
Strain A747B Unknown			Possible *Cellulomonas, Microbacterium,* or *Curtobacterium*

TABLE 4.3 (Cont.)

Identification	Linear Distance of Trench (ft)	Depth of Sample (ft)	Comment
Strain A748A Unknown	125	7	Possible *Corynebacterium*
Strain A748B Unknown			Possible *Corynebacterium*
Strain A748C Unknown			Similar to A745B and A747A
Bacillus inolitus	140	8	See above
A749A Unknown			Possible *Corynebacterium*
A750A Unknown	160	8	Gram negative; possible *Alcaligenes*
Bacillus sp. (2)	205	8	Possible *B. insolitus*
Bacillus megaterium	225	8	Very versatile
Bacillus insolitus			See above
Bacillus sp. (2)			
A752B Unknown			Possible *Corynebacterium*
A752D Unknown			Similar to A745B and A747A
A752E Unknown			Insufficient growth; no identification
A752F Unknown			Unusual gram-positive organism (rod-shaped)

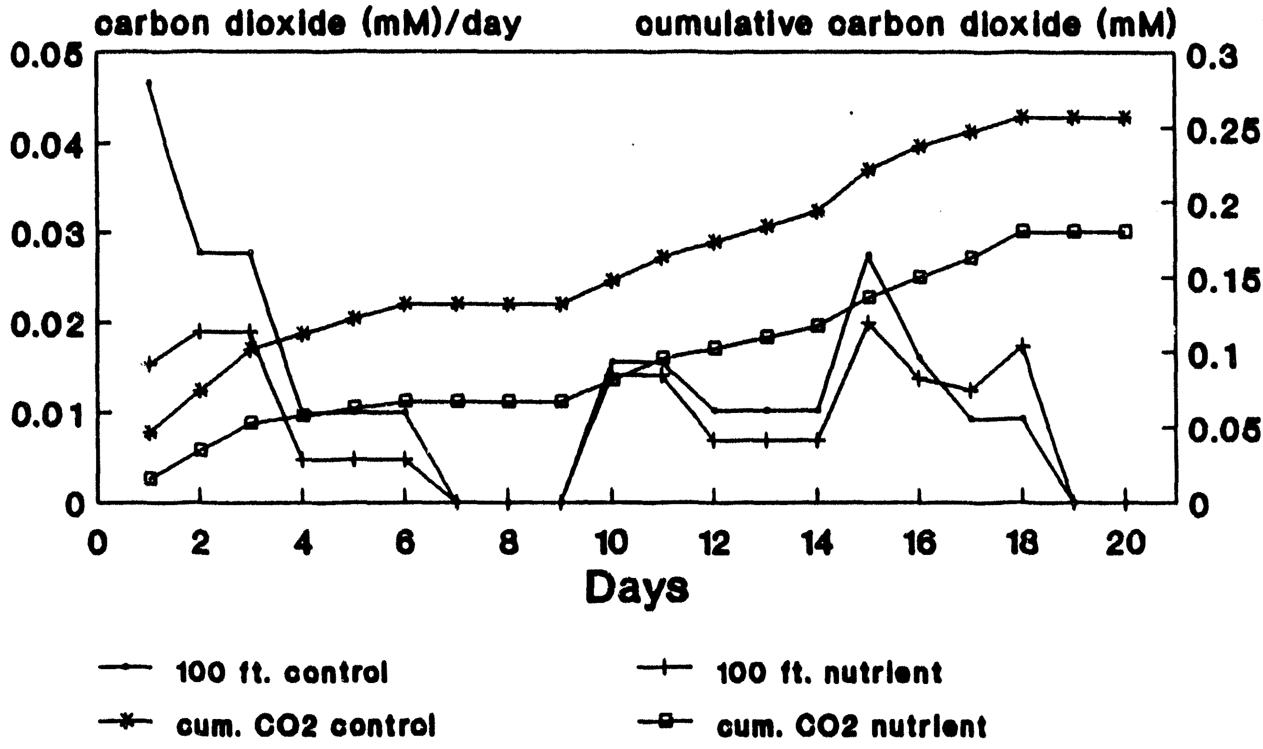


FIGURE 4.12 Carbon Dioxide Production: Sample 100-9

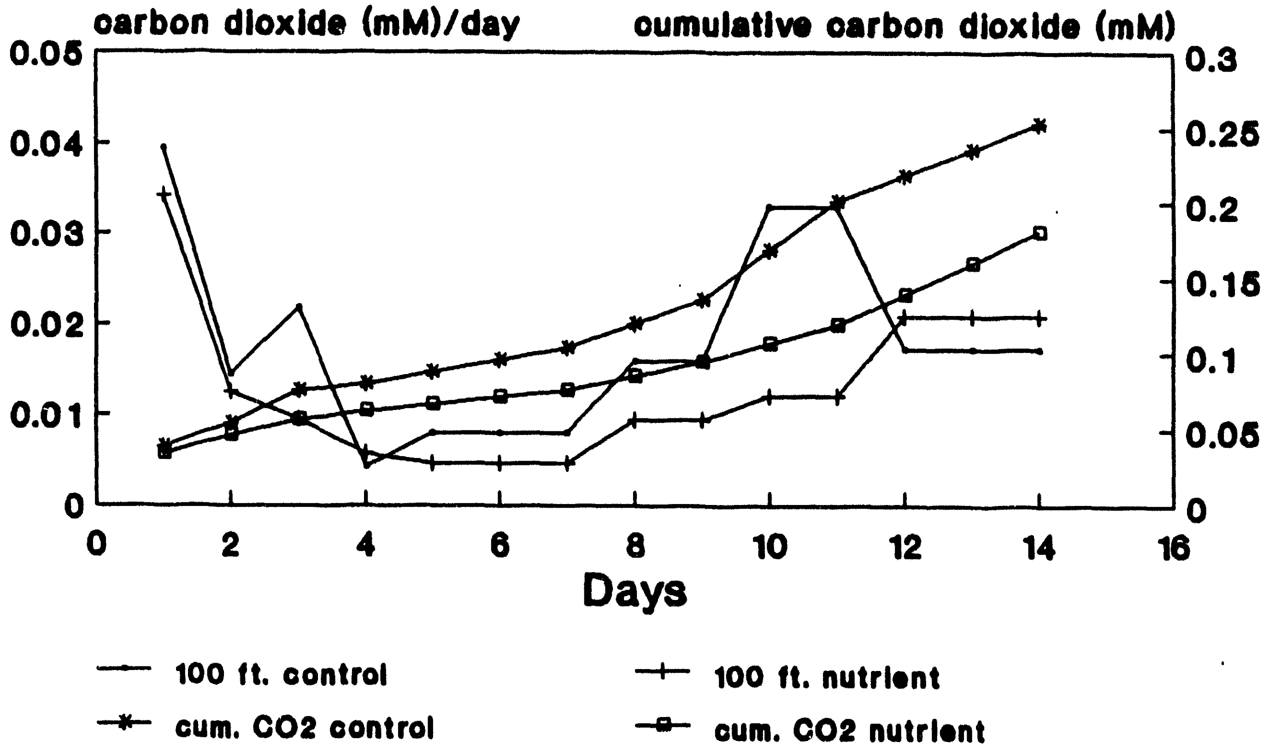


FIGURE 4.13 Carbon Dioxide Production: Sample 100-9, as collected

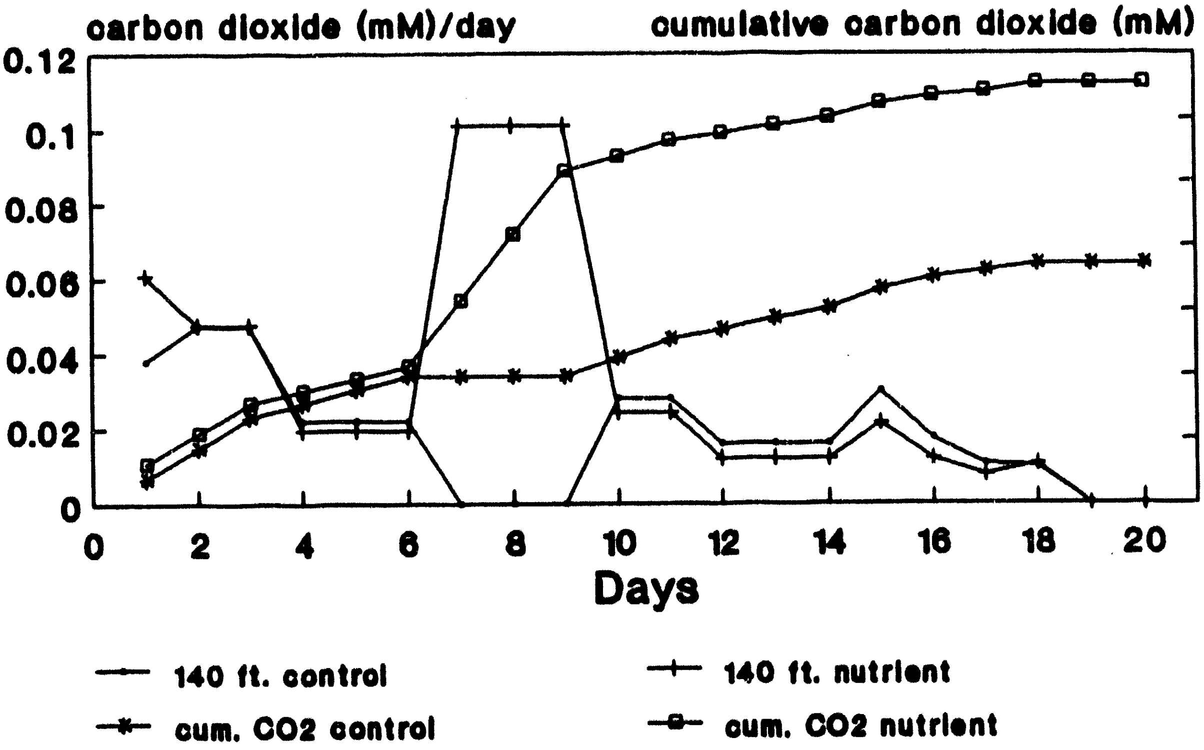


FIGURE 4.14 Carbon Dioxide Production: Sample 140-8

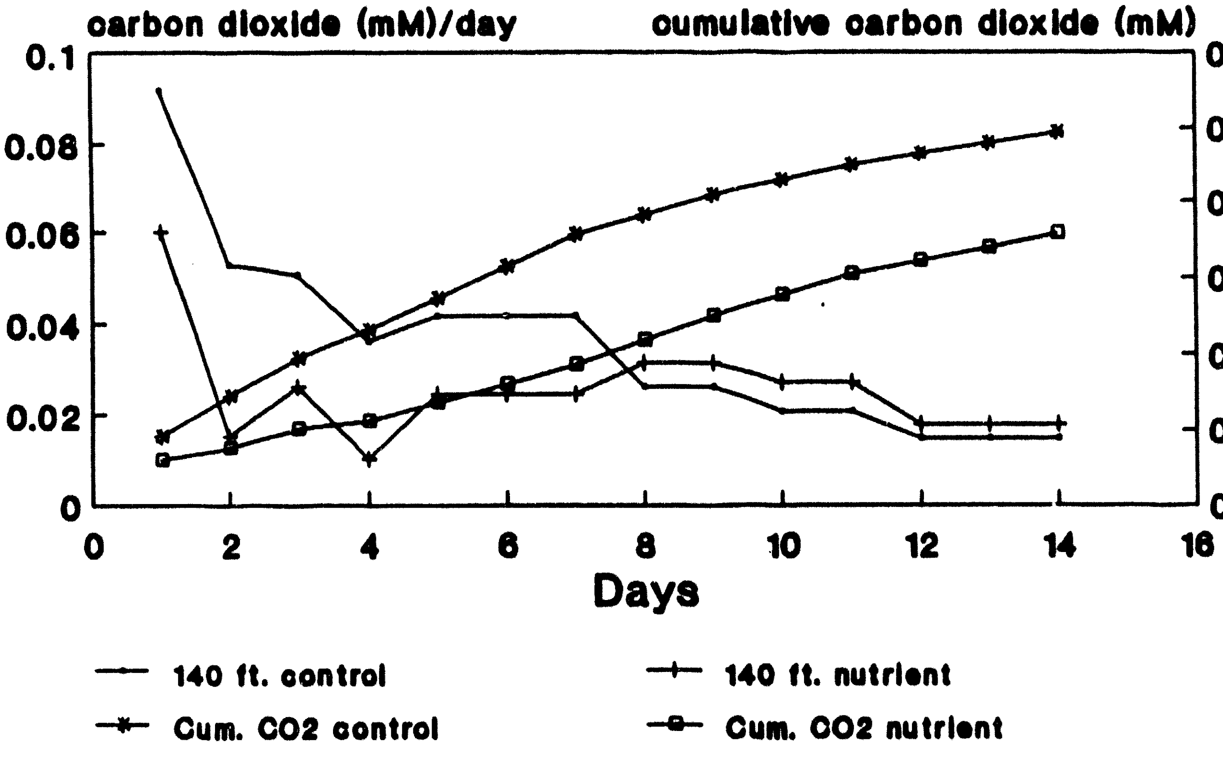


FIGURE 4.15 Carbon Dioxide Production: Sample 140-8, as collected

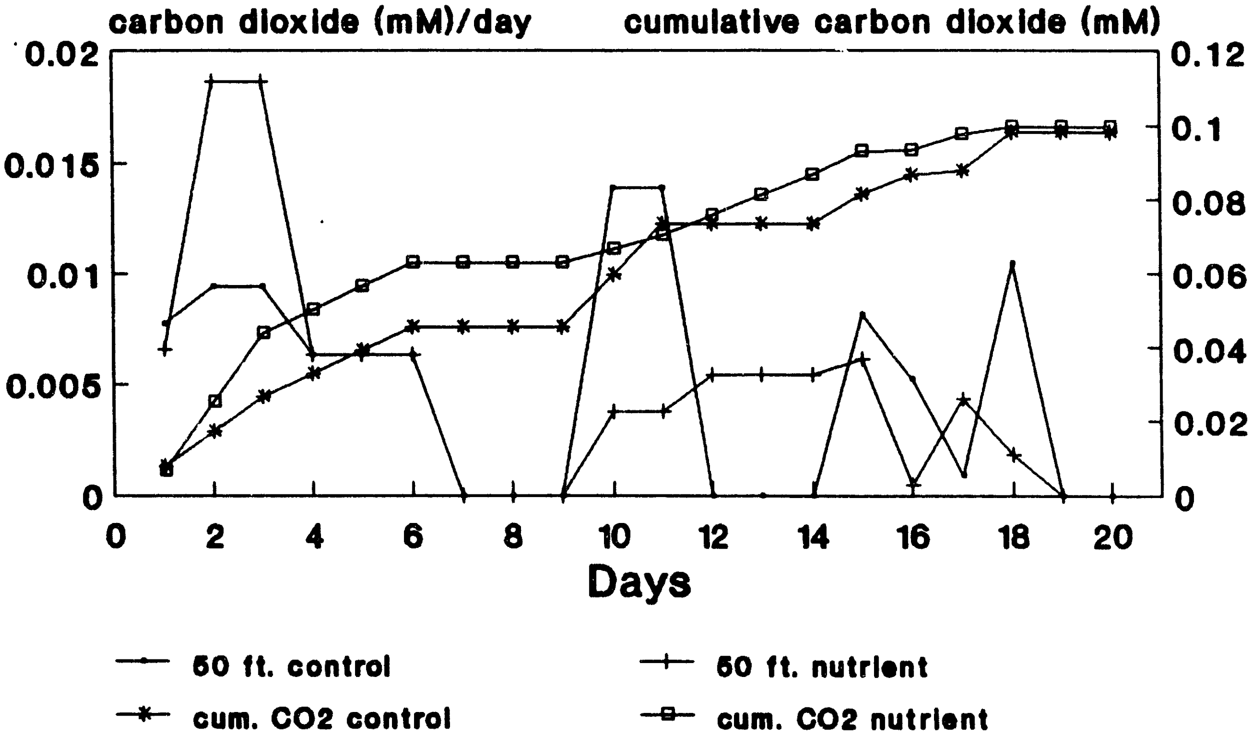


FIGURE 4.16 Carbon Dioxide Production: Sample 50-5

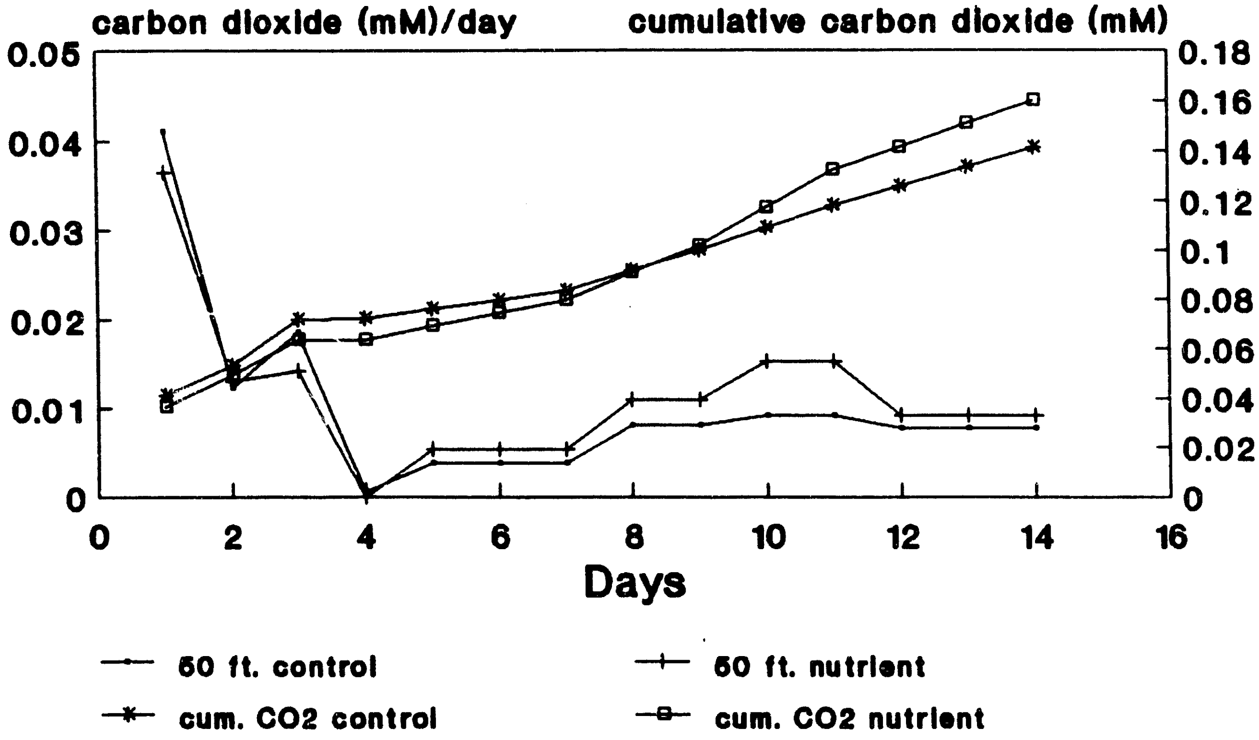


FIGURE 4.17 Carbon Dioxide Production: Sample 50-5, as collected

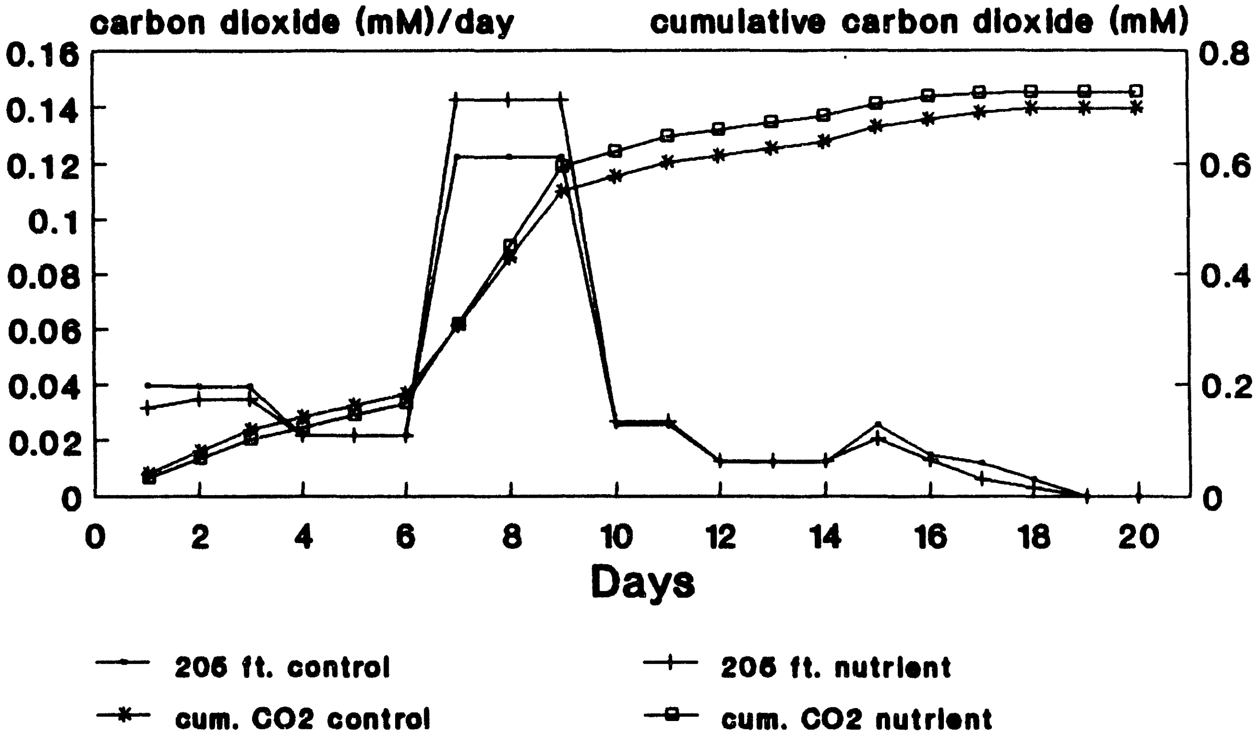


FIGURE 4.18 Carbon Dioxide Production: Sample 205-8

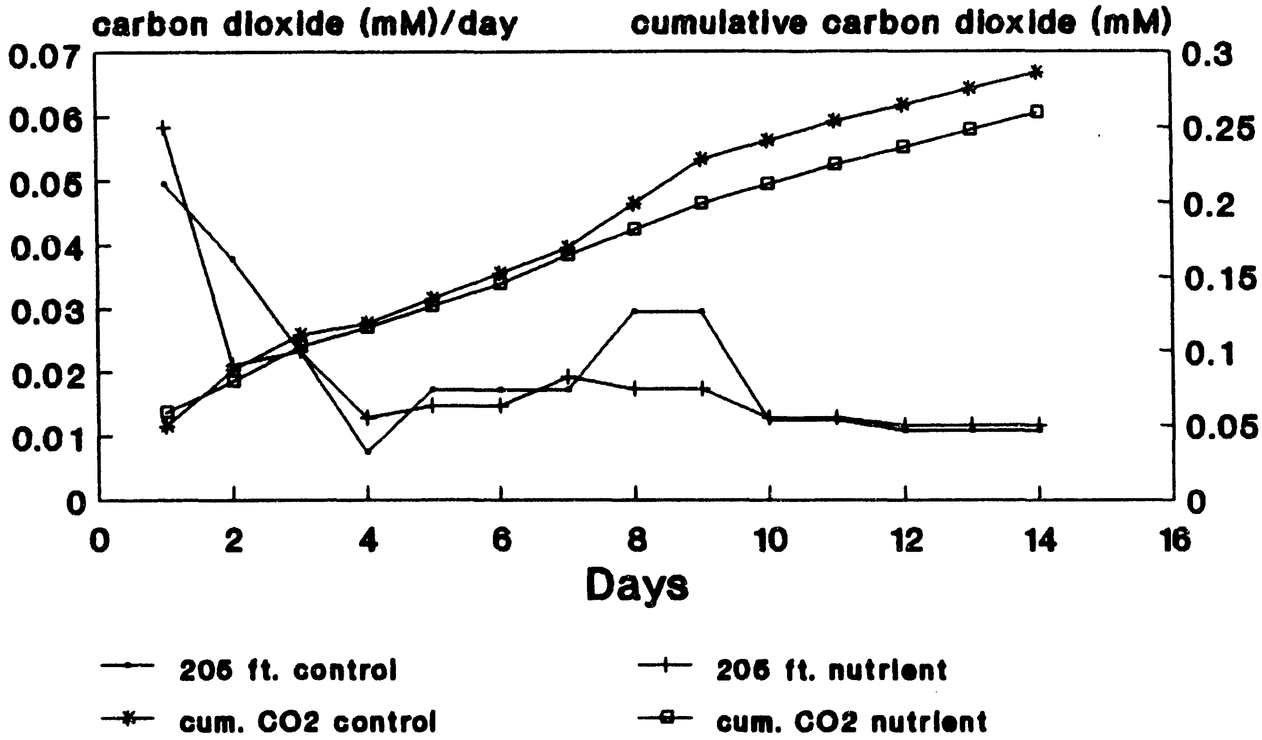


FIGURE 14.19 Carbon Dioxide Production: Sample 205-8, as collected

TABLE 4.4 TPH Detected in Soil after Use in Biometer Flasks

	Unsupplemented Flasks			Supplemented Flasks		
Linear Distance of Trench (ft)	Carbon Dioxide Evolved (mM)	Initial TPH at Alternative Sites (ppm)	TPH Remaining (ppm)	Carbon Dioxide Evolved (mM)	Initial TPH at Alternative Sites (ppm)	TPH Remaining (ppm)
12	0.336		460	0.334		110
25		26			26	
50	0.095		160	0.098		380
75		180			280	
100	0.257		700	0.181		800
125		320			320	
140	0.370		140	0.652		150
160		27			27	
205	0.696		190	0.733		80
225		<10			<10	

TABLE 4.5 Toluene Detected in Soil after Use in Biometer Flasks

	Unsupplemented Flasks			Supplemented Flasks		
Linear Distance of Trench (ft)	Carbon Dioxide Evolved (mM)	Initial Toluene (ppb)	Toluene Remaining (ppb)	Carbon Dioxide Evolved (mM)	Initial Toluene (ppb)	Toluene Remaining (ppb)
12	0.336	84	<2	0.336	84	<2
50	0.095	580	<2	0.095	580	<2
100	0.257	180	530	0.257	180	490
140	0.370	53,000	38	0.370	53,000	14
205	0.696	2	<2	0.696	2	<2

TABLE 4.6 Ethylbenzene Detected in Soil after Use in Biometer Flasks

	Unsupplemented Flasks			Supplemented Flasks		
Sample	Carbon Dioxide Evolved (mM)	Initial Ethylbenzene (ppb)	Ethylbenzene Remaining (ppb)	Carbon Dioxide Evolved (mM)	Initial Ethylbenzene (ppb)	Ethylbenzene Remaining (ppb)
12	0.336	28	<2	0.336	28	<2
50	0.095	690	<2	0.095	690	<2
100	0.257	81	1300	0.257	81	1300
140	0.370	57,000	32	0.370	57,000	14
205	0.696	4	<2	0.696	4	<2

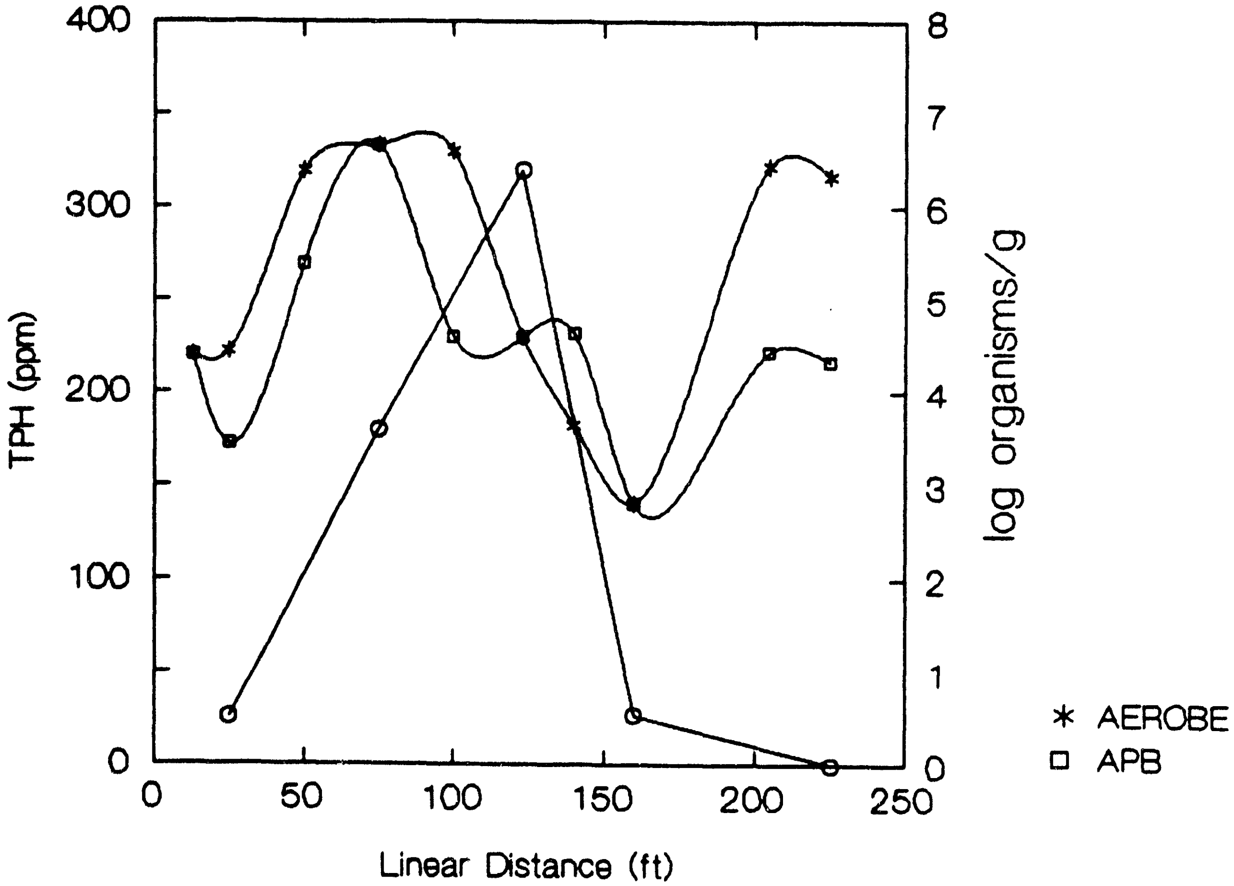


FIGURE 4.20 Relationship of TPH and Viable Bacteria with Linear Distance of the Trench

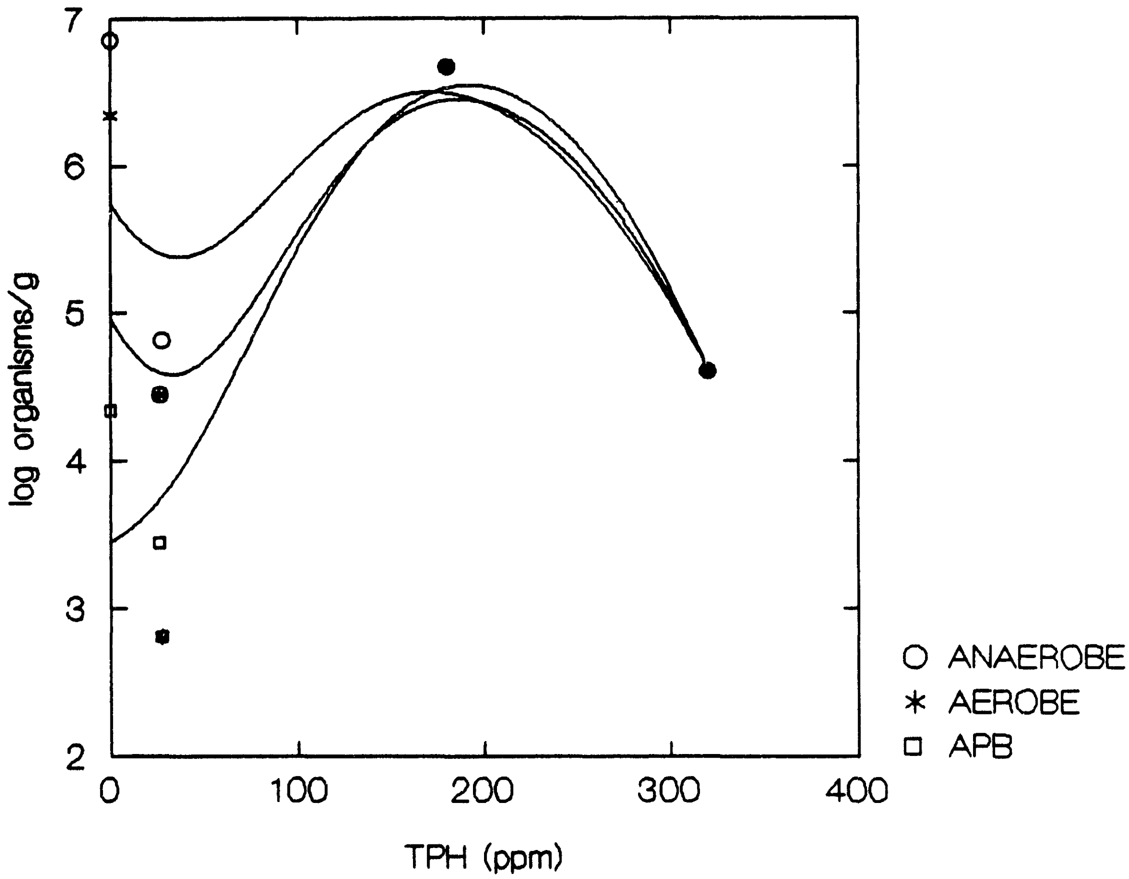


FIGURE 4.21 Relationship between Viable Bacteria on TPH Concentration

4.3.3 Possible Nutrient Limitations

Analysis of soil samples for the levels of anions that play important roles in bacterial metabolism revealed the following:

- Phosphate, which is the basis of chemical energy within the cell, was not detected in any of the samples (Table 4.7).

- Sulfate concentrations were low over the distance of the trench (Figure 4.22; well 2 at 100–160 ft). Iron levels were high and relatively constant, suggesting that organisms capable of using ferric iron would be well supplied.

- Nitrate was present at trace concentrations (Table 4.7), suggesting that its availability as a terminal electron acceptor would be limited.

TABLE 4.7 Soluble Anions Recovered from Soil Cores[a]

Linear Distance of Trench (ft)	Depth of Sample (ft)	Soluble Anions Recovered (µg/g of soil)			
		Chloride	Nitrate	Phosphate	Sulfate
12	6	28.9	trace	ND	1.75
25	8	29.5	trace	ND	7.92
50	5	9.82	trace	ND	2.58
75	8	21.6	trace	ND	7.86
100	9	15.2	trace	ND	2.52
125	7	59.5	trace	ND	2.85
140	8	21.5	trace	ND	2.90
160	8	36.1	trace	ND	5.13
205	8	99.4	trace	ND	6.11
225	8	199.9	trace	ND	4.13

[a] Values were determined by using ion chromatography (see Materials and Methods, Appendix D) and adjusted according to the weight of the soil sample used for culture.

[b] ND - Not Detected.

Sims and Bass (1984) reported that at available carbon-to-nitrogen-to-phosphorus ratios greater than 300:15:13, degradation will be slowed and nitrogen and phosphorus addition should be considered. Since phosphate and nitrate were not detected in any of the soil samples, only C:N ratios could be estimated. For the samples studied, the C:N ratios (based on TPH concentrations and ammonia nitrogen; see Table 4.8) ranged between 15:15 and 675:15, suggesting that the ratios may not be optimal at some locations.

4.3.4 Biometer-Flask Studies

The biometer-flask experiments were done in flasks with soil adjusted to contain 70% moisture by weight (wt%) and in flasks with soil in the "as-received" condition (i.e., moisture content was not adjusted in the laboratory). Duplicate flasks were prepared for each condition. One of each flask pair received a supplement of nitrate (100 ppm), phosphate (100 ppm), and ammonium chloride (10 ppm); the other received no supplements.

The sample point at 100 ft in well 2 contained the highest level of product vapor and was adjacent to the location with the highest measured levels of TPH and BTEX. Although microbial populations were high at this location, biometer-flask studies showed that CO_2 production was relatively low, an indication that degradation was not optimal (Figures 4.12 and 4.15). However,

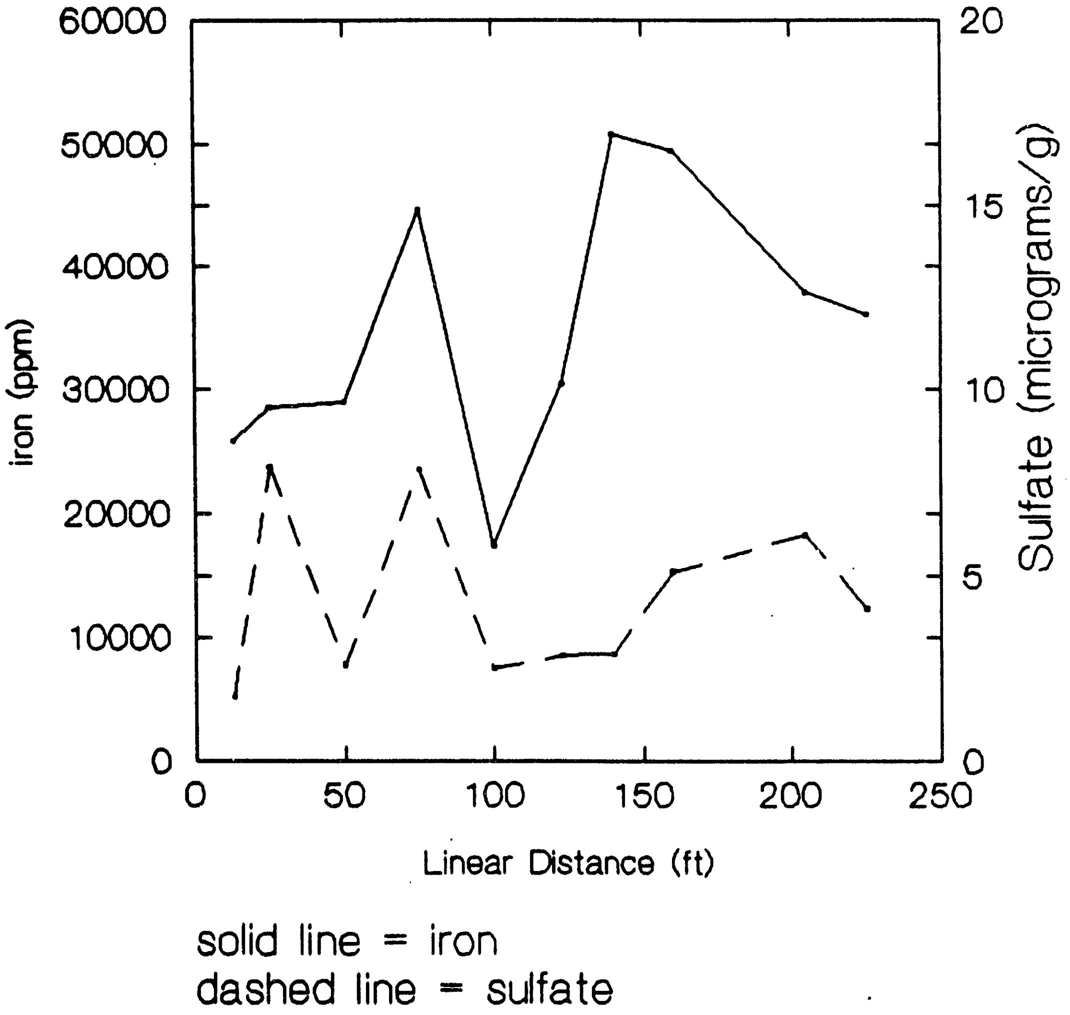


FIGURE 4.22 Occurrence of Iron and Sulfate

the sample collected from the 140-ft location in well 3 (which had the highest measured levels of products)[4] had only a moderate microbial population but superior overall CO_2 production in the biometer flasks (Figures 4.14 and 4.15) and among the lowest concentrations of TPH (also see Section 4.2.3.4).

These data suggest that air (oxygen) supplied to the vadose zone by the SVES could be expected to enhance microbial activity.

---

[4] The term "product" will be used as a general term for all components of weathered gasoline beneath the parking lot.

TABLE 4.8 Nitrogen Detected as NH_3 in Soil Cores[a]

Linear Distance of Trench (ft)	Depth of Sample (ft)	Ammonia (µg/g of soil)
12	6	5.5
25	8	4.0
50	5	5.0
75	8	16.0
100	9	10.0
125	7	7.0
140	8	29.0
160	8	27.0
205	8	32.0
225	8	15.0

[a] Values were determined using HACH kit for NH_3 - N. Because of high Ca^+ and Mg^+, samples were pretreated with Rochelle Salts before testing.

4.4 References

Kobayashi, H., and B.F. Rittmann 1982, *Microbial Removal of Hazardous Organic Compounds*, Environmental Science Technology *16*:170A-183A.

Pramer, D., and R. Bartha, 1965, *Features of a Flask and Method for Measuring the Persistence and Biological Effects of Pesticides in Soil*, Soil Science *100*:68-70.

Riser-Roberts, E., 1992, *Bioremediation of Petroleum Contaminated Sites*, Introduction and Appendix A, Section 5.5, C.K. Smoley, Boca Raton, Fla.

Sims, R., and J. Bass, 1984, *Review of In-Place Treatment Techniques for Contaminated Surface Soils, Volume 1: Technical Evaluation*, U.S. Environmental Protection Agency (EPA) report EPA-540/2-84-003a, Washington, D.C.

5 Determination of Soil Vapor Properties and the Permeability of Fill Material to Air

5.1 Air-Phase Permeability

Argonne anticipated performing three-dimensional numerical airflow modeling of the Cameron Station site to help design the most effective vapor-extraction system. The optimal venting system was to be modeled by using the AIRFLOW computer program, which could indicate the relative merits of various horizontal and vertical well scenarios. First, however, it was necessary to conduct experiments to estimate the air-phase permeability of the subsurface fill material in the area of the existing trenches and to gather data to calibrate the model.

Two procedures are discussed for conducting pneumatic pump tests to estimate the air-phase permeability in the unsaturated zone by means of the two-dimensional analytical airflow model AIRTEST. The field techniques include a full-scale permeability test and a small-scale permeability test.

A full-scale permeability test is an in-situ procedure for determining the horizontal (k_r) and vertical (k_z) components of air permeability in the unsaturated zone. The procedure is directly analogous to the calibration (or parameter determination) problem in aquifer testing. The test procedure involves injecting or withdrawing air through a well screened in the unsaturated zone. The induced airflow stresses the domain, and the resulting pressure distribution, at steady state, can be measured by using a network of probes surrounding the well. Air pressure measurements at the surrounding probes are made under static flow conditions in the pipe connecting the probe to the land surface, and measurements are made with manometers or pressure transducers. The mass flow rate at the well at steady state is also measured. If the pressure at specific points in the domain and the airflow rate are known, then estimates for k_r and k_z (and, if applicable, k') are obtained by calibrating the appropriate analytical solution by means of AIRTEST. AIRTEST executes the calibration procedure by using a least-square parameter search. By refining the scale of the test, it is possible to determine air permeability over smaller volumes of sediment. A major advantage of a full-scale test is that it provides estimates of all air permeability components, whereas a small-scale permeability test determines a single composite permeability; however, full-scale tests require more effort and time to implement.

The small-scale permeability test is intended to provide an air permeability estimate over a small volume. Homogeneity ($k = k_r = k_z$) must be assumed because only one data point is obtained at the air withdrawal/injection location. The test procedure involves injecting or withdrawing air through a probe located in the unsaturated zone (see Figure 5.1). Pressure is measured at ground surface by attaching a water manometer to the pipe connecting the probe. The surface pressure measurement is used to determine the pressure at the probe by correcting for pressure losses due to pipe flow, which can be significant for small-diameter pipes and high flow rates. The mass flow rate at steady state must also be measured. If the pressure at the probe and

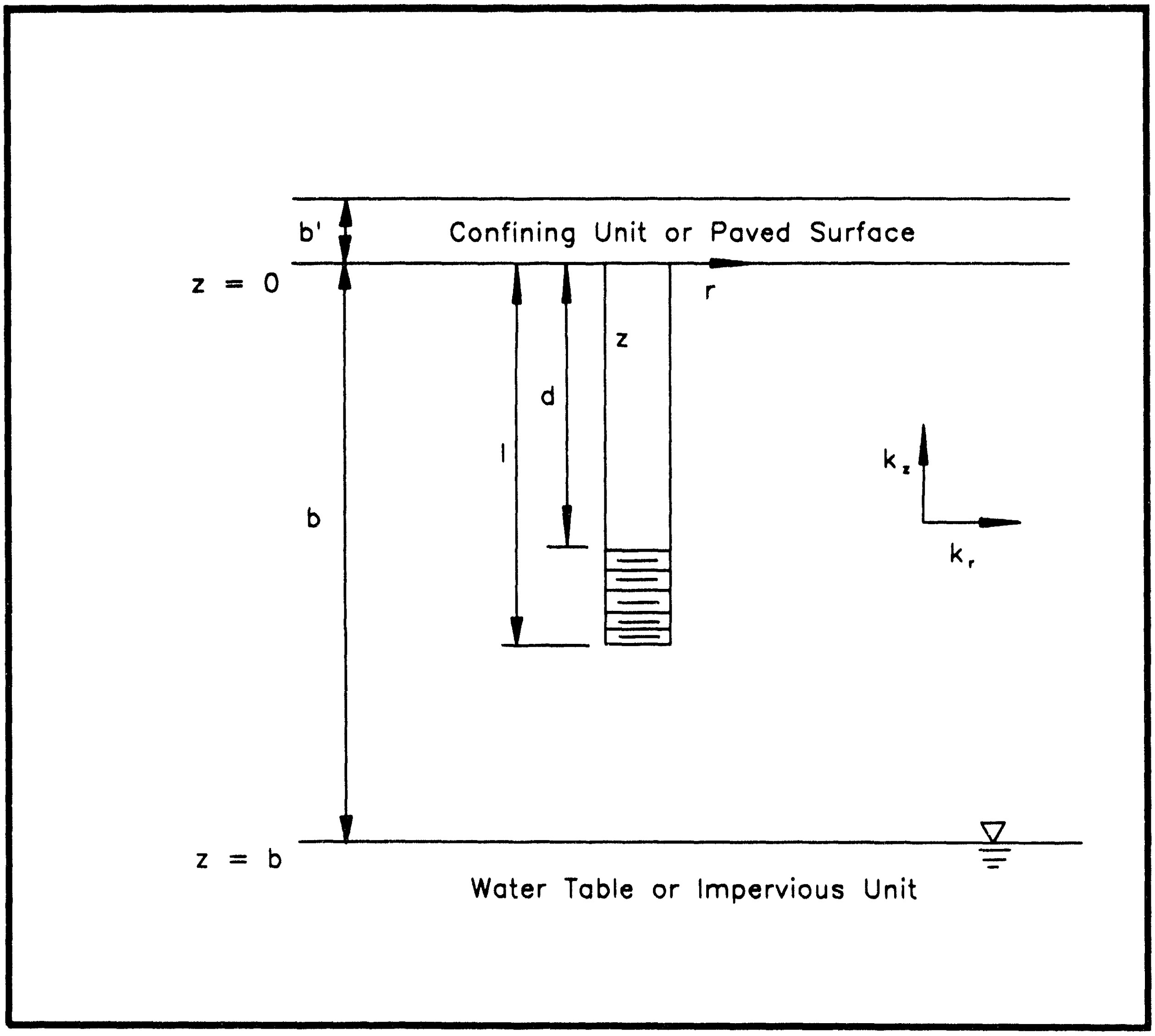


FIGURE 5.1 Schematic of Test Setup

the mass flow rate are known, then a composite estimate of air permeability ($k = k_r = k_z$) may be obtained by calibrating the appropriate airflow model by means of AIRTEST. The small-scale permeability technique is conceptually equivalent to performing a full-scale permeability test by using a single pressure measurement in the domain. In the design of venting systems, an aerial survey consisting of several small-scale permeability tests can be used to identify high-permeability strata along which air will preferentially flow. With this information available, it is possible to more realistically model subsurface airflow behavior by using the three-dimensional simulator.

5.2 Full-Scale Permeability Field Tests

The equipment, procedures, and measurements that constitute the full-scale permeability tests are described below. The field data collected from the full-scale tests may be used to calibrate the analytical airflow models using AIRTEST. Basic data for the groundwater monitoring wells, individual probes, probe clusters, and flow-enhancement borings installed by Argonne for this study are given in Appendix F.

5.2.1 Equipment and Measurements

The equipment needed to perform the full-scale permeability evaluations of the air phase in the unsaturated zone is as follows:

- A well screened in the unsaturated zone with a flow meter, pressure probe, and thermistor installed in line with well stand up for determining mass flow rate;
- A pneumatic pump and power supply;
- Pressure probes and thermistor for subsurface P and T measurements;
- Pressure transducer(s) and/or manometers; and
- Barometer for determining prevailing atmospheric pressure.

Before the test, atmospheric pressure and temperature are recorded. Each test involves injecting or withdrawing air through the well screened in the unsaturated zone. The pressure response throughout the monitoring network and the mass flux through the screen are measured during the test. If possible, several different flow rates are used to obtain flow versus pressure relationships over a range of values. Only steady-state pressure readings should be used to calibrate AIRTEST models. The steady-state condition is reached when the airflow meter and water manometer/pressure transducers stabilize. It is possible, however, to measure transient responses when pressure transducers are used. In particular, the transient mass flow rate calculated with well instrumentation is useful in determining when steady conditions are achieved.

5.2.2 Site Classification and Geometry

Definition of the domain geology is largely based on an interpretation of the boring logs from well and probe installation. The following geologic data should, at a minimum, be recorded:

- Presence or absence of an upper confining unit,
- Thickness of upper confining unit,
- Thickness of domain (namely distance between ground surface and water table),
- Depth to top of sand pack for well screen from ground surface or bottom of upper confining unit, and
- Depth to bottom of sand pack for well screen from ground surface or bottom of upper confining unit.

The geologic conditions at the site serve as the basis for determining the appropriate selection of the analytical model and form a large part of the data input to AIRTEST.

5.3 Small-Scale Permeability Field Tests

In the case of a small-scale permeability test, the only recorded pressure is that of the injection/withdrawal probe. Airflow along the tube connecting the probe to the surface experiences a drop in pressure that can be significant (for narrow tubes and higher flow rates) compared with the pressure drop attributed to flow in the porous media. Hence, the loss in pressure must be taken into account when implementing the airflow models. AIRTEST can account for this loss by incorporating pipe-flow equations from elementary fluid mechanics.

Basic components of the field equipment necessary to perform the small-scale permeability evaluations of the unsaturated zone include the following:

- Length of pipe with a probe at the end of the pipe,
- Water manometer or pressure transducer,

- Flow meter (e.g., rotometer),
- Chamber to trap water,
- Pneumatic pump (and power supply),
- Thermometer or thermistor, and
- Barometer for determining prevailing atmospheric pressure.

Figure 5.2 gives a general schematic of the setup for the test equipment.

Before the test, atmospheric pressure and temperature are recorded. This information is needed to correct rotometers for nonstandard flow conditions and to normalize the model. The pneumatic pump is then turned on and adjusted to give the desired airflow rate through the vapor probe. Tests should be performed over a range of flow rates. The system should be allowed to reach steady state before data are collected. Bentonite seals between vertically adjacent probes can be tested by pumping one probe and by measuring the pressure in the other. For intact seals, no pressure change is recorded, because the adjacent probe should be in a dead zone of the induced flow field.

5.4 Equipment and Procedures Used

5.4.1 Description of Equipment

To measure the chemical and physical properties of vapor being evacuated by the V4 extraction/destruction units, 4 ft of vertical 2-in. PVC pipe was removed in the line going to the water trap and the V4 and replaced with PVC piping with fittings. The fittings included a sampling inlet for removing samples of the vapor with a syringe, a thermocouple for measuring the vapor temperature, a vacuum gauge for measuring vacuum in the pipe, and a venturi device for measuring the flow rate of vapor through the system (Table 5.1).

The instrument used for measuring the concentrations of carbon dioxide and oxygen was a Gas Techtor Carbon Dioxide/Oxygen Indicator, Model 3252OX, with a carbon dioxide detection range of 0–5% and an oxygen detection range of 0–25%. The instrument used for measuring the total petroleum hydrocarbon (TPH) concentration was a Gastech Environmental Monitor (GEM) Trace-Techtor Portable Hydrocarbon Vapor Tester that has three ranges: 0–100 ppm, 0–1,000 ppm, and 0–10,000 ppm. The carbon dioxide/oxygen indicator was calibrated and adjusted for (1) carbon dioxide by using air (0.05% carbon dioxide) and a standard sample of 5%

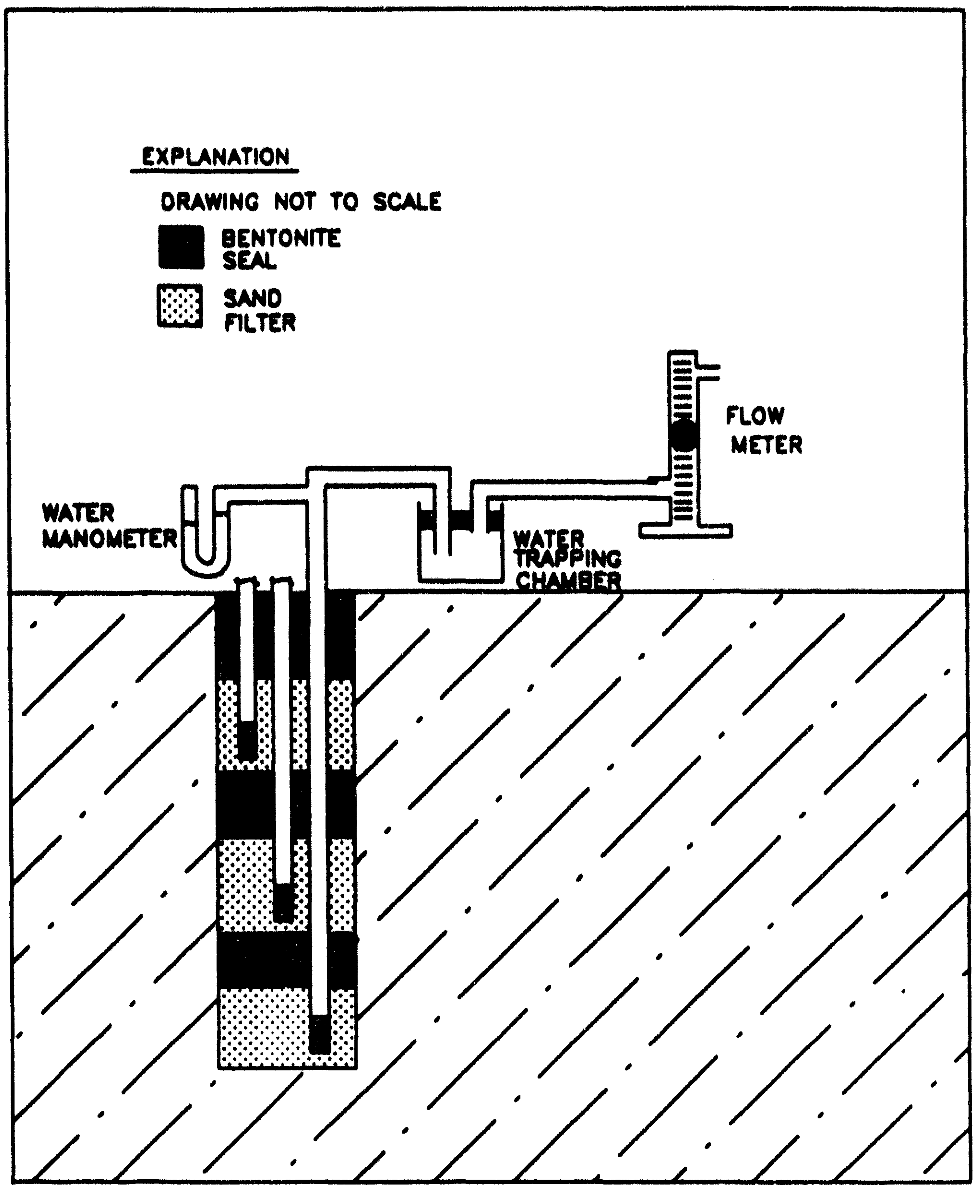


FIGURE 5.2 Schematic of Test Setup Equipment

carbon dioxide and (2) oxygen by using air (20.5% oxygen) and a sample of nitrogen. The hydrocarbon vapor tester was calibrated and adjusted by using air (less than 1 ppm TPH) and a standard sample containing 375 ppm hexane in air. The hexane standard must be in air for the instrument to work properly. Each instrument was calibrated on the day of use according to the manufacturer's specifications.

Because the vapor-extraction system is under vacuum, the measurement of the concentration of carbon dioxide, oxygen, and TPH is not straightforward; Techtor instruments have small pumps that are not capable of overcoming the vacuum present in the PVC pipe of the vapor-extraction system. Thus, the concentration of carbon dioxide, oxygen, and TPH could not

TABLE 5.1 Vapor Flow, Temperature, and Pressure Measurements Determined by Using Precision Pipe Sensors

	Supply Pipe Sensors			
Time (min)	Flow (scfm)	Temperature (°F)	Vacuum (in. water) Masthead	Differential Pressure (in. Water)
2	0.0	68	0	0.2
3	16.5	59	16	0.6
4	17.8	58	19	0.7
8	22.6	57	42	1.2
11	24.7	56	34	1.4
14	13.6	57	13	0.4
17	13.6	57	12	0.4
22	13.6	57	12	0.4

be measured directly by attaching the instrument to the pipe and withdrawing a sample. A septum was set up, and a 2-L syringe with a side-port needle was used to withdraw vapor samples into the syringe. The vapor was then transferred to a 2-L sampling bag that had both a septum and a port (Cali-5-Bond five-layer gas-sampling bag). The concentrations of carbon dioxide, oxygen, and TPH were then determined by allowing the pumps of the Tector instruments to withdraw samples from the sampling bag.

When measurements are taken with the Techtor instrument, approximately 30 s is needed for the instrument to reach 90% of the actual value of the concentration. During this time, approximately one liter of sample gas passes through the instrument. To reach 99% of the actual value, the instrument requires an additional 30 s. (The approach to the actual value is approximately exponential.) In these experiments, the calibration and the measurement of the vapor were done as close as possible to 30 s after the start of sampling by the instrument. In this way, the carbon dioxide/oxygen instrument was attached to the sampling bag, and a reading of carbon dioxide was taken approximately 30 s later. The oxygen concentration was measured immediately thereafter, only a few seconds after the carbon dioxide reading. The sampling bag was then attached to the Hydrocarbon Vapor Tester, and a reading of TPH was made after 30 s.

To measure the temperature of the vapor, a thermocouple of the T type (copper-constantan junction), housed in a 304 stainless-steel sheath, was used. Readings were made with a digital thermometer. The thermocouple was calibrated against a thermometer with a range of 18–89°F that is traceable to NIST.

The vacuum in the pipe was measured with a 0–100-in. water vacuum gauge with a diaphragm sensing element.

To measure the rate of flow through the PVC pipe, a Barco venturi system with a medium taper (483) was coupled to a manometer along with a balancing valve to zero the manometer. The flow rate was calculated from the measured temperature of the vapor, the vacuum in the pipe, and the differential pressure between the inlet and the outlet of the taper of the venturi. Vapor flow rate could not be calculated directly from the measured differential pressure in the usual way (with the graphs supplied by the manufacturer) because the differential pressure measured was too low; the flow was lower than anticipated. Therefore, the flow of vapor, F_V (in scfm), through the pipe was calculated by using the formula

$$F_V = C d_0^2 c\, F_A F_C Y \sqrt{\frac{\Delta H\, P_a}{T_R}}\ , \tag{5.1}$$

where:

C = a constant (128.8 in this case);

$d_0^2 c$ = the venturi flow coefficient, which, for a 2-in. venturi with a 483 taper, equals 1.005;

F_A = the throat expansion factor, which equals 1.0 in this case;

F_C = the Reynolds number, which equals 1.0 in this case;

Y = an expansion factor;

ΔH = the differential pressure before and after the venturi taper, in inches of water;

P_a = the absolute pressure inside the PVC pipe, in psia; and

T_R = the temperature of vapor inside the pipe, in degrees Rankin.

Therefore, the formula is

$$F_V = 128.8 \times 1.005 \times 1.0 \times 1.0 \times Y \sqrt{\frac{\Delta H\, P_a}{T_R}}\ . \tag{5.2}$$

The formula can be further simplified to

$$F_V = 129.44\, Y \sqrt{\frac{\Delta H\, P_a}{T_R}}\ . \tag{5.3}$$

If P_w is the pressure inside the pipe in inches of water, then

$$P_a = \left(\frac{406.38 - P_w}{406.38}\right)(14.7)\,, \tag{5.4}$$

and if T_F is the temperature of the vapor inside the pipe in degrees Fahrenheit, then

$$T_R = T_F + 459.67. \tag{5.5}$$

The flow of vapor, F_V, in scfm through the pipe is

$$F_V = 129.44\, Y \sqrt{\frac{\Delta H \left(\frac{406.38 - P_w}{406.38}\right)(14.7)}{T_F + 459.67}}\ . \tag{5.6}$$

In experiments done thus far, the differential pressure, ΔH, ranged from 0.2 to 1.4 in. water in one set of experiments and from 0.30 to 0.65 in. water in another set of experiments (see Tables 5.1 and G.7 [in Appendix G]). Because Y has values that are close to 1 at these differential pressures (for example, 0.9993 at 0.5 in. water, 0.9985 at 1.0 in. water, and 0.9978 at 1.5 in. water, within the accuracy of these measurements), Y can be set equal to 1.0 for these sets of experiments. The equation can therefore be simplified further to

$$F_V = 129.44 \sqrt{\frac{\Delta H \left(\frac{406.38 - P_w}{406.38}\right)(14.7)}{T_F + 459.67}}\ . \tag{5.7}$$

To measure soil permeability to air, a soil probe, screened over a specific length and inserted to a specific depth, was evacuated with a vacuum pump. Selected probes remote to the probe being pumped were monitored with manometers to determine the response of the soil to the vacuum created at the pumped probe. The probe being pumped was fitted with a flowmeter to measure the flow rate, a vacuum gauge to measure vacuum, and a thermocouple with a digital readout to measure the temperature of the extracted vapor.

A Gast vacuum pump/compressor, Model 0523-V4-G180DX, with a free-air capacity of 4.5 cfm and capable of achieving a vacuum of 26.5 in. of mercury (360 in. of water), was used. The vacuum produced by the vacuum pump was measured by using a 0–100-in. water vacuum gauge with a diaphragm sensing element. To measure the temperature of the vapor, a thermocouple of the T type (copper-constantan junction), housed in a 304 stainless-steel sheath, was used. Readings were made with a digital thermometer (readout). The thermocouple was calibrated against a thermometer with a range of 18–89°F that is traceable to NIST. A Gilmont (division of Barnant Company) flowmeter, size 4 (Model F-1460), with a range of 1–36 L/min, was used to determine the flow rate of vapor during evacuation. The flowmeter had to be calibrated so that a corrected reading could be obtained from any observed reading. Using formulae from Gilmont's catalog of laboratory instruments and assuming that the density and viscosity of the vapor each are approximately equal to that of air, the corrected values for several flowmeter values were calculated, plotted, and fitted to a second-degree polynomial (Figure 5.3).

The best fit was

$$F_v = 1.64R^2 + 1.29R - 1.31\ , \tag{5.8}$$

where:

F_v = corrected flow in L/min and

R = flowmeter reading.

From this equation, a corrected value for the flow rate can be obtained for any reading on the flowmeter. Once the corrected value was obtained, it was converted to STP conditions (1 atmosphere pressure and 70°F temperature) by using the formula

$$F_{STP} = F\sqrt{\left(\frac{406.38 - P_w}{406.38}\right)\left(\frac{529.67}{T_F + 529.67}\right)}\ , \tag{5.9}$$

where:

F = measured flow rate, corrected;

F_{STP} = flow rate at STP (1 atmosphere [406.38 in. water]) pressure and 529.67°R [70°F] temperature);

P_w = measured vacuum in probe, in inches of water; and

T_F = measured temperature of vapor, in degrees Fahrenheit.

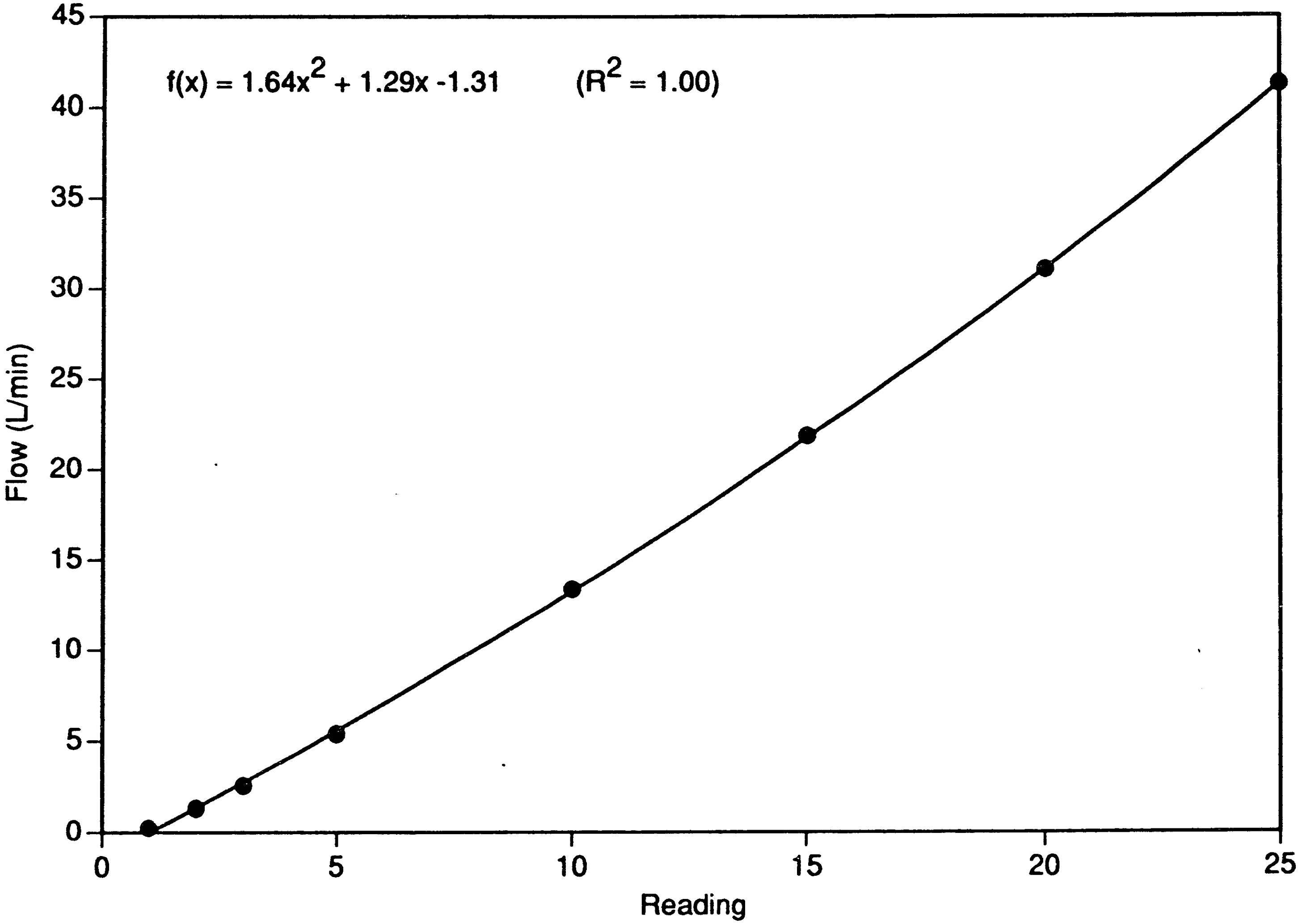


FIGURE 5.3 Plot of Flow Versus Flowmeter Reading

5.4.2 Field Procedures

The following procedures were used in the field to determine the permeability of the fill material ("soil") to air and the basic properties of the incoming VES air system.

5.4.2.1 Procedure for Measurement of Soil Permeability to Air

1. Before beginning the experiment, the thermocouple probes should be calibrated against the thermometer that is NIST traceable.

2. Develop a field data sheet and enter the well number, test run number, date, and time at start. If the well is 4 or 5, enter the location of the monitoring probe, the perpendicular distance of the probe to the vent well, and the manometer reading. Enter the local weather conditions at start.

3. If known, record scheduled times for measuring parameters in the table under "Time, Schld."

4. Record the air temperature in °F, barometric pressure in mbars, and the local weather conditions under "Ambient Conditions."

5. Drop the tubing containing the thermocouple down into the well and record the depth and temperature under the "Temperature" category of "Subsurface Measurements." Withdraw the thermocouple probe.

6. Drop the pressure probe down into the well and record the depth and pressure under the "Pressure" category of "Subsurface Measurements." Withdraw the probe.

7. Attach to the well pipe the system for measuring the temperature, pressure, and flow of the evacuated gas.

8. Record the temperature in °F, pressure in inches H_2O, and flow under "Evacuated Gas." Also enter the units of flow just under "Flow."

9. Initial under "Observer, Initials."

10. Repeat measurements, as scheduled or required.

11. Record local weather at the top of the data sheet at the end of the experiments.

12. Record end time at the top of the data sheet at the end of the experiments.

5.4.2.2 Procedure for Measurement of Air to VES Units During Evacuation

1. Before beginning the experiment, make certain the GEM Trace-Techtor Portable Hydrocarbon Vapor Tester (for measuring hydrocarbon levels) and the Gas Techtor Carbon Dioxide/Oxygen Indicator (for measuring carbon dioxide and oxygen levels) have been calibrated. Also, the thermocouple probe should be calibrated against the thermometer that is NIST-traceable.

2. Develop a field data sheet and enter the well number, test-run number, date, and time at start. If the well is 4 or 5, enter the location of the probe, the perpendicular distance of the probe to the vent well, and the manometer reading. Enter the local weather conditions at start.

3. If known, record scheduled times for measuring parameters in the table under "Time, Schld."

4. Record the air temperature in °F, barometric pressure in mbars, and local weather conditions under "Ambient Conditions."

5. Near the VES unit, on the line going into the water trap, record under "T, P, F Conditions" the temperature in °F, pressure in mbars, and soil-vapor flow. Also, enter the units of flow just under "Flow."

6. Connect the 2-L gas syringe with an adapter-to-pipe fitting to the gas-sampling port. Slowly withdraw the plunger of the gas syringe over two minutes. The exact amount of gas withdrawn is not critical.

7. Disconnect the Luer adapter-to-pipe fitting and attach the Luer hub needle. Inject the gas sample into a collapsed Cali-5-Bond 2-L gas-sampling bag.

8. Connect the Gas Techtor Carbon Dioxide/Oxygen Indicator to the on-off valve of the sampling bag and open the valve by twisting it counterclockwise one turn.

9. After 30 s, take a reading of the percent oxygen and record under "Composition of Gases," O_2 (%).

10. Repeat steps 6 through 9 and measure the percent of carbon dioxide and record under "Composition of Gases," CO_2 (%).

11. Repeat steps 6 through 9 using a mylar sampling bag and measure the ppm concentration of total hydrocarbons by using the Techtor Portable Hydrocarbon Vapor Tester. Record results under "Composition of Gases," TPH (ppm). (If the oxygen concentration is low [<10%] and the combustible gas level is very high [greater than 5,000 ppm], there might not be sufficient oxygen to react with all the combustible gas present. In such cases, the dilution fitting should be used.)

12. Initial under "Observer, Initials."

13. Repeat measurements as required.

14. At end of experiment, enter, at the top of the data-acquisition page, the time (end) and the local weather conditions.

5.5 Description of Field Experiments

5.5.1 Vapor-Flow and Vapor-Property Measurements of Vapor Extracted by V4, April 5, 1993

While vapor was being extracted by the V4, the temperature of the vapor, the vacuum, and the concentration of carbon dioxide and of oxygen in the vapor were measured at a point 30 ft from the V4 vapor extraction/destruction unit. The vacuum at the masthead varied from 10 to 48 in. of water, depending upon which well was being pumped. The vacuum in Trench 1 was also measured at probes N, O, P, and Q (see Figure 2.1); it varied from 0.0 to 0.5 in. water. Measurement results are tabulated in Table G.1 in Appendix G.

5.5.2 Intermediate-Scale Soil Permeability-to-Air Tests

An initial test (Test Run 1, Test Run 2, and Test Run 3) was performed on April 6, 1993. A setup test (Test Run 4 and Test Run 5) was performed on April 7, 1993. A vapor-properties test (Test Run 6) was performed on April 8, 1993.

Initial Tests. In initial tests of the setup, it was found that the large flowmeter, with a range of 25–100 L/min, was too large, and the smaller flowmeter, with a scale of 1–36 L/min, would be more suitable for the range of flow rates that were anticipated. Also, the vacuum encountered at flow rates in the 5–40-L/min range were above the expected range (0–30 in. water vacuum); therefore, the vacuum gauge was changed to a gauge with a range of 0–100 in. water.

Test Run 1. In the first test, probe A was evacuated while the intermediate and deep probes of probe clusters F and G were monitored. The vacuum on probe A was adjusted to give the highest flow possible without going off the flowmeter scale. After approximately 5 min (300 s), at an average vacuum of 61 in. water, water started coming through the piping. The experiment was stopped at approximately 13.5 min because the water trap was nearly full. Flow varied from 31.5 to 32.9 L/min (corrected for vapor temperature and pressure), and the vacuum was 61–62.5 in. water (before the water came through) and 75–77.5 in. water (after the water came through). Data collected in this run are tabulated in Table G.2 in Appendix G.

Test Run 2. In this run, vapor flow was reduced to one-third of the previous run to avoid collecting water. Vapor flow decreased during the run and had to be repeatedly adjusted upward to maintain as constant a flow as possible. Vapor flow varied from 11.3 to 8.7 L/min (corrected for vapor temperature and pressure) during the course of the experiment, and the vacuum range was 16.9–20.0 in. water. The experiment was run for 80 min. Data collected in this run are tabulated in Table G.3 in Appendix G.

Test Run 3. Immediately after Test Run 2 (that is, after the vacuum pump was turned off), the intermediate and deep probes of probe clusters F and G were monitored for 14 min to develop data on the rate of recovery. Data collected in this run are tabulated in Table G.4 in Appendix G.

Test Run 4. In this run, probe E was pumped while the intermediate and deep probes of probe clusters L and M were monitored. Vapor flow was relatively constant, varying only 0.5 L/min from 20.7 to 21.2 L/min (corrected for vapor temperature and pressure) during the duration of the experiment (90 min). The vacuum also remained relatively constant, varying from 94.5 to 95.3 in. water before dropping off to 91.8 in. water at the end of the experiment. Data collected in this run are tabulated in Table G.5 in Appendix G.

Test Run 5. In this run, the intermediate-depth probe of probe cluster L was pumped while the shallow and deep probes of the same probe cluster (L) and all three (the shallow, the intermediate depth and deep) probes of probe cluster M were monitored for 90 min. Vapor flow remained relatively constant, varying from 28.7 to 29.7 L/min (corrected for vapor and pressure), and the vacuum increased gradually from 22.3 to 30.0 in. water. Data collected in this run are tabulated in Table G.6 in Appendix G.

5.5.3 Measurement of Vapor Properties during Evacuation

Test Run 6. In this run, wells 1, 2, 3, 4, and 5 were pumped successively, and the temperature, vacuum, and flow of the vapor were measured along with the concentration of Total Petroleum Hydrocarbons (TPH), carbon dioxide, and oxygen. The concentration of carbon dioxide and oxygen remained relatively constant, and the values obtained were typical of air (whereas the TPH concentration varied from 13 to 35 ppm). Data collected in this run are tabulated in Table G.7 in Appendix G.

5.6 Results of AIRTEST Modeling

The data collected in Test Runs 1, 2, 4, and 5 were used to calibrate a two-dimensional, radially symmetric air-flow model by means of the computer program AIRTEST, with the objective of estimating air-phase permeability in soil. For Test Runs 1 and 2, the simulation was performed by using pressure measurements at intermediate probe F only. Pressure measurements at deep probe F were neglected because it was submerged. Because only one probe observation point was available for model calibration, it was assumed that $k_r = k_z$. Test Runs 1 and 2 differ mainly in the length of time of the test. For Test Run 4, only the pressure measurements at intermediate probe M were used. Pressure measurements at deep probe M and intermediate probe L were neglected because they were submerged. Similarly, for Test Run 5, only data at intermediate probe M and shallow probe L were used.

The results of the AIRTEST calculations are presented in Tables 5.1–5.4. Horizontal permeability of the vadose zone fill material to air ranged from a low of 0.427E-07 cm^2 to a high of 0.425E-06 cm^2. Vertical permeability ranged from 0.0634E-07 cm^2 to 0.425E-06 cm^2.

5.7 Summary

To calibrate the three-dimensional model, it was planned that Test Run 6, in addition to obtaining TPH, O_2, and CO_2 data, would also provide pressure data at various probe clusters, depending on which well(s) were pumped. Unfortunately, because of the high groundwater level, useful pressure and flow data could not be obtained. Although it is still possible that the available permeability data can be used for a simplified model calculation, calibrating the model against measured pressure and flow data will yield the best results. Once this comparison is made, the influence of proposed well/trench configurations on the subsurface airflow patterns can be calculated.

TABLE 5.2 Data Summary for Test Run 1

Item	Value/Notes
Test run	1
Test scope	Pumping on probe A and monitoring vacuums on intermediate and deep probes at clusters F and G
Test date	4/6/93
Well summary	Air extraction on probe A Depth to top of well screen = 167.6 cm Depth to bottom of well screen = 228.6 cm Depth to water table at well = 288.0 cm Radius of well boring = 7.9 cm
Probe summaries	Probe location F Radial distance from probe A to probe F = 470.0 cm Depth to mid-screen intermediate probe = 167.6 cm Deep probe submerged below water table
	Probe location G Radial distance from probe A to probe G = 1,056.7 cm Inconsistent readings at intermediate probe Deep probe submerged below water table
Temperature	Air temperature = 72°C Soil temperature = 11.7°C
Pressure	Barometric pressure = 408.7 in. water System pressure = 331.2 in. water
Field measurements	See Table G.2 (time 13.5 min)
Simulation results	Mass flow = 0.555 g/s Horizontal permeability = 0.425E-06 cm^2 Vertical permeability = 0.425E-06 cm^2

TABLE 5.3 Data Summary for Test Run 2

Item	Value/Notes
Test run	2
Test scope	Pumping on probe A and monitoring vacuums on intermediate and deep probes at clusters F and G
Test date	4/6/93
Well summary	Air extraction on probe A Depth to top of well screen = 167.6 cm Depth to bottom of well screen = 228.6 cm Depth to water table at well = 288.0 cm Radius of well boring = 7.9 cm
Probe summaries	Probe location F Radial distance from probe A to probe F = 470.0 cm Depth to mid-screen intermediate probe = 167.6 cm Deep probe submerged below water table
	Probe location G Radial distance from probe A to probe G = 1,056.7 cm Inconsistent readings at intermediate probe Deep probe submerged below water table
Temperature	Air temperature = 72°C Soil temperature = 11.7°C
Pressure	Barometric pressure = 407.9 in. water System pressure = 387.9 in. water
Field measurements	See Table G.3 (time 80.0 min)
Simulation results	Mass flow = 0.172 g/s Horizontal permeability = 0.237E-06 cm^2 Vertical permeability = 0.237E-06 cm^2

TABLE 5.4 Data Summary for Test Run 4

Item	Value/Notes
Test run	4
Test scope	Pumping on probe E and monitoring vacuums on intermediate and deep probes at clusters L and M
Test date	4/7/93
Well summary	Air extraction on probe E Depth to top of well screen = 167.6 cm Depth to bottom of well screen = 228.6 cm Depth to water table at well = 290.0 cm Radius of well boring = 10.5 cm
Probe summaries	Probe location M Radial distance from probe E to probe M = 1,237.5 cm Depth to mid-screen intermediate probe = 167.6 cm Deep probe submerged below water table. Probe location L Radial distance from probe F to probe L = 1,400.3 cm Inconsistent readings at intermediate probe Deep probe submerged below water table
Temperature	Air temperature = 6.8°C Soil temperature = 14.4°C
Pressure	Barometric pressure = 409.5 in. water System pressure = 317.7 in. water
Field measurements	See Table G.5 (time 90.0 min)
Simulation results	Mass flow = 0.342 g/s Horizontal permeability = 0.427E-07 cm^2 Vertical permeability = 0.427E-07 cm^2

TABLE 5.5 Data Summary for Test Run 5

Item	Value/Notes
Test run	5
Test scope	Pumping on probe L and monitoring vacuums on intermediate and deep probes at cluster M and shallow and deep probes at cluster L
Test date	4/7/93
Well summary	Air extraction on probe L Depth to top of well screen = 167.6 cm Depth to bottom of well screen = 228.6 cm Depth to water table at well = 290.0 cm Radius of well boring = 10.5 cm
Probe summaries	Probe location M Radial distance from probe E to probe M = 600.8 cm Depth to mid-screen intermediate probe = 167.6 cm Inconsistent readings at shallow probe Deep probe submerged below water table Probe location L Radial distance from probe E to probe L = 1,400.3 cm Depth to mid-screen shallow probe = 45.7 cm Deep probe submerged below water table
Temperature	Air temperature = 14.4°C Soil temperature = 13.9°C
Pressure	Barometric pressure = 409.9 in. water System pressure = 379.9 in. water
Field measurements	See Table G.6 (time 90.0 min)
Simulation results	Mass flow 0.561 g/s Horizontal permeability = 0.264E-06 cm^2 Vertical permeability = 0.634E-07 cm^2 Leakage ratio (k/b) = 0.338E-13 cm^2 Anisotropy ratio (k_r/k_z) = 4.16

6 Implementation of SVE Program

6.1 Equipment Description

6.1.1 Overview of Vapor Extraction Equipment

Numerous types of vapor extraction equipment have been used for the removal of hydrocarbon pollutants (in vapor form) from soil contaminated by leaking underground storage tanks.

Argonne chose computer-controlled, IC vapor extraction units, manufactured by VR Systems, Inc., of Anaheim, California, to volatilize hydrocarbon pollutants in the zone of influence of the horizontal wells, draw the vapor generated into the intake manifold of the engines, and then combust the hydrocarbon vapors to render the engine exhaust environmentally safe. These engines had proven useful in soil vapor extraction around leaking oil tanks at refineries in the Los Angeles area, and Argonne believed that the units could be deployed at Cameron Station, assuming that the geohydrological system could allow vapor extraction by horizontal wells.

6.1.2 Background on the Equipment

The VR Systems' equipment provides a method for economically decontaminating vadose-zone soils without significantly affecting air quality. VR Systems' vapor extraction equipment evolved from an IC engine, mounted in a steel frame and operated manually by on-site personnel, to a computer-driven, self-contained system that can be controlled and monitored via computer modem and cellular telephone.

The IC engine provides vacuum through the intake manifold for the extraction of hydrocarbon vapors. Vapors are combusted in the engine, providing some percentage of the operational fuel, and then the primary combustion products of carbon dioxide and water are generated. A catalytic converter was added to the engine's exhaust system to further reduce emissions. The catalytic converter used is of small size and conventional design, much like that normally used for controlling automobile exhaust emissions.

The vacuum present in the intake manifold of the IC engine is exposed to the contaminated soil through an interface consisting of a well casing placed in the soil with perforations in the zone of hydrocarbon contamination. The manifold vacuum creates suction in the slotted horizontal (or vertical) well pipe and, in turn, a negative pressure gradient in the soil. This zone of reduced pressure volatilizes hydrocarbons present in the soil or at the surface of the product floating on the groundwater table. The hydrocarbon vapors are then drawn into the intake manifold of the engine.

6.1.3 Summary of the Equipment Operations

To start up the engine and conduct initial engine/well-suction operations, a supplemental fuel was used. The horizontal wells for collecting the hydrocarbon vapors are gradually exposed to the vacuum of the engine's intake manifold. As pressure is reduced in the well, hydrocarbon vapor begins to accumulate and flow into the engine's intake manifold. As the hydrocarbon vapors begin combusting in the engine, the flow of supplemental fuel may be reduced or eliminated entirely. The engine is further controlled by regulating the engine air intake both for the supplemental fuel and a secondary air intake.

The majority of the soil hydrocarbon vapors are burned in the engine. The small fraction of vapors that may enter the exhaust unburned, together with the combustion products of the engine, are removed from the exhaust by using a standard catalytic converter.

After the initial start-up has been completed, the computer can be set to operate the system according to preset limitations or as a fully automated operation. The computer is programmed to react to information supplied by sensors at strategic locations in the system and make necessary adjustments for smooth operations. Safeguards are incorporated into the system to shut it down automatically should a variety of problems occur, such as low oil in the sump, low oil pressure, high temperature in the oil or water, and low battery voltage.

An automated fire-suppression system is activated in case of fire. The fire system can also be activated manually. Once the fire system has been activated, the IC engine's operational capabilities are disabled by the computer until repairs are made and the fire system has been replenished and returned to service.

6.2 Equipment Operation and Upgrades

During the course of work at Cameron Station, Argonne used two vapor-extraction machines, one VR Systems V2B and one V4.

6.2.1 V2B Vapor Extraction Equipment

The V2B vapor extraction machine delivered to Argonne was a new design manufactured by VR Systems. The concept of the design was that of a machine that would perform at approximately 75% of the capabilities of VR Systems' V3 machine (the V3 is powered by a single V-8 Ford industrial engine).

6.2.2 V2B Components

The V2B components are described as follows:

- The engine is a Volkswagen, liquid cooled, 1,800-cm^3 (110-in.^{3}), 4-cycle, industrial engine.

- The frame and housing has "slide-in/slide-out" engine capability. The housing is insulated, and cooling air is ducted for "quiet run" operation. In addition, the housing has "slide-in/slide-out" capability from the transport trailer.

- The electrical power is a 12-V automatic system with a 37-amp alternator. An inverter is included to provide 110 V for the computers. (This component allows stand-alone operation of the system.)

- The electronics are provided by an on-board, user-friendly computer/processor that collects data from several points in the fuel and combustion system and controls the Master Control Unit. Well gas bypass and supplemental air valves maintain a proper air/fuel ratio over the entire rpm* range, regardless of the source of fuel. The Master Control Unit is operated by the computer/processor, which reads an oxygen sensor in the exhaust system. An additional computer/processor is provided (with a monitor and a floppy-disk drive) for operational reporting.

- The engine is equipped with a muffler and catalytic converter.

- A "high liquid" switch is installed at the inlet to the engine (from the well) to prevent the engine from running if the well produces water instead of vapor.

- A 2.5-gal reservoir and automatic valve maintains proper engine oil levels for extended unsupervised operation of the system

6.2.3 V2B Start-Up

Argonne personnel alternated the V2B system among horizontal wells 1, 2, and 3 during the period July 1992 through October 1992. The V2B was initially operated on horizontal well 1, which was nearest to the PX gas station. The concept was to decrease the amount of free product as much as possible to prevent further migration across the parking lot. When the computer

---

* revolutions per minute.

indicated that product use was down and supplemental fuel use was up, the V2B was transferred to another well. While the V2B was removing product from an alternate well, more product was able to be volatilized in the other two wells.

6.2.4 V2B Operational Upgrades

Because the V2B vapor extraction equipment was of a new design, Argonne personnel were able to do more than just operate and maintain the machine. Working closely with VR Systems, Inc., Argonne personnel suggested numerous revisions and adjustments to the V2B design, as follows:

- Problems with exhaust temperatures were resolved by relocating the catalytic converter outside of the engine compartment.

- Problems with high oil temperatures were resolved by adding a supplemental oil cooler.

- Difficulties with high water temperatures were resolved by relocating the converter.

- The need for numerous ignition-coil replacements was alleviated by relocating the ignition coil to a vibration-isolated location. In addition, constant vibration caused many wires to break at or near their termination points. Argonne suggested that the engines in VR Systems' next V2B manufacturing run be isolated from vibration.

- The on-board computer/processors operated through computer modems and keyboards were not considered necessary. At times, the computer would note a software problem and the screen would read, "Push any key to continue." As a result, the computer had to be removed and a temporary keyboard had to be installed. The problem was resolved by installing a "push-button" on the face of all VR Systems' computers as a substitute for the keyboard.

- The on-board computer/processors were powered by a low-voltage battery that, when discharged, would cause the system to stop. The battery was replaced with a transformer connected to the main electrical system.

6.2.5 V2B Operation on Vertical Wells

During October 1992 through April 1993, VR Systems allowed Argonne to keep the V2B system at Cameron Station at no cost to the government. Argonne chose to connect the V2B system to vertical wells PX-4, MWS-7, PX-5, PX-6, and PX-17 through a common header. Under these circumstances, comparisons could be made between extraction efficiencies of horizontal wells and vertical wells. (During rainy periods, the water table would rise, and the "high liquid" switch on the V2B would shut down the system.)

Only vertical wells PX-4, MWS-7, and PX-5 appeared to have product. PX-6 and PX-17 were connected to provide additional combustion air, if required, because they exhibited no product. During the first days of operation, wells PX-6 and PX-17 were not needed and were shut down. Wells PX-4, MWS-7, and PX-5 were connected to the V2B for the duration of the operation. Over the course of pumping, the vacuum created by the V2B system caused weathered product to accumulate in wells MWS-7 and PX-5. Argonne intended to use hand-bailers to remove the product periodically; however, the sponsor decided to install skimmers. During the operation of the V2B system on the vertical wells, no "high liquid" shutdowns were experienced.

6.2.6 V4 Vapor Extraction Equipment

In October 1992, Argonne installed two more horizontal wells (4 and 5), so an additional vapor extraction machine was ordered from VR Systems. A V4 machine was received and installed at the Cameron Station site. It was used October 1992 through April 1993. The V4 machine was operated on wells 1 through 5 (predominantly on wells 4 and 5) on an alternate basis for the duration of the study.

The V4 model had the same equipment and concept as the V2B model, except that the system consisted of two Ford, liquid-cooled, 460-in.^{3}, 4-cycle, industrial engines and two 10-gal reservoirs and automatic valves to maintain proper engine oil levels for extended unsupervised operation of the system.

6.3 Measurement of Equipment-Operational and Related Environmental Variables

6.3.1 Capacities of the V2B Extraction Equipment

As previously stated, the V2B was designed to operate at approximately 75% of the capacity of the V3 machine. Safe operation of the engine covers a range between 2,400 and 3,200 rpm. The V2B is capable of drawing up to 55 ft^3/min of air from a well, depending on rpm. Well vacuum readings at the machine range from very low to 110 in. of water (again dependent on rpm). The V2B is capable of creating a much higher vacuum; however, the computer is set for an upper limit of 110 in. of water. This upper limit prevents the collapse of the steel barrels that are installed in the piping system leading to the VES from the well. In addition, the permeability of the soil in the zone of influence is a major contributing factor for vacuum and air flow.

Supplemental fuel usage can vary from 0 to 3 ft^3 when natural gas is used as a fuel or 0 to 1.3 ft^3 when propane is used as the fuel. Supplemental fuel is added (as required) to the fuel derived from the well, depending on the ability of the well to produce the amount of fuel to support the engine rpm. The V2B machine is capable of removing up to 15 lb/h of hydrocarbons at a destruction efficiency of 99.97%

The V2B machine was in operation July 1992 through April 1993. Volatilized product removal (see Table 6.1) from the wells via the V2B machine was calculated by using the on-board computer data and the appropriate fuel-rate curve (see Figure 6.1)

6.3.2 Capacities of the V4 Extraction Equipment

The V4 was designed for safe operation of the engine at a range between 1,500 and 2,600 rpm. The V4 is capable of drawing up to 400 ft^3/min of air from the well, depending on rpm. Well vacuum readings at the machine range from very low to 110 in. of water, again depending on rpm. In addition, permeability of the soil to air in the zone of influence is a major contributing factor.

The V4 machine was in operation between October 1992 and April 1993. Volatilized product removal (see Table 6.1) from the wells via the V4 machine was calculated by using on-board computer data and the appropriate fuel-rate curve (see Figure 6.1). The V4 machine is capable of removing up to 110 lb/h of hydrocarbons at a destruction efficiency of 99.97%.

6.3.3 Weather Conditions Related to the V2B and V4 Vapor Extraction Equipment and Horizontal Wells

The operations of the computers associated with the V2B and V4 vapor extraction equipment were affected by cold weather (i.e., air temperature below 20°F). VR Systems, Inc., is designing a heat-transfer system to collect the heat from the engine and catalytic converter to heat an enclosure around the piping and computer equipment.

During heavy rain, the water table would rise in the gravel columns containing the horizontal wells, and the "high liquid" switch would cause the machines to shut down.

TABLE 6.1 Estimated Removal of Volatilized Free Product at Cameron Station, Virginia (July 1992–February 1993)

V2B					V4				
Month	Well	Vacuum Hours	Product Removed (gal)	Product Removed (gal/h)	Well	Vacuum Hours	Product Removed[a] (gal)	Product Removed[a] (gal/h)	Grand Total (V2b + V4, gal)
July		{ 50	20.6	0.41					
August	1-3	{283	203.7	0.72					
September		{480	345.5	0.72					
October	PX-4,5,	{267	27.5	0.10		{ 47	58.0	1.23	
November	and	{201	62.0	0.31		{557	229.2	0.41	
December	MWS-7[c]	{359	36.9	0.10	1,4,5	{416	171.2	0.41	
January		657	67.5	0.10	2, 5[b]	{564	58.0	0.10	
February		506	26.0	0.05		215	44.2	0.21	
			789.7				560.6		1350.3

[a] Two engines operating.

[b] Well 5 was evacuated for approximately 48 h only.

[c] Wells PX-4,5, and MWS-7 were monitored from October through February.

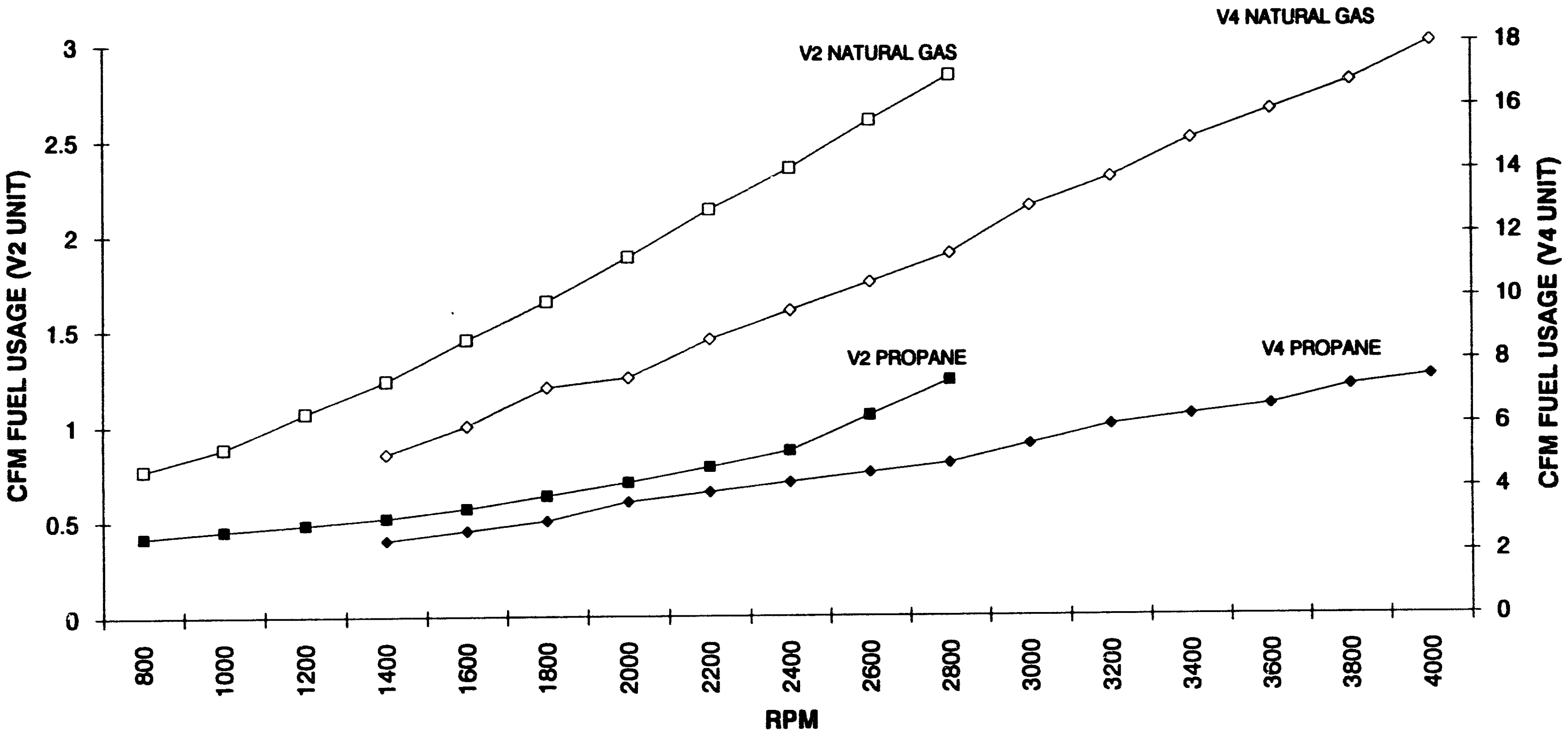


FIGURE 6.1 Fuel Rate Curve — V2 and V4

6.3.4 Monitoring of Free-Product Thickness and Groundwater Elevations

Throughout the course of the pilot-scale study, Argonne elected to monitor free-product levels and thicknesses in groundwater monitoring wells to determine the success of the SVE system(s). Argonne monitored free-product thickness as an adjunct to its computation of volatilized free-product removal (see Table 6.1). In addition, as specified in Section 6.5 of the Virginia Underground Storage Tank Technical Standards and Corrective Action Requirements (VR 680-13-02), an owner/operator must remove free product to the maximum extent practicable, as determined by the VWCE, while continuing any actions initiated to characterize a site and/or to prepare a corrective action plan and corrective action permit.

Free product and groundwater-surface elevations were monitored by using a Soloinst™ down-hole measuring device. Monitoring wells MWS-7, PX-4, PX-5, PX-7, PX-8, PX-9, PX-10, and PX-11 were monitored. One or more of the wells were monitored on the following dates: 8/1/92, 8/30/92, 9/12/92, 10/24/92, 12/4/92, 12/8/92, 12/18/92, 12/23/92, 1/13/93, 2/17/93, and 3/26/93. Because many of the monitoring wells are located in a parking lot that was frequently filled to capacity with vehicles, not all wells could be monitored during each measurement episode.

Hydrographs for a subset of the monitoring, wells MWS-7, PX-4, PX-5, PX-8, PX-9, and PX-11, are depicted in Figures 6.2–6.7. The hydrographs depict the change in groundwater-surface elevation (and, when present, product surface elevations) during specific monitoring dates. The monitoring episodes are plotted on the hydrographs as "days from first measurement," with the first measurement episode being 8/1/92. Groundwater-surface elevations shown in the hydrographs have not been corrected for the influence of floating product or the influence of vacuum generated by the SVE system.

The hydrographs in Figures 6.3 and 6.6 indicate that floating product decreased to a point at which it was nonmeasurable in wells PX-4 and PX-9. In addition, the hydrographs for wells PX-8 and PX-11 (Figures 6.5 and 6.7) also indicate a trend of decreasing product thickness. However, as pointed out by Drinkwater, McElroy, and Kanzler (Site Remediation, Fall 1992), this decrease in product thickness could be caused by the associated increase in groundwater-surface elevations.

The hydrographs for wells MWS-7 and PX-5 (Figures 6.2–6.4) depict wide fluctuations in product elevations. Although product thickness appears to be decreasing for the first half of the study, there is no clear decreasing trend in product thickness in wells MWS-7 and PX-5. In addition, an apparent side effect of SVE is that the floating product in wells PX-5 became so viscous that the monitoring probe could not penetrate the product to reach the water table.

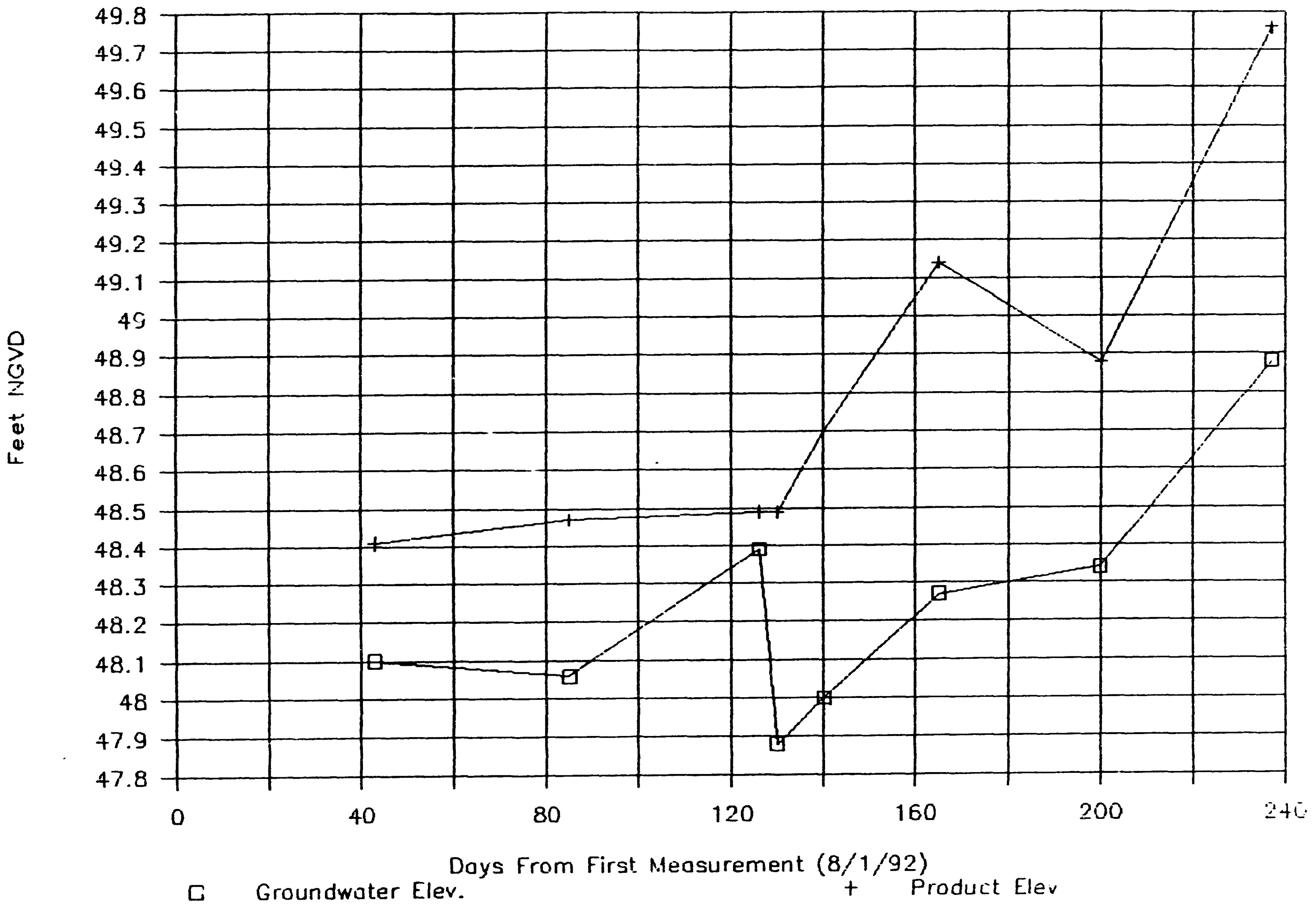


FIGURE 6.2 Hydrograph MWS-7

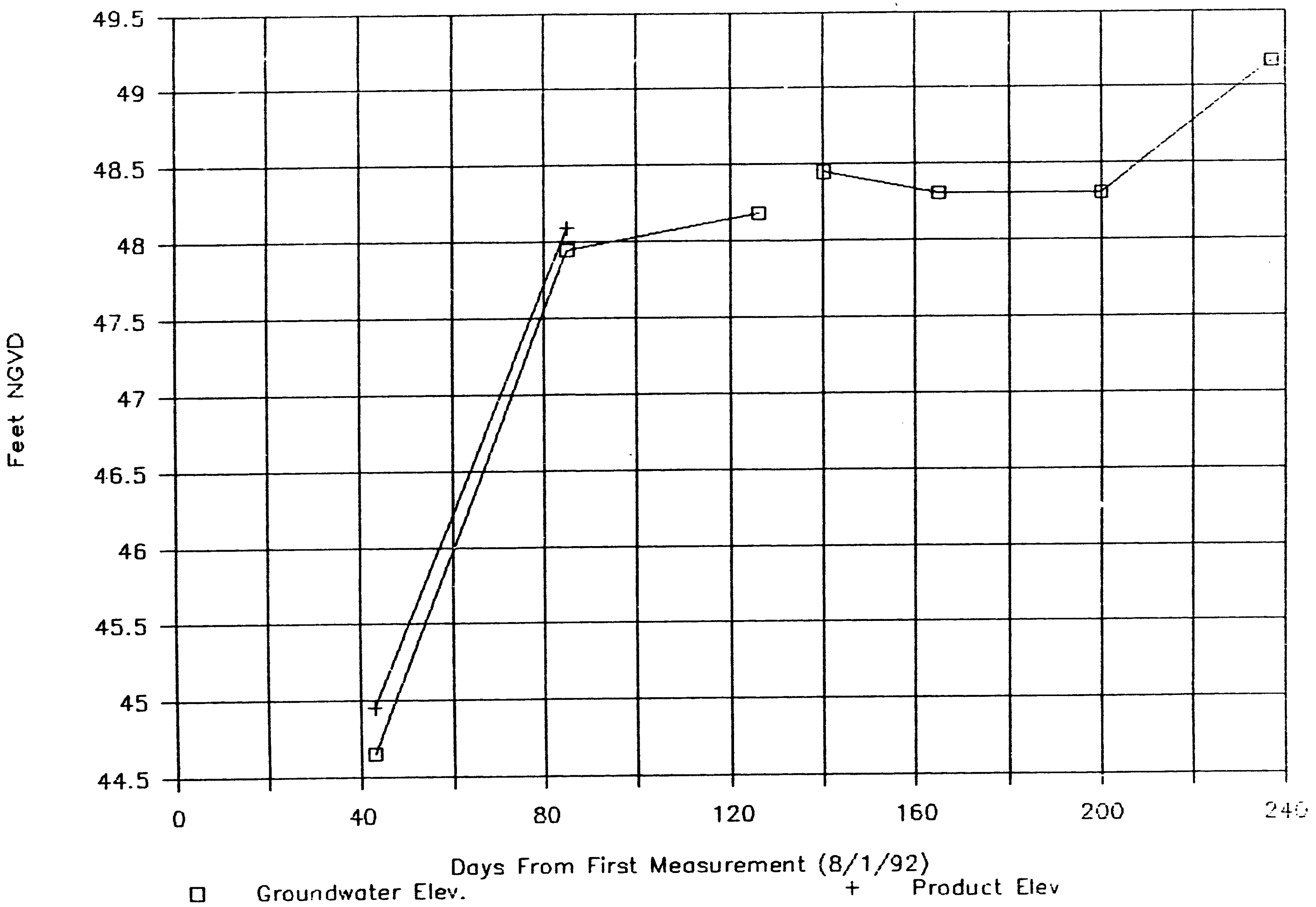


FIGURE 6.3 Hydrograph PX-4

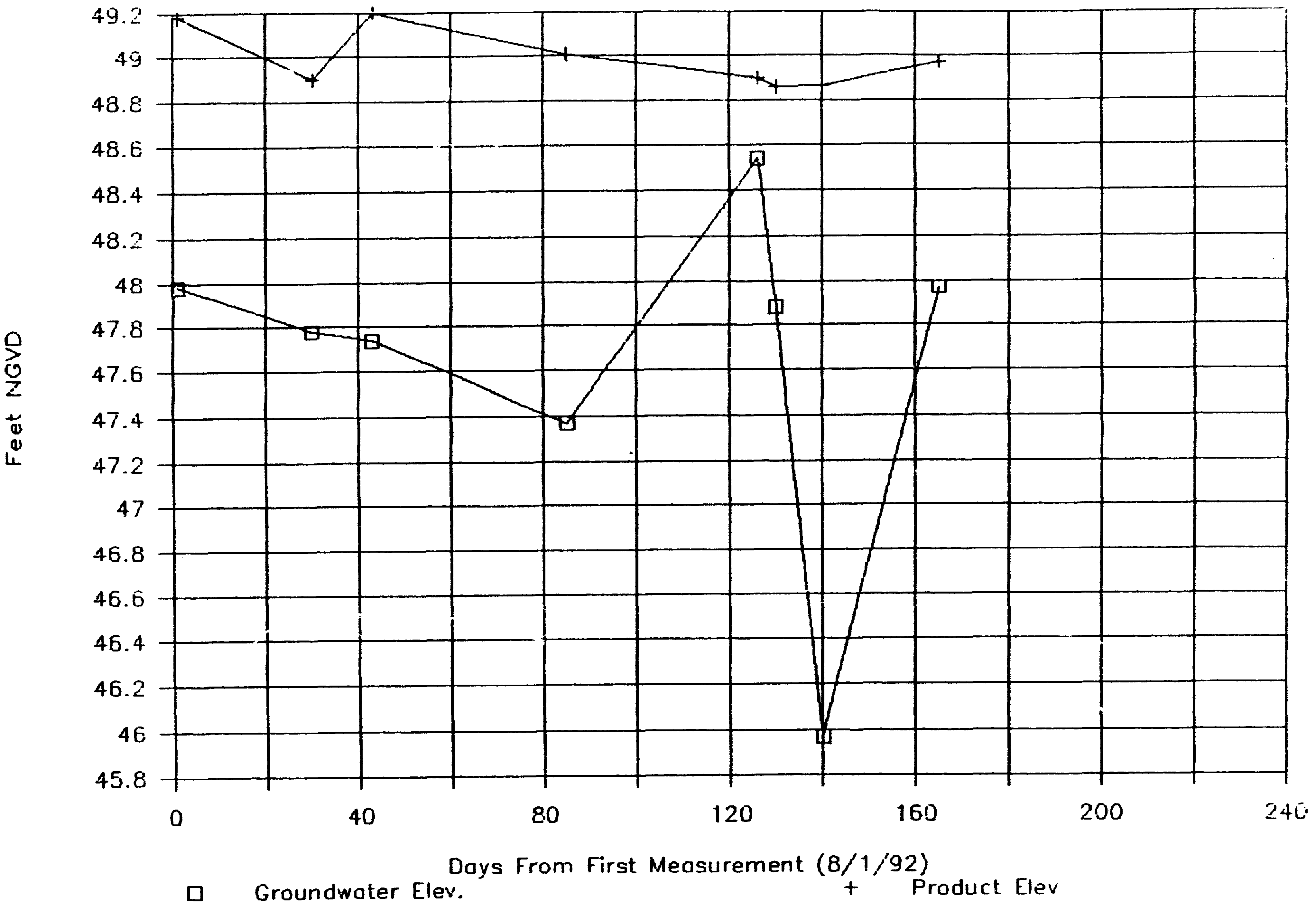


FIGURE 6.4 Hydrograph PX-5

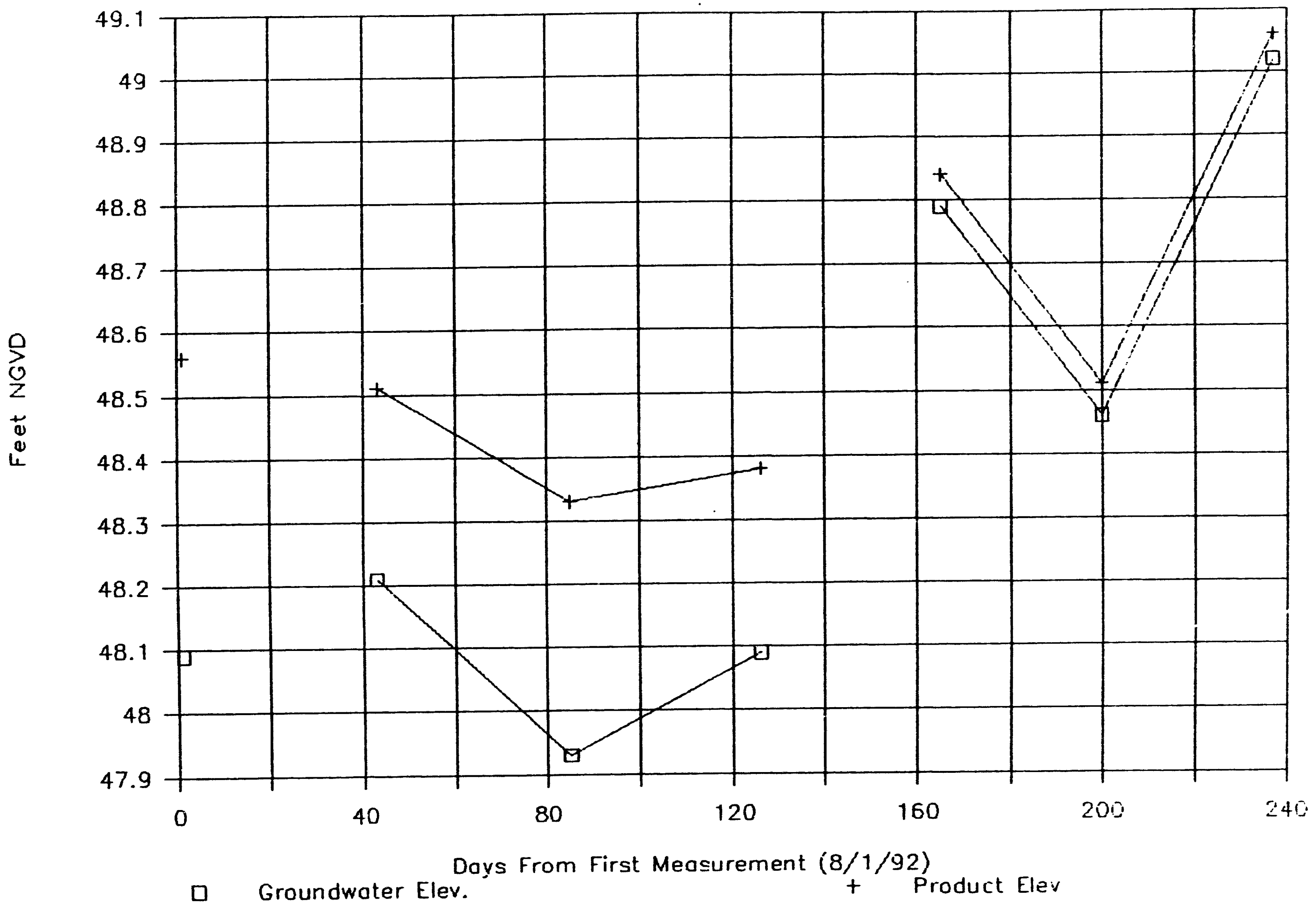


FIGURE 6.5 Hydrograph PX-8

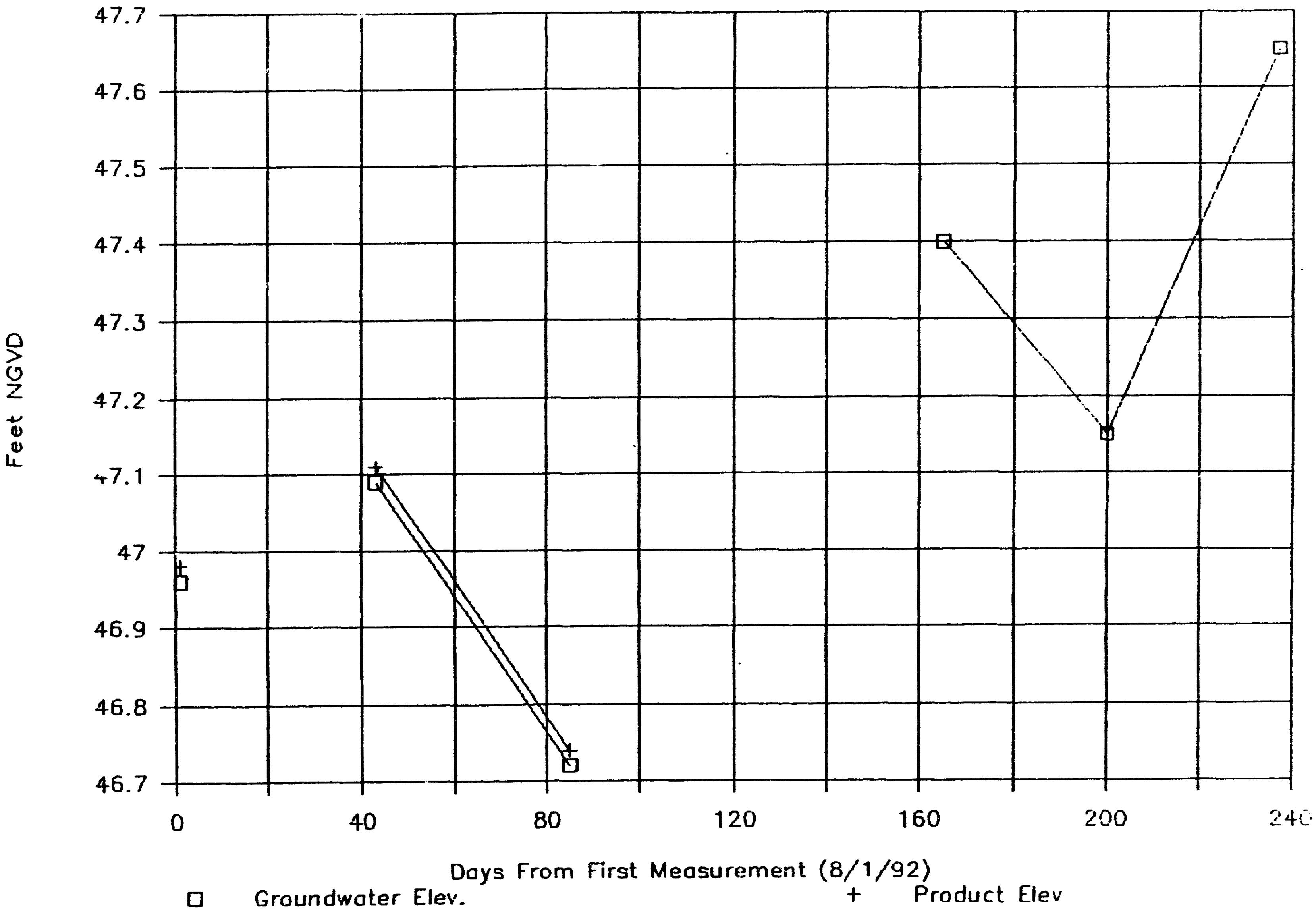
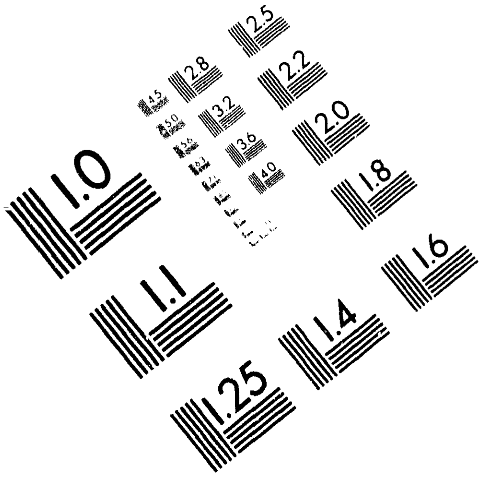


FIGURE 6.6 Hydrograph PX-9

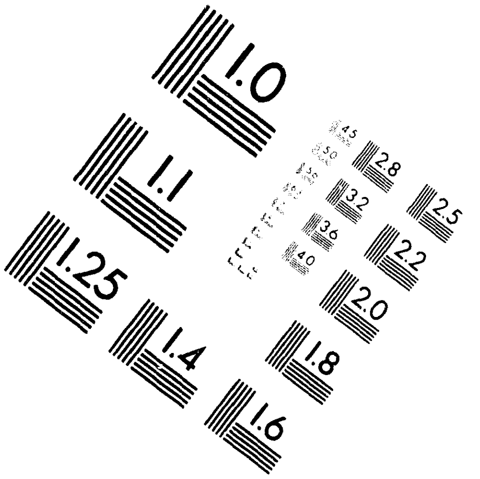


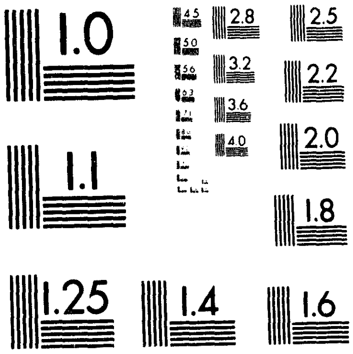
AIIM

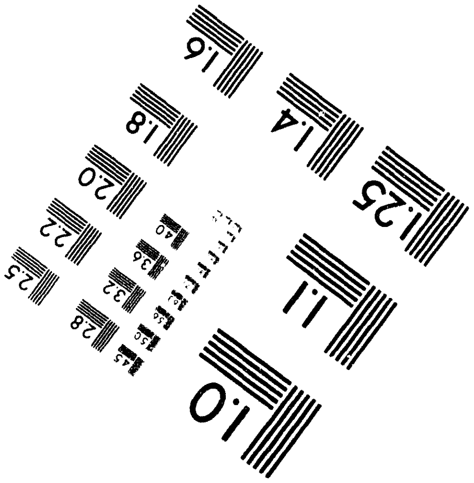
Association for Information and Image Management

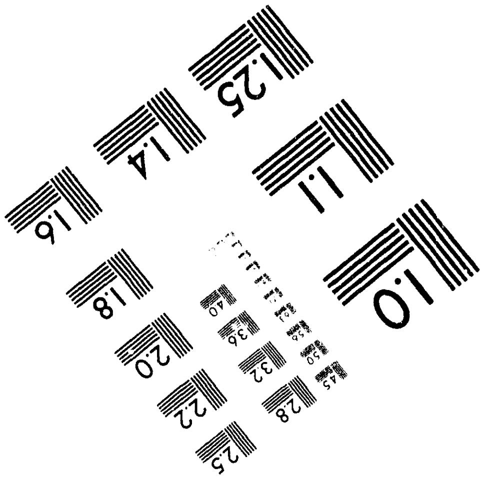
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202









MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

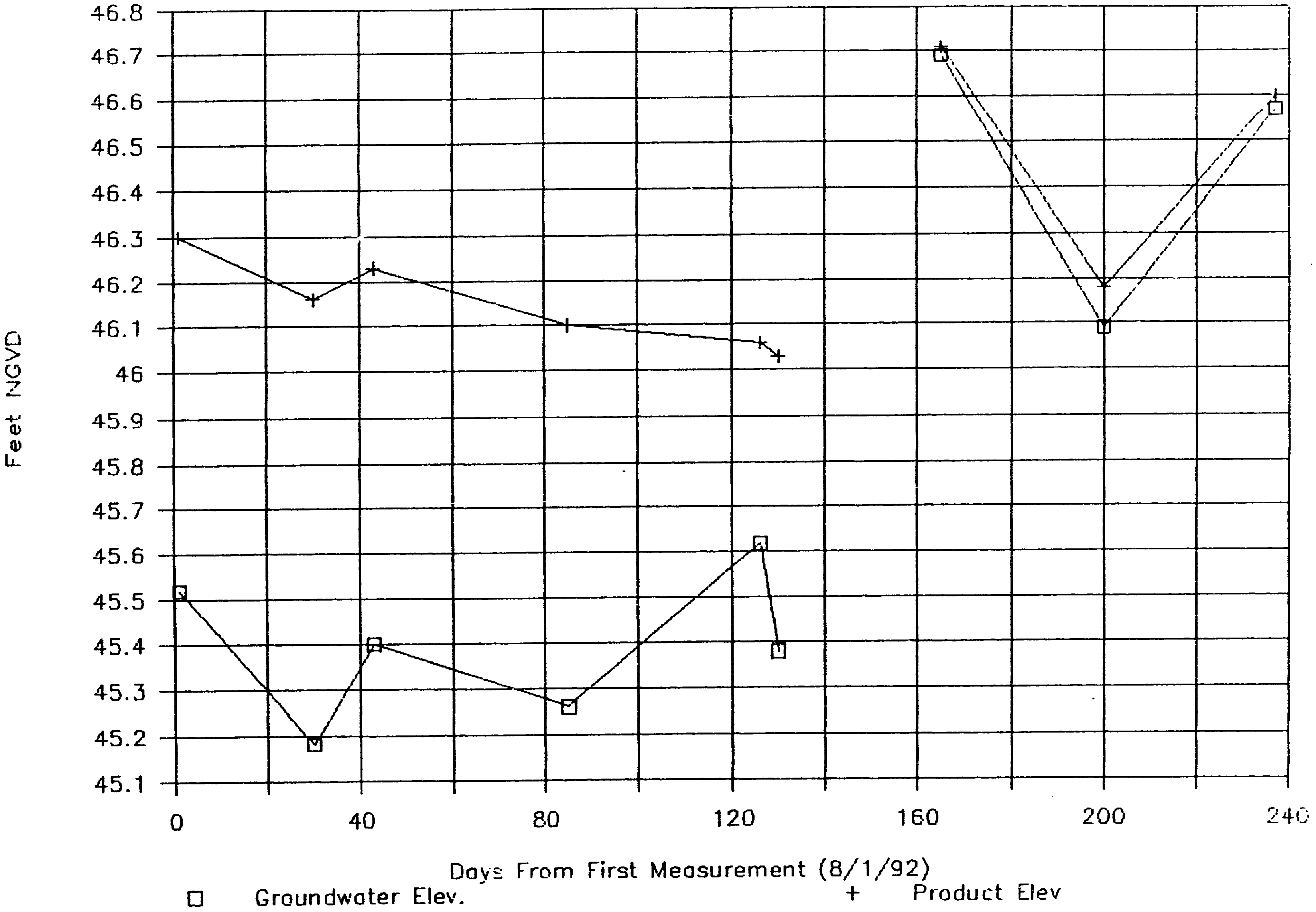


FIGURE 6.7 Hydrograph PX-11

7 Conclusions and Recommendations

7.1 Conclusions

During the relatively dry months of July 1992–February 1993, the SVE units removed approximately 1,350 gal of volatilized free product. However, the ability of the SVE units to extract vapor was reduced markedly during January–March 1993 because of increased precipitation and concomitant flooding of the horizontal wells. As noted below, the SVE operation led to a reduction in free-product thickness in two wells. However, in general, Argonne personnel did not notice a consistent decrease in product thickness in all of the wells sampled during the pilot-scale study.

The hydrogeology and the stratigraphy beneath the parking lot is not particularly well suited for using SVE in conjunction with horizontal wells. The vadose zone beneath the parking lot primarily consists of fill material. The fill contains a variety of natural and anthropogenic materials, including massive blocks of concrete and building foundations that lead to preferential flow paths to the wells. Under these conditions, vacuum development is inefficient over the predicted radius of influence for a given well. In addition, some of the more massive blocks of rubble prohibit the orientation and installation of horizontal wells as designed. The size and extent of some of the debris in the fill will necessitate "plumbing" horizontal extraction wells above and/or around debris that cannot otherwise be moved. Because the obstructions prohibit incorporating a design slope into the placement of horizontal wells, the wells can fill up with water and hinder the operation of the extraction system being used. Furthermore, the water table is close to the base of the clayey fill most of the year. There is a small interval between the underlying permeable sandy formation and the base of the fill, and this interval is very often saturated with high groundwater conditions. This interval precludes vapor flow through the very permeable sands, reduces volatilization, and greatly diminishes the vapor-extraction efficiency of an SVES.

On the basis of microbial studies performed on indigenous soils, it appears that air (oxygen) supplies to the vadose zone by the SVES could be expected to enhance microbial activity. Thus, if the difficulties associated with horizontal vapor-extraction wells could be overcome, or if vertical wells could be installed, bioventing could result in the degradation of the refractory product not treated by SVE.

The results of using SVE with existing vertical monitoring wells were mixed. The thickness of floating products increased or remained the same in wells MWS-7 and PX-5. One side effect of vapor extraction on well PX-5 was an apparent hardening of the floating product in that well. The hardening progressed to a point at which measurements of floating-product or groundwater-surface elevations became impossible. Hardening may have occurred as SVE concentrated the more viscous components of the aged product by removing the volatile fractions. Although the thickness of product increased in wells MWS-7 and PX-5, the thickness of floating product in well PX-4 decreased from 0.30 ft to "nonmeasurable" during the term of the Phase 3 test. In addition, the thickness of product also decreased to "nonmeasurable" in well PX-9.

Because of (1) the unfavorable nature of the geohydrologic system beneath the parking lot at Cameron Station and (2) the resultant impracticalities associated with using SVES with horizontal wells, Argonne determined that attempting to design a contamination remedy based upon horizontal SVE wells was inappropriate and thus terminated the pilot-scale study.

7.2 Recommendations for Further Study

The groundwater characterization results presented in Section 3 indicated that the total phosphorus concentration extractable from the soil should be determined; such information would indicate the amount of phosphorus that could be available for bioremediation. Several experiments need to be performed to determine (1) if phosphorus concentrations is a limiting factor and (2) the impact of varying the phosphate concentration on the biodegradation rate of the contaminants. Such studies could also investigate the effect of C:N and C:P ratios on the contaminant degradation rate.

The U.S. Army corps of Engineers may wish to evaluate the efficacy of a dual-vacuum extraction system (DVES) that extracts and treats both water and air at the Cameron Station site. A DVES has a number of advantages, including the following:

- A DVES using vertical wells could be designed to extract and treat both soil gas and groundwater. Groundwater contamination could likely "drive" the remedy selected for the Base Closure ROD and the CAP. The DVES would more directly address the most sensitive environmental media than vapor extraction alone.

- A DVES will artificially lower the water table by evacuating water from test wells in the form of water droplets. High vacuums associated with a DVES (i.e., >100 in. water vacuum) would simultaneously remove volatilized free product and groundwater from the artificially produced cone of depression. Artificially lowering the water table would provide "access" to the more permeable layers and thus enhance the capability of the DVES to extract vapors.

- A DVES could enhance the in-situ biodegradation of product present in the subsurface by bioventing.

- Should a groundwater pump-and-treat system be installed at Cameron Station, a vapor extraction system could be retrofitted to the groundwater pump and treatment system.

Appendix A:

Wells 1, 2, and 3 — Installation Description for Horizontal-Well SVE

Appendix A:

Wells 1, 2, and 3 — Installation Description for Horizontal-Well SVE

A.1 Background

The horizontal-well system (wells 1, 2, and 3) used in the initial SVE tests began at the gasoline service station and ran in a southeasterly direction, as shown in Figure A.1. Well piping consisted of three lateral runs of 2-in.-diameter, schedule 80 PVC slotted pipe and screens laid in a 260-ft-long straight trench. A fourth solid pipe, designated as manifold A, ran the full length of the 260-ft excavation and consisted of a series of solid pipe sections, with plugged tees at 20-ft intervals. All piping was positioned at a nominal elevation of 30 in. below the parking lot surface (elevation 0).

When completed, each of the three wells consisted of gravel-filled cells 1 ft wide and 6 ft high. The gravel well cells ran from 2 ft below the parking lot surface (-2 ft) down to a depth of 8 ft (-8 ft). Well 1, located near the filling station, was 40 ft long (in two sections). Well 2 was 107 ft long. Well 3, at the far end of the trench, was 55 ft long. See Figure A.2. The full length of each well was serviced by the slotted pipe screen, positioned approximately 3 in. below the top of the gravel. During construction of the trench, barriers were left between the designated well areas. The 3-ft-deep barriers separated the well sections and gave support for the solid-pipe conduits. The solid conduit connected the end of the pipe screen to the manifolding at the start of the well system.

The design called for excavation of a continuous 1-ft-wide by 8-ft-deep trench, separated by two 3-ft-deep barriers, as shown in Figure A.2. Enough material was left in place between the adjacent 8-ft-deep trenches to provide a natural dam or barrier to retard soil vapor flow between wells. This barrier isolated each well from the adjacent well(s) when the SVE system was put into operation.

During construction, large chunks of concrete were encountered at elevations below -2 ft. The concrete monoliths, which were mixed with the other fill material in the upper levels of soil under the parking lot surface, were so large the contractor could neither break them into small fragments nor remove them en masse. Consequently, they were left in place and the back-hoe operator removed the soil around them. Where possible, the trenching operations were continued at the original dimensions. Fortunately, the large concrete masses were encountered only in a 6-ft-long area and thus affected only one of the well trenches. The concrete obstruction area was bridged with solid pipe, and the rest of the trenching and well construction were conducted as planned.

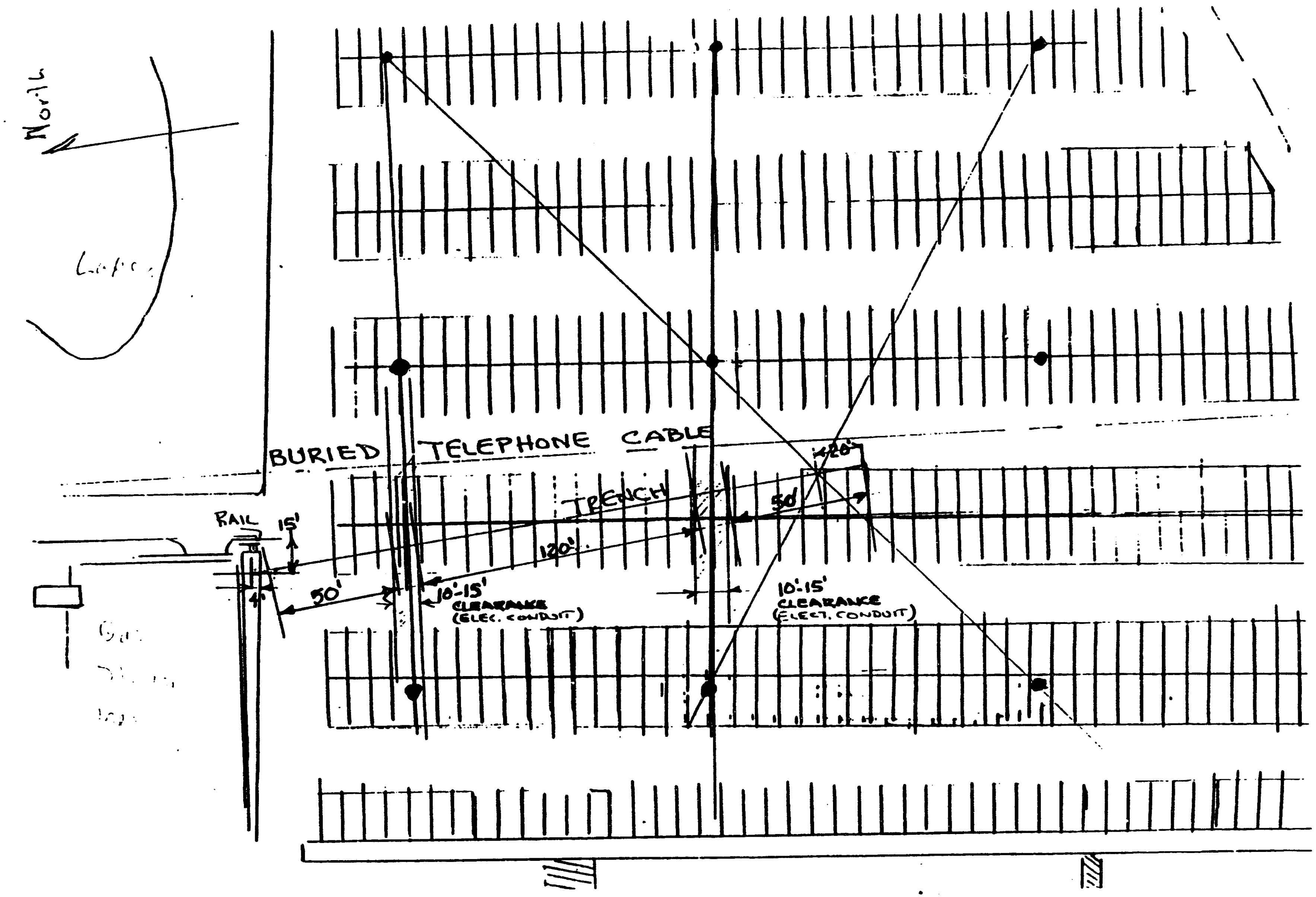


FIGURE A.1 Lateral Well System Layout

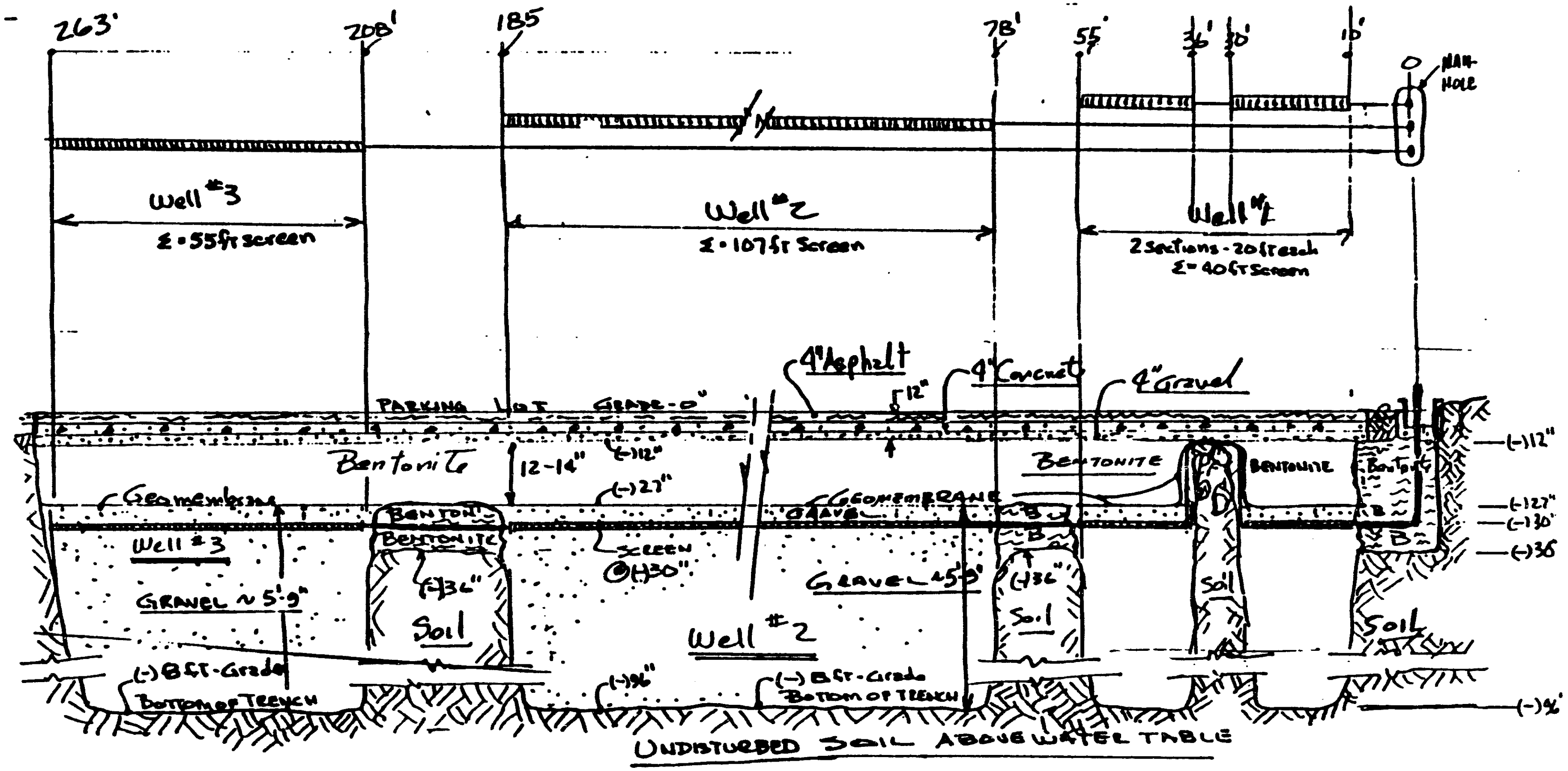


FIGURE A.2 Lateral Well System As-Built Elevation

The design called for the length of each well to correspond to the free space between the electrical conduit runs that serve the parking lot lights. (The electrical conduits run roughly at a right angle to the trench.) By allowing adequate space on either side of the electrical conduits, enough material was left in place between the adjacent 8-ft-deep trenches to prevent possible damage to the electrical conduit and to provide a natural dam or barrier between the wells. Plans supplied to the project showed the electrical conduit located 5 ft below the parking-lot surface. However, during excavation the conduits were found to be only 6 in. below the surface. Fortunately, only minimal damage was done to the conduit when struck by the back-hoe.

During excavation, as soon as the fill material was removed from the well areas, the trench was backfilled with pea gravel. This step was taken to prevent the trench walls from caving in, which would cause the loss of free surface area needed for vapor aspiration.

Once the pea gravel was graded to the -30-in. elevation datum in the wells, the preassembled 2-in. slotted and solid PVC pipe was laid in place. Bridging pipe was run at a -15 in. elevation in the 6-ft-long strip of the trench over the concrete monolith. Three inches of gravel was then placed above the slotted pipe screen and the area was graded to an elevation of -24 to -27 in. Bentonite clay was placed around and under the solid pipe running across the 3-ft-deep barriers. A double layer of 3-mil polyethylene sheet (geomembrane) was then spread over the gravel-filled well areas and the bentonite-covered sections to form a continuous seal that spanned the full width and length of the 260-ft-long trench. Figure A.3 shows the installation sequence.

Once in place, the double-layer polyethylene sheet (geomembrane) was covered with a minimum of 12 in. of bentonite clay. The bentonite was then graded to a -12-in. elevation across the trench wells and over the conduit sections (barriers). This sealed the trench from the atmosphere should any cracks occur in the parking lot surface. The bentonite was then flooded with water and allowed to sit for several hours so it could absorb the water and swell to a stable dimension.

Restoration of the parking lot consisted of pouring a 4-in. course of pea gravel sub-base, adding a 4-in.-deep continuous subsurface ribbon of concrete, and topping the underlying layers with a 4-in.-deep layer of asphalt. Reinforcing bars were placed over the area where the in-situ concrete monoliths had to be bridged with solid pipe. This step prevented excessive traffic loads from being transferred to the pipe.

A.2 Description of As-Built System

The well piping was positioned a nominal 30 in. below the surface of the parking lot and ran parallel to the inclined surface of the lot and the water table. Figure A-4 shows a typical trench cross section.

Installation Sequence

Final. Step- compact soil, fold over Geomembrane Liner and patch the parking lot.

Fourth Step- Install Geomembrane material liner so as to cover the bottom, ends and sides of the partially filled trench. Backfill trench with Bentonite and raise the level of the soil in the liner to elevation (-) 4 inches, (ie approx. 2 ft. deep). see sketch C-2.

Third Step- Raise level of Bentonite and Pea Gravel zone to uniform elevation of (-)27 inches. (ie, submerge pipe and screen by at least 2 inches).

Second Step- Place 2" pipe and screens in trench with C elev. to be at (-) 30". See sketch C-2.

First Step- Place Bentonite Clay over solid soil area to depth of 6 inches, (-) 30" elev. Raise level of Pea Gravel to elevation, (-) 30".

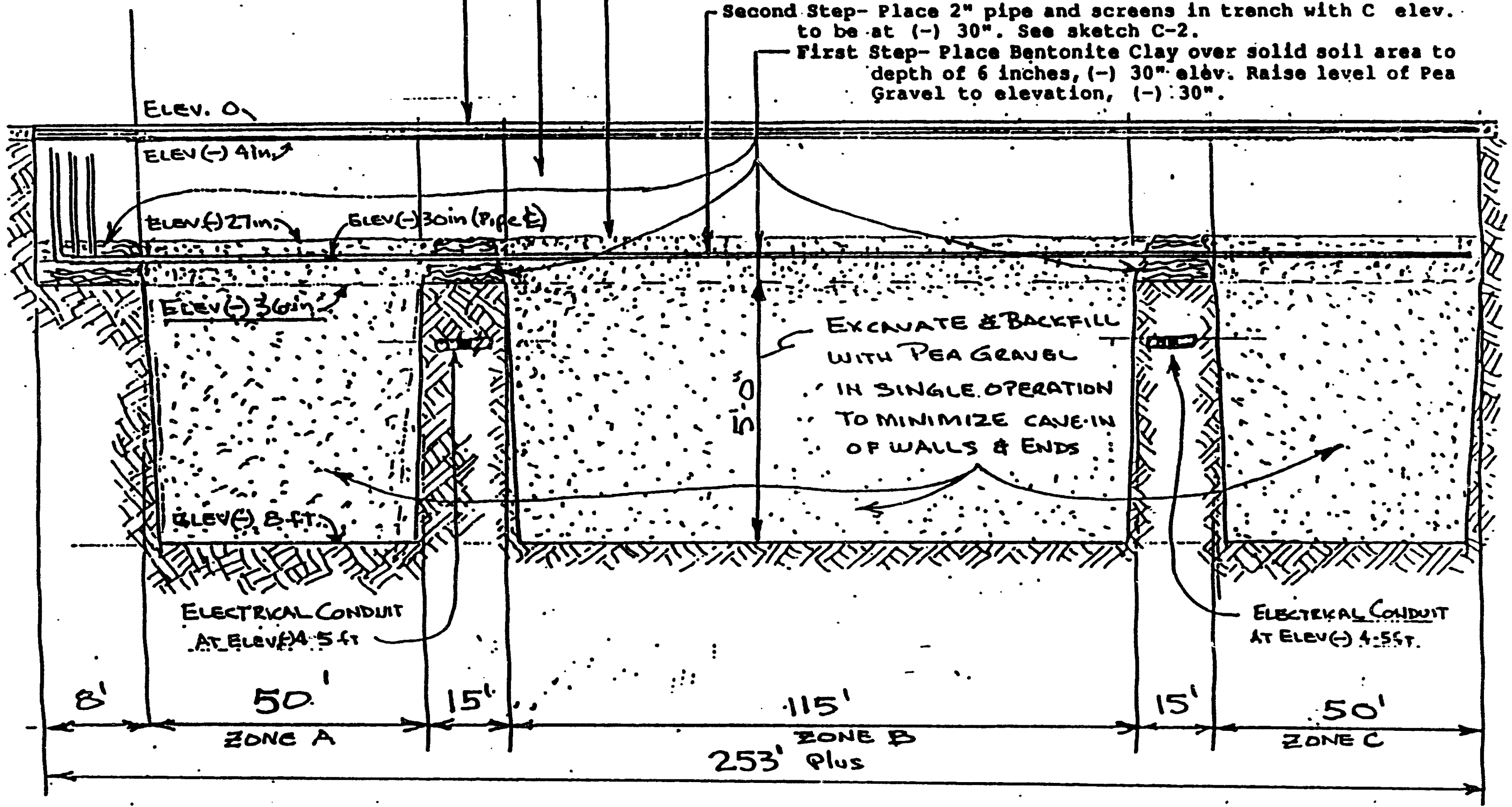


FIGURE A.3 Lateral Well System Elevation — Design

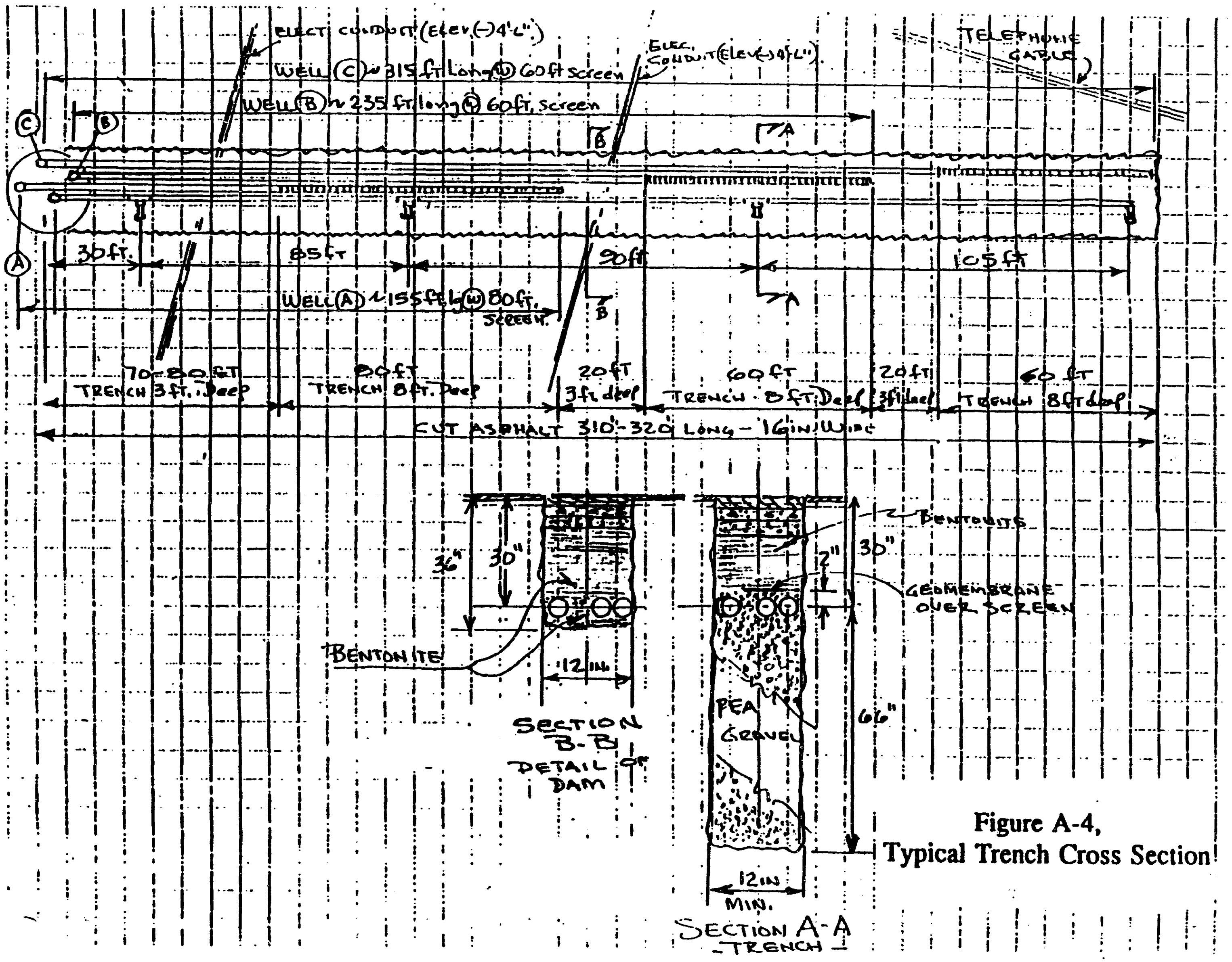


Figure A-4,
Typical Trench Cross Section

FIGURE A.4 Typical Cross Section

The bottom of the gravel-filled excavation is about 3 ft above the water table. A nominal 3 ft of wet, mixed sand and clay soil separates the bottom of the pea gravel and the water table. Each filled well had a 1-ft-wide bottom and 6-ft-high walls that communicated with the surrounding material. This provided a large surface area for the diffusion/evacuation of petroleum product vapors into the pea gravel and, subsequently, into the evacuation system screen and piping. Table A.1 lists the physical characteristics of the three wells and manifold A.

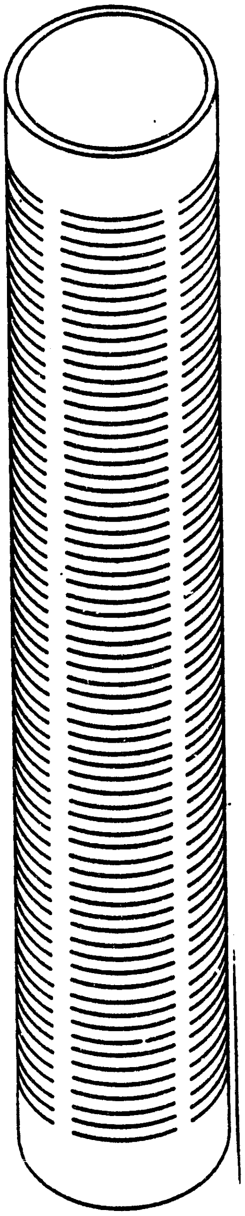
The well screen used was 2-in.-diameter, schedule 80 PVC pipe. The pipe is slotted with 0.020-in.-wide slots, spaced in four rows, as shown in Figure A.5. This arrangement gives 4.51 in.^{2} of open area per linear foot of pipe. Each 20-ft section, therefore, has 90 in.^{2} of open area for transmission of vapors/gases. Schedule 80 pipe was used (instead of the weaker schedule 40) to lessen the chance of pipe failure caused by shifting soil and gravel or by uneven load transfer from the parking lot. A cap was placed on the end of the slotted pipe to minimize intrusion of clay and gravel. All solid pipe and screened pipe sections were connected by rigid couplings cemented in place. In areas where differential loads could occur, flexible hose-type connections were used.

The fourth pipe, designated as manifold A, was installed during the closure process. It consisted of a 2-in.-diameter, schedule 80 PVC solid, rigid-wall pipe, running the length of the 260-ft-long trench. It was provided as a contingency for connection to future trenches that may be

TABLE A.1 Physical Characteristics of Wells 1, 2, 3, and Manifold A

Features[a]	Well 1	Well 2	Well 3	Manifold A
Radial distance from terminus (ft)				
Beginning of screen	10 (1A) 36 (1B)	78	208	20/tee
End of screen	30 (1A) 55 (1B)	185	263	258 (last tee)
Length of screen (ft)	39	107	55	none
Screen slot width (in.)	0.020	0.020	0.020	solid
Screen flow area (ft^2)	1.22	3.35	1.72	none
Nominal depth of screen (elev.; in.) (pipe in the case of manifold A)	-30	-30	-30	-30
Well elevation:				
Top of gravel (in.)	-24 to -27	-24 to -27	-24 to -27	-24 to -27
Bottom of gravel (ft)	~-8	~-8	~-8	~-8

[a] Pipe size for all wells and manifold A was 2-in. schedule 80.



ASI
WELL SCREEN

PVC construction

Designed for use in natural or artificial gravel packed wells

Available with choice of end fittings

Dimensions

Pipe Size: 2 inch diameter, schedule 80 PVC
Length per Section: 20 ft.
Slot Size: .020 in.
Slot Flow Area per Foot of Screen: 4.51 sq.in./ft.

FIGURE A.5 Screen Pipe Detail

required to extend the horizontal evacuation system out into the parking lot, beyond the end of well 3. The fourth pipe was placed in the trench once the backfill was brought up to a uniform elevation. A uniform elevation is needed so the rigid pipe would not be over-stressed by irregularities in the contour of the base soils used for support. The pipe was positioned 30 in. below the pavement. This solid pipe was equipped with plugged ties at 20-ft intervals along its length. Only a single, removable cap was placed at the far-end of the pipe. The proximal end of manifold A, near the filling station, has an elbow and short vertical stub that extended up out of the trench. This pipe is terminated with a temporary cap.

All piping at the terminus by the filling station was run up in vertical headers. The spacing of the vertical headers and the horizontal piping is a nominal 2.5 to 3.0 in. on center. Figure A.6 shows piping and header location.

Like the horizontal piping, the area around the vertical headers is packed with bentonite clay. The bentonite extends from the underground pea-gravel (-36 in.) up to 10 in. below the surface of the manhold cover. A nominal 4 in. of concrete (Sakrete mix) was placed above the bentonite to fix the headers in place in the manhole.

A.3 External Manifold Piping Description

The terminus of the underground piping system was midway between the edge of the parking lot and the concrete apron surrounding the filling station. Rigid elbows were used to connect the horizontal pipe to the vertical headers. A 14-in. manhole cover was concreted in place, with the headers terminating at an elevation of about 2 in. below the cover plate (Figure A.2). Thus, when the experiment is completed, the flexible connectors used to attach the headers to the aboveground manifolding will be removed, the headers capped, and the manhole cover put in place. The system then will be unobtrusive and pose no hazards or inconveniences to any personnel walking or working in the area.

A.4 External Manifolding and Measurement Devices

The aboveground manifolding connects the headers to the SVE vapor-destruction unit. Two-inch schedule 80 PVC pipe, elbows, tees, and flexible couplings are used to make the connection. Each line contains a ball-valve for isolation from the 2-in.-diameter main that connects to the V4 vapor-destruction unit made by VR Systems, Inc. Reducer bushings are used to connect the 2-in. well piping to the aboveground manifolding.

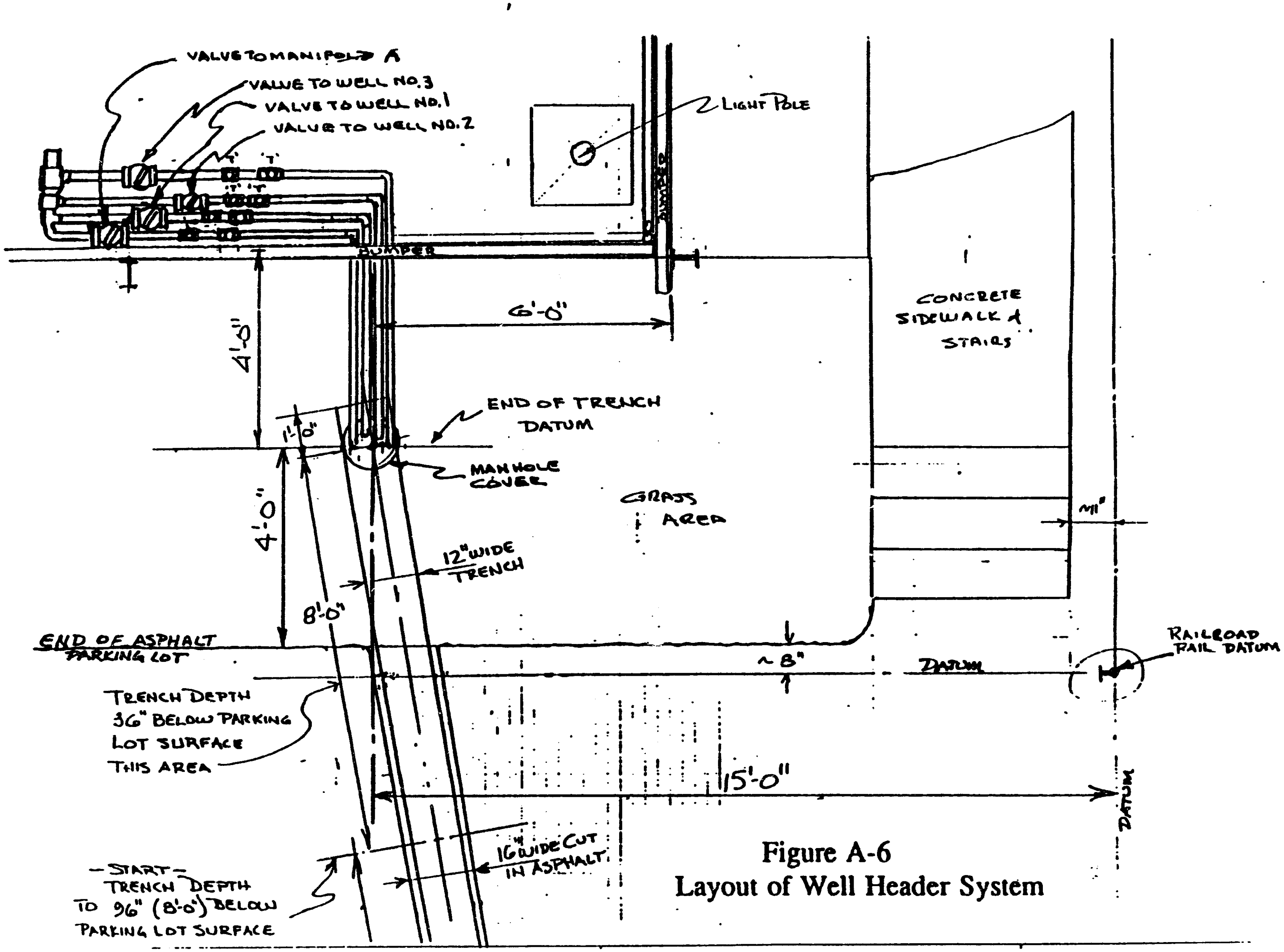


FIGURE A.6 Layout of Well Header System

A.5 Construction Materials List for Wells 1–3 and Manifold A

Table A.2 lists the construction materials used for wells 1, 2, and 3, and manifold A. A list of the materials used in the construction of the piping and manifolding for wells 1–3 and manifold A can be obtained from Argonne National Laboratory (Audrey Arns, 708-252-3309).

TABLE A.2 Construction Materials List

Well and Buried Manifold A Materials Dimensions
Pipe Size: 2-in.-diam. schedule 80 PVC
Length per section: 20 ft
Screen Slot Size: 0.020 in.
Screen Slot Flow Area / Ft of Screen: 4.51 in.^{2}/ft

Description	Trench Materials List	Quantity
PVC-well screen	2 in. SCH 80 x 20 ft long, 0.020 in.-slots	11
PVC-pipe	2 in. SCH 80 x 20 ft long	28
PVC-pipe tees	2 in. SCH 89, plain ends	16
PVC-pipe elbows	2 in. SCH 89, plain ends	4
PVC-pipe caps	2 in. SCH 89, plain ends	4
PVC-pipe plugs	2 in. SCH 89, plain ends	12
PVC-couplings	2 in. SCH 89, plain ends	27
16-in. steel manhole	16-in. nonlocking cover	1
Bentonite pellets (3/8 in.)	360 ft^3, 35 x 45 x 48-in. bags	9 bags, min.
Pea gravel (3/8 in.)	1,290 ft^3 min.	48 yd^3

Description	Above-Grade Manifolding Materials List	Quantity
PVC single-entry ball valves	2 in. SCH 89, plain ends	4
PVC reducing tees	3 x 3 x 2 in. SCH 89, plain ends	4
PVC reducer tees	2 x 2 x 1 1/2 in. SCH 89, plain ends	4
PVC reducer bushings	4 x 3 in. SCH 89, plain ends	2
PVC reducer bushings	3 x 2 in. SCH 89, plain ends	4
PVC reducer bushings	2 x 3/4 in. SCH 89, plain/threaded	4
PVC reducer tees	4 x 4 x 3 in. SCH 89, plain ends	2
PVC 90 ells	2 in. SCH 89, plain ends	8
PVC 90 ells	3 in. SCH 89, plain ends	2
PVC 90 ells	4 in. SCH 89, plain ends	2
PVC tees	2 in. SCH 89, plain ends	14
PVC plugs	2 in. SCH 89, plain ends	4
PVC caps	2 in. SCH 89, plain end	6
PVC caps	4 in. SCH 89, plain end	2
PVC pipe	2 in. SCH 89, 20 ft long	2
PVC pipe	3 in. SCH 89, 10 ft long	1
PVC pipe	4 in. SCH 89, 20 ft long	1

Appendix B:

Wells 4 and 5 — Installation Description for Horizontal-Well SVE

Appendix B:

Wells 4 and 5 — Installation Description for Horizontal-Well SVE

B.1 Background

After testing wells 1–3 of the original trench and evaluating the movement of the petroleum product plume under the parking lot, it became evident that another horizontal-well system should be installed. The trench for this system was (1) to coincide with the maximum concentration of the petroleum product, (2) to be dug down to the water table, and (3) to run out to the vicinity of test boring PX-11. The second trench originated at the filling station about 4 ft from the first trench and ran in a 340-ft-long straight line to within 6 ft of PX-11. The gravel-filled wells were 1 ft wide and 6 ft deep (–5 ft to –11 ft elevation), with slotted pipe laid 6 ft below the parking lot. A third solid pipe, designated manifold B, was run the length of the trench.

Construction of the second 340-ft-long trench was similar to that of the first trench. Once again, occasional concrete monoliths were encountered that required modifications to the emplacement of the slotted pipe screens. The original plan called for this second trench to be divided into two equal-length sections (for wells 4 and 5), each approximately 140 ft long, and separated by approximately 40–50 ft of undisturbed fill (Figure B.1). When actually completed, however, well 4 was only 55 ft long, and well 5 was only 130 ft long. The full active length of each well was serviced by the 4-in. slotted pipe screen (Figure B.2).

The well sections were excavated 1 ft wide to a depth of –11 ft elevation. As soon as fill material was excavated from the well areas, the trench was backfilled with pea gravel to an elevation of –6 ft. The trench was backfilled to prevent the trench walls from caving in, which would cause the loss of free surface area needed for vapor aspiration.

The 4-ft-deep trenches were dug between the designated well areas to permit the installation of the solid-pipe conduits to connect the screen intakes to the manifolding at the beginning of each well system.

Large chunks of concrete were encountered, mixed in with other fill material, along the length of the second trench at elevations below –3 ft. The tops were trimmed so that the solid conduit pipe could be placed as close as possible to the intended –4-ft elevation. The excavation operation removed the soil from around the concrete monoliths, and the trenching operations were continued at the dimensions originally intended. Both wells 4 and 5 were affected, as shown in Figure B.3.

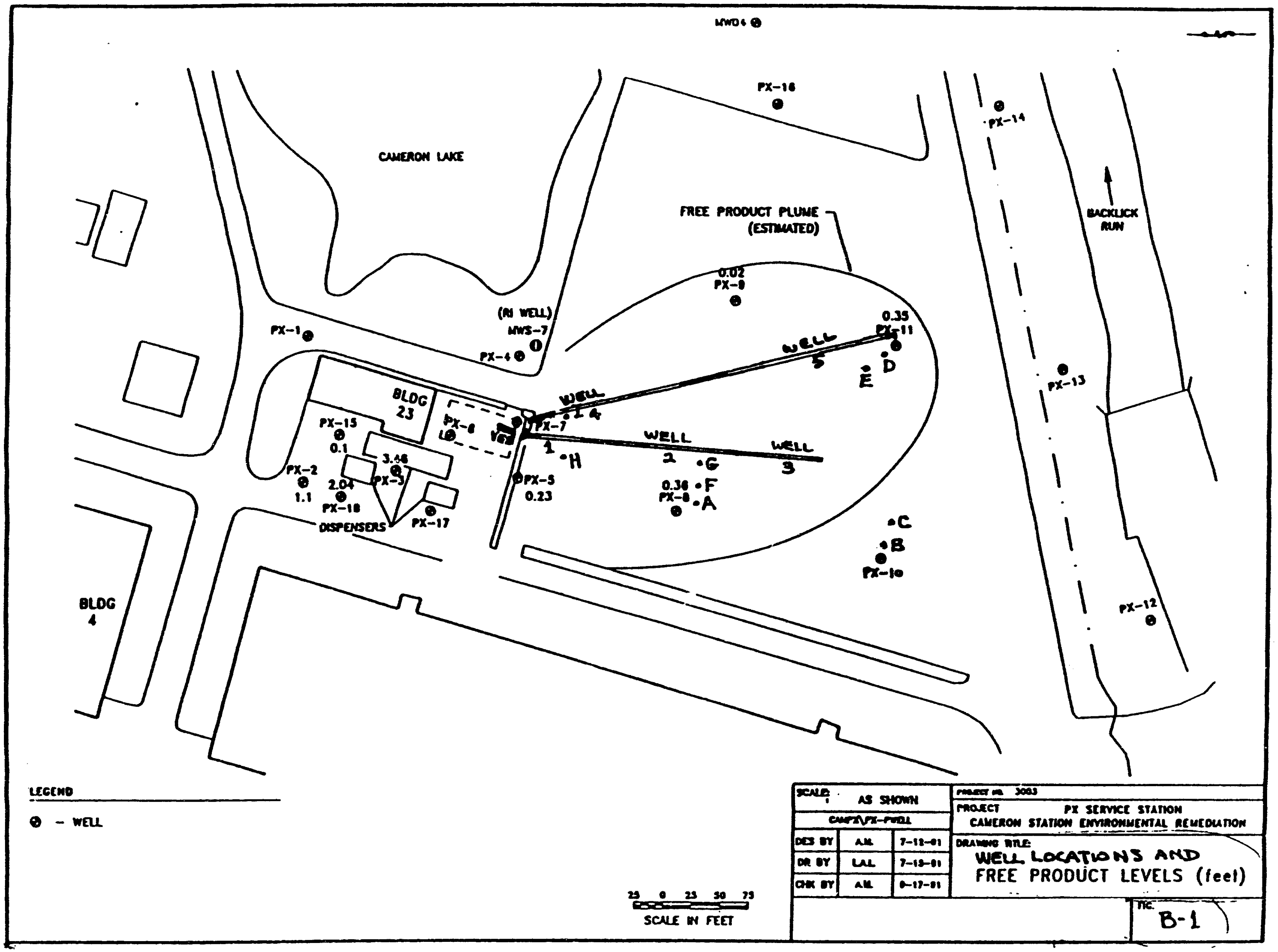


FIGURE B.1 Well Locations and Free Product Levels

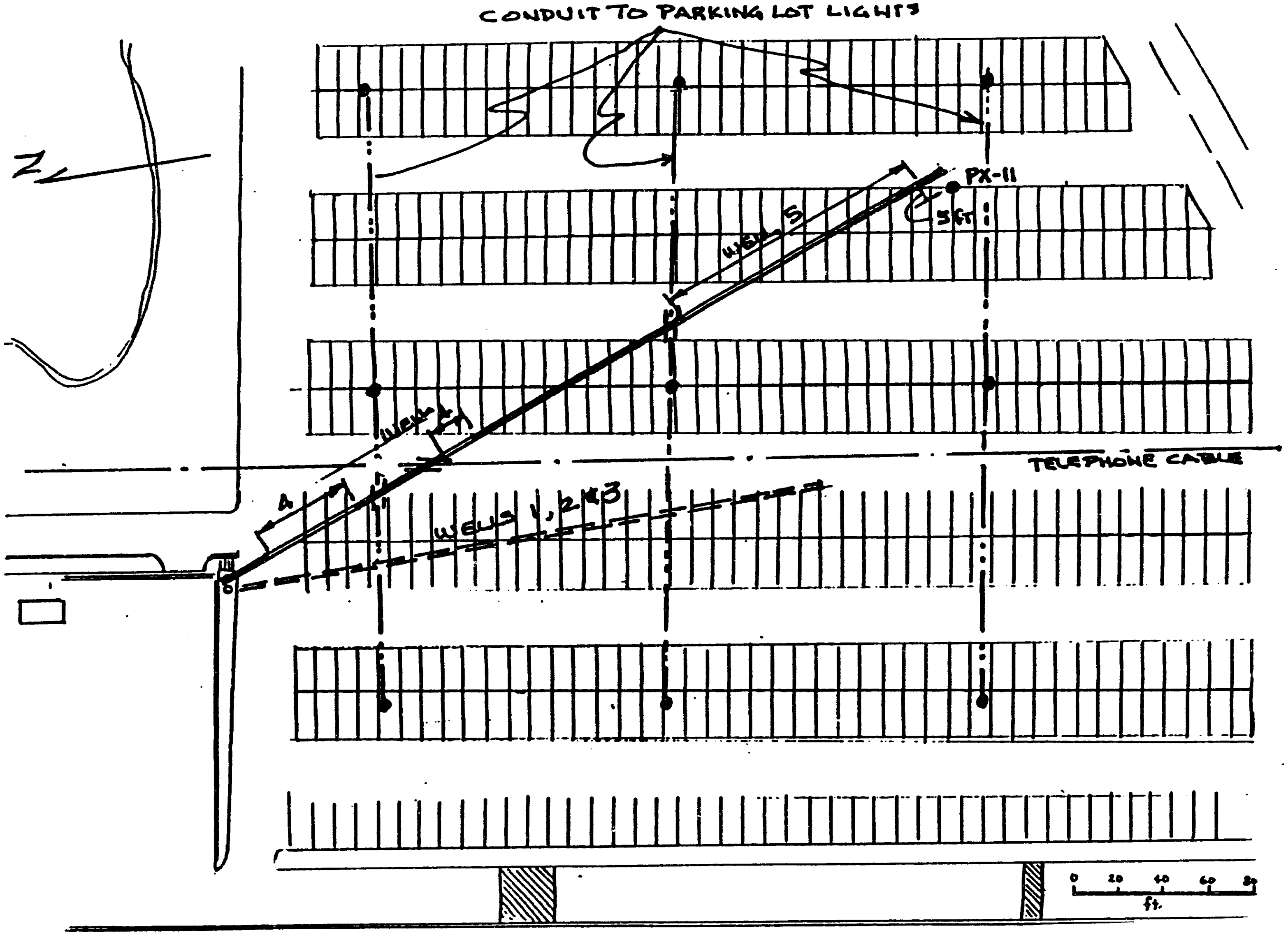


FIGURE B.2 As-Built Trench/Well Layout

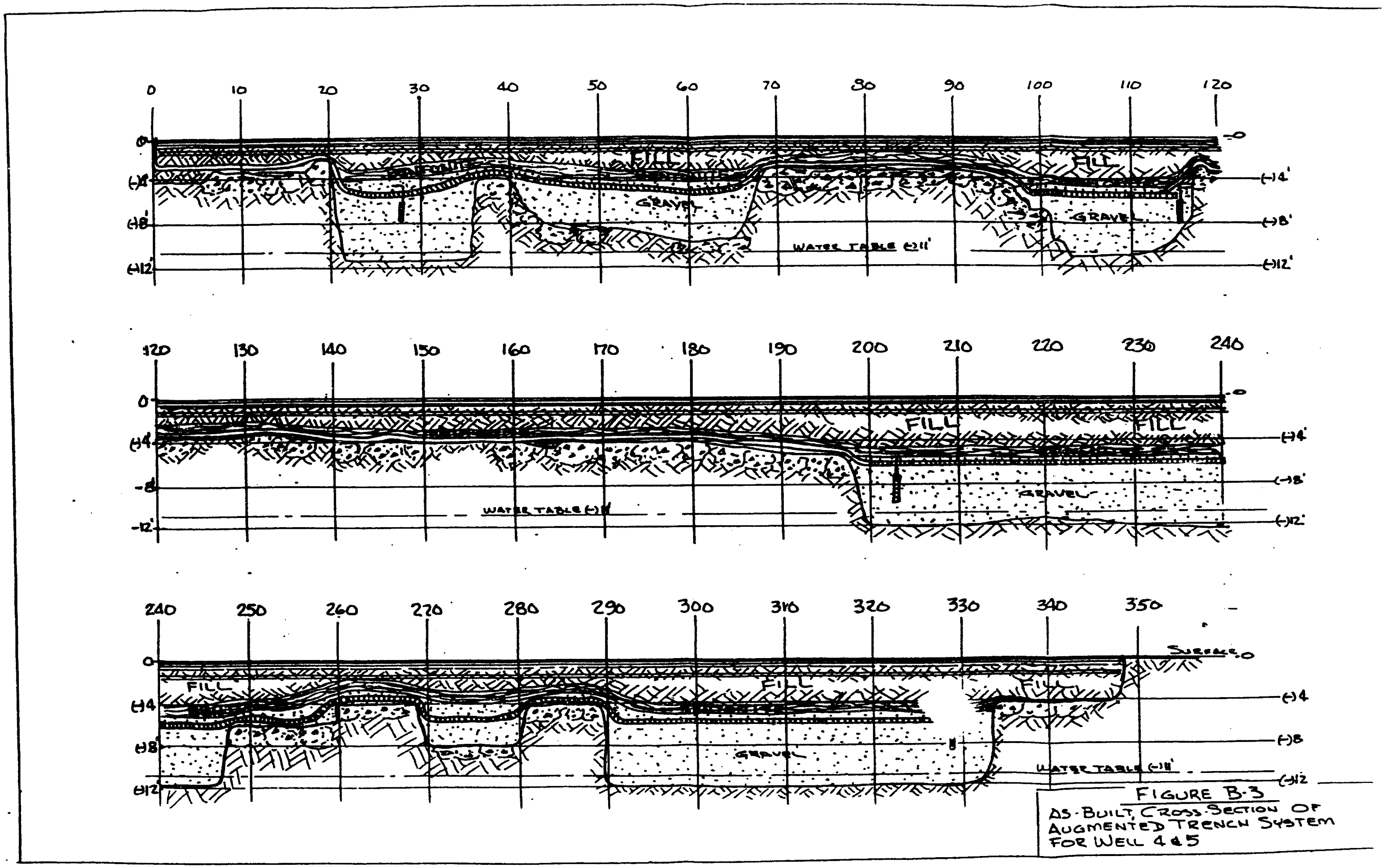


FIGURE B.3 As-Built Cross Section of Augmented Trench System for Wells 4 and 5

In addition to the unexpected concrete pieces, the excavation operation had to detour around the electrical conduits for the parking lot lights, which were only 6–8 in. below the surface. An AT&T main telephone fiber-optic trunk line and conduit that was about 2 ft below the surface, at the point where the second trench crossed it, also required special care. An AT&T representative was present and assisted in the hand-excavation of the telephone line. He also provided a concrete cover over the exposed fiber-optic plastic pipe conduit so that the conduit would not be damaged during the installation of the well and during subsequent backfilling operations. There was some damage to the electrical conduits to the parking lot lights. One conduit was hand-excavated with no damage, one conduit was severed during stripping of the asphalt pavement, and a third conduit was severed because its location had not been marked.

Once the pea gravel was graded to the –6-ft elevation, the preassembled 4-in. polyethylene flexible pipe was laid in place. The pipe consisted of solid flexible drain pipe (as conduit) and as flexible slotted drain pipe (as screen sections). Bentonite clay was placed around and under the solid pipe in the 4-ft-deep trench areas and graded to an elevation of –3 ft. Additional gravel was then placed over the slotted pipe screen in the active, deep trench areas and graded to an elevation of –5 ft. A double layer of 3-mm polyethylene sheet was then spread over the well gravel area to form a barrier between the gravel and the bentonite clay. Bentonite clay was then placed over the active well area to a depth of approximately 12 in. or an elevation of –3 to –4 ft. The bentonite covering prevented the infusion of air from above the wells. Such an infusion would interfere with vapor extraction from the lower elevations. The 4-ft-deep sections were also filled with 12 in. of bentonite clay and then backfilled with soil, excavated earlier from the trench, to 12 in. below the parking lot surface. This construction provided an impermeable seal around the conduits and between adjacent wells. This same type of construction was used in those areas where the buried concrete monoliths required the piping to be less than 4 ft below the surface of the parking lot.

Before covering, the bentonite was flooded with water and allowed to sit for several hours so it could absorb water and swell to a stable condition. While the clay was responding to the water, backfill was placed in the trench to a depth of 12 in. below the surface of the parking lot. Additional water was placed in the trench to help settle the soil and to further hydrate the bentonite.

Restoration of the parking lot surface consisted of a 4-in. course of pea gravel sub-base, a 4-in. deep continuous subsurface ribbon of concrete, and a 4-in.-deep layer of asphalt.

B.2 Description of the As-Built System

The slotted well pipe screen was positioned a nominal 6-ft below the surface of the parking lot. It ran parallel to the inclined surface of the lot and the water table.

As shown in Figure B.3, the bottom of the gravel-filled excavation was maintained at or near the surface of the water table. Thus, the pea gravel could be in direct contact with the groundwater table and the petroleum product in the zone above the water table. Each well, with a 1-ft-wide bottom and 6-ft-high walls, provided a large surface area for the diffusion/evacuation of product vapors into the gravel zone and, therefore, into the screen and piping of the evacuation system. Table B.1 lists the physical characteristics of the two wells and manifold B.

The well screen used in this installation was a standard, 4-in.-diameter, flexible and corrugated pipe, typically used for field drainage. The pipe is slotted with 1.25-in.-long by 1.25-in.-wide slots, spaced 60° apart in six rows. The open area for transmission of vapors/gases is approximately 2.01 in.^{2} per linear feet of corrugated drain pipe. The 55-ft-long well 4, therefore, has a total vent area of approximately 110.6 in.^{2}; the 130-ft long well 5 has a total vent area of approximately 261.4 in.^{2}. The cross-sectional flow area of this type of pipe is a nominal 12.6 in.^{2}. This type of flexible PVC pipe was used (instead of the rigid pipe used in the original trench/well installation) because, at the lower installation elevation, the problem of uneven transfer of loads from the surface of the parking lot surface was considered to be minimal. Caps were not placed on the end of the screened pipe sections since the ends were buried in gravel and were, therefore, not subject to plugging. The unplugged ends effectively increase the vent area by 12.6 in.^{2}.

Because of the variable soil conditions, the evacuation-well-zone screen configuration consisted of a series of solid duct and screen sections of varying lengths. As shown in Figure B.3, solid flexible pipe was used over the concrete obstructions, and slotted flexible pipe

TABLE B.1 Physical Characteristics of Wells Number 4 and 5 and Manifold B

Features	Well 4	Well 5	Manifold B
Radial distance from terminus (ft)			
Beginning of screen	23 (4A) 98 (4B)	200	NA
End of screen	57 (4A) 116 (4B)	331	348 (end of pipe)
Length of screen (ft)	52	131	NA
Pipe size	4 in. Flexible	4 in. Flexible	4 in. SCH 40
Screen slot width (in.)	0.080	0.080	solid
Screen flow area (ft^2)	7.22	18.19	none
Nominal depth of screen (elev; ft) (pipe in the case of manifold B)	-5 to -6	-4 to -6	-2
Well elevation (ft):			
Top of gravel	-4 to -5	-4 to -5	NA
Bottom of gravel	~-11	~-11	NA

was used wherever the trench below was deep enough to allow communication between the pipe and the loose fill material at or near the water table. In cases where the joints were subjected to stress, rubber couplings were used to clamp the slotted flexible pipe to the solid flexible pipe. All solid flexible pipe was 4-in.-diameter corrugated polyethylene drain pipe, with the exception of a 50-ft length of 3-in.-diameter pipe that had to be purchased locally.

The third pipe, designated as manifold B, was installed during the closure process. It consisted of a 4-in.-diameter, schedule 40 PVC solid, rigid-wall-pipe, running the length of the 347-ft-long trench. It was provided as a contingency for connection to future trenches that may be required to extend the horizontal evacuation system out into the parking lot, beyond the end of well 5. The third pipe (identified as well 6 in Figure B.4) was placed in the trench once the backfill was brought up to a uniform elevation. A uniform elevation is needed so the rigid pipe would not be over-stressed by irregularities in the contour of the base soils used for support. The pipe was positioned 15–24 in. below the gravel sub-base required under the pavement. This pipe has no means for intermediate connections along its length. Only a single, removable cap was placed at the far end of the pipe. The proximal end of manifold B, near the filling station, has an elbow and short vertical stub that extended up out of the trench. This pipe is terminated with a temporary cap.

As shown in Figure B.5, the proximal terminus of the underground piping system was located within 2 ft of the edge of the concrete apron surrounding the filling station. Rigid elbows were used to connect the horizontal pipe to vertical headers. These headers terminated approximately 12 in. above the concrete apron. When the experiment is completed, the flexible connectors used to attach the headers to the aboveground manifolding will be removed, the headers capped, and the pipe stubs left in place. The pipe stubs are located sufficiently close to the concrete apron so there are no hazards or inconveniences to personnel walking or working in the area. The spacing of the vertical headers and the horizontal pipe is a nominal 12.0 in. on center. The location of each well's respective header is shown on Figure B.5. Like the horizontal pipe ducts, the vertical headers were packed around with bentonite clay and backfill soil.

B.3 External Manifolding and Measurement Devices

The aboveground manifolding that connects the headers to the V4 SVE unit consists of 4-in.-diameter, schedule 40 PVC pipe, elbows, tees, and flexible couplings. Each line contains a ball-valve for isolation from the 2-in.-diameter main that connects to the V4, SVE vapor-destruction unit. (The existing V2B vapor extraction unit will continue to be used for evacuation of product from vertical wells PX-4, PX-5, PX-6, and MWS-7 [see Figure B.1]). Within the 2-in.-diameter main that connects to the V4 unit, there is a removable section containing a pressure sensor, a Venturi flow tube, and a thermometer. Data collected from these instruments permit determination of the mass flow rate of gas being sucked out of a given well (well 4 and 5 or, eventually, well 6).

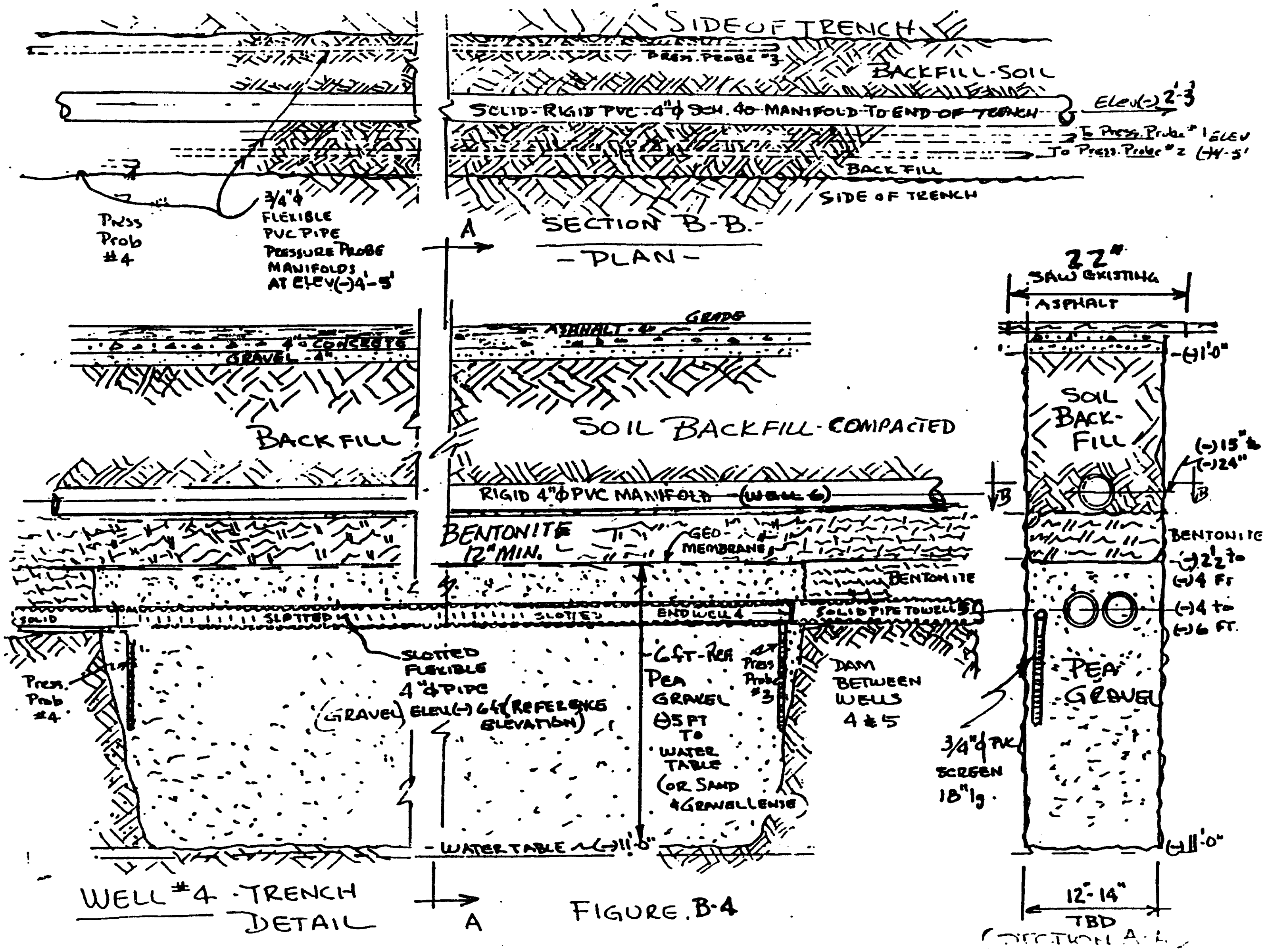


FIGURE B.4 Well 4 — Trench Detail

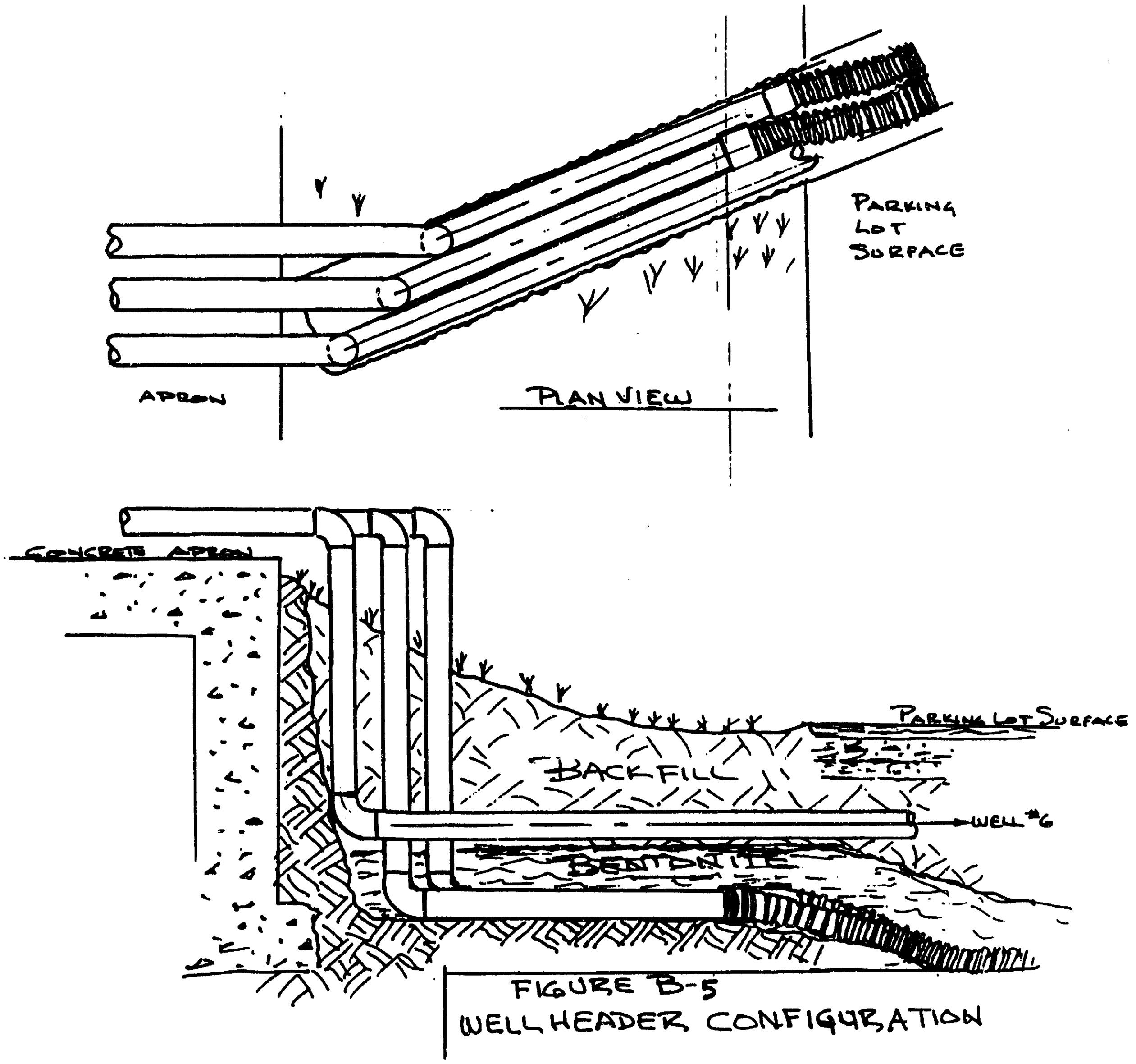


FIGURE B.5 Well Header Configuration

B.4 Physical Characteristics and Material List for Wells 4 and 5 and Manifold B

Table B.1 lists the physical characteristics of wells 4 and 5 and manifold B.

A list of the materials used in construction of the piping and manifolding for the second trench containing wells 4 and 5 and the solid, rigid, 4-in.-diameter PVC pipe duct (manifold B) can be obtained from Argonne National Laboratory (Audrey Arns, 708-252-7861).

Appendix C:

Size Gradation Curves for Fill Samples

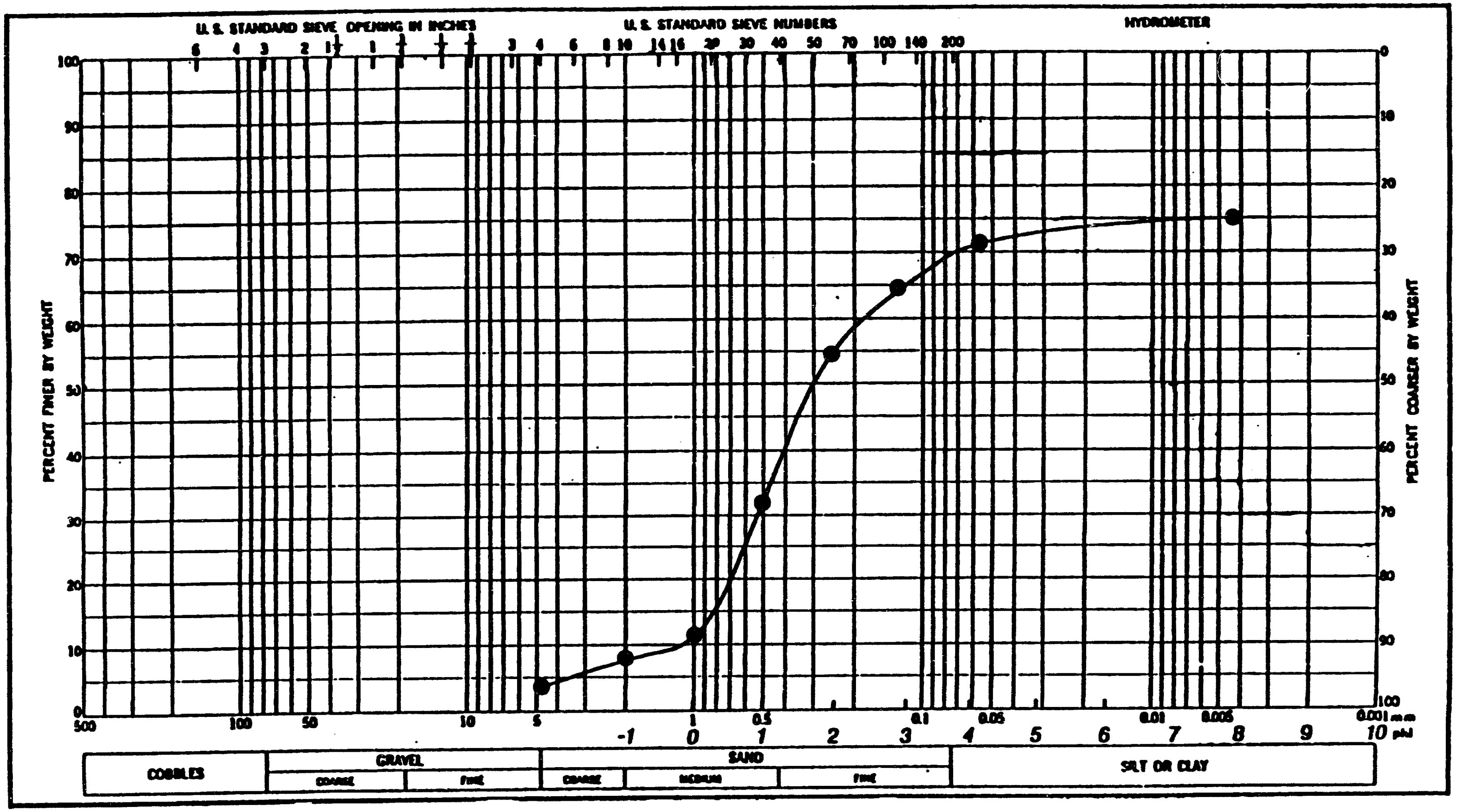


FIGURE C.1 Gradation Curve — Cameron Station, Sample CA-12, Argonne National Laboratory

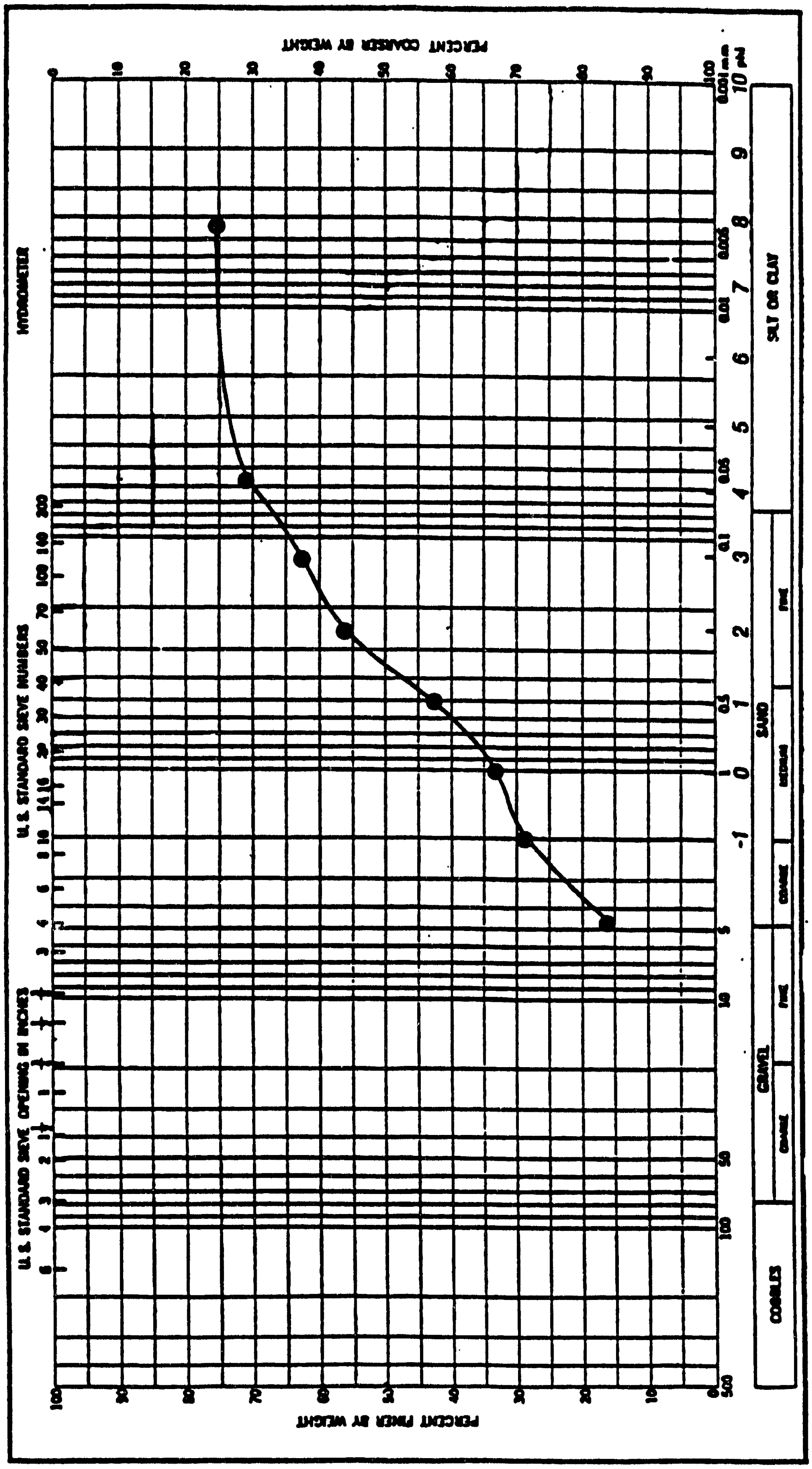


FIGURE C.2 Gradation Curve — Cameron Station, Sample CA-25, Argonne National Laboratory

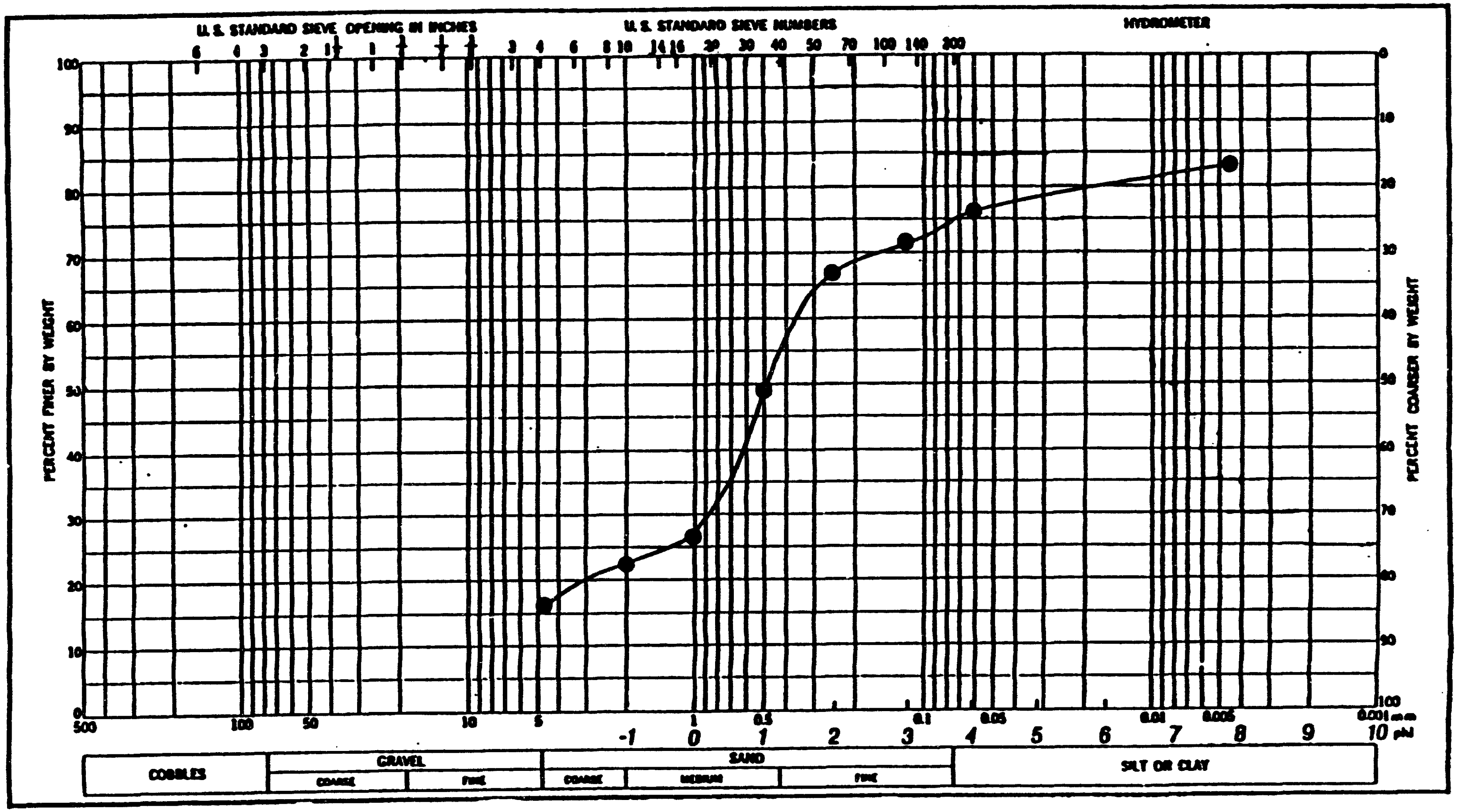


FIGURE C.3 Gradation Curve — Cameron Station, Sample CA-50, Argonne National Laboratory

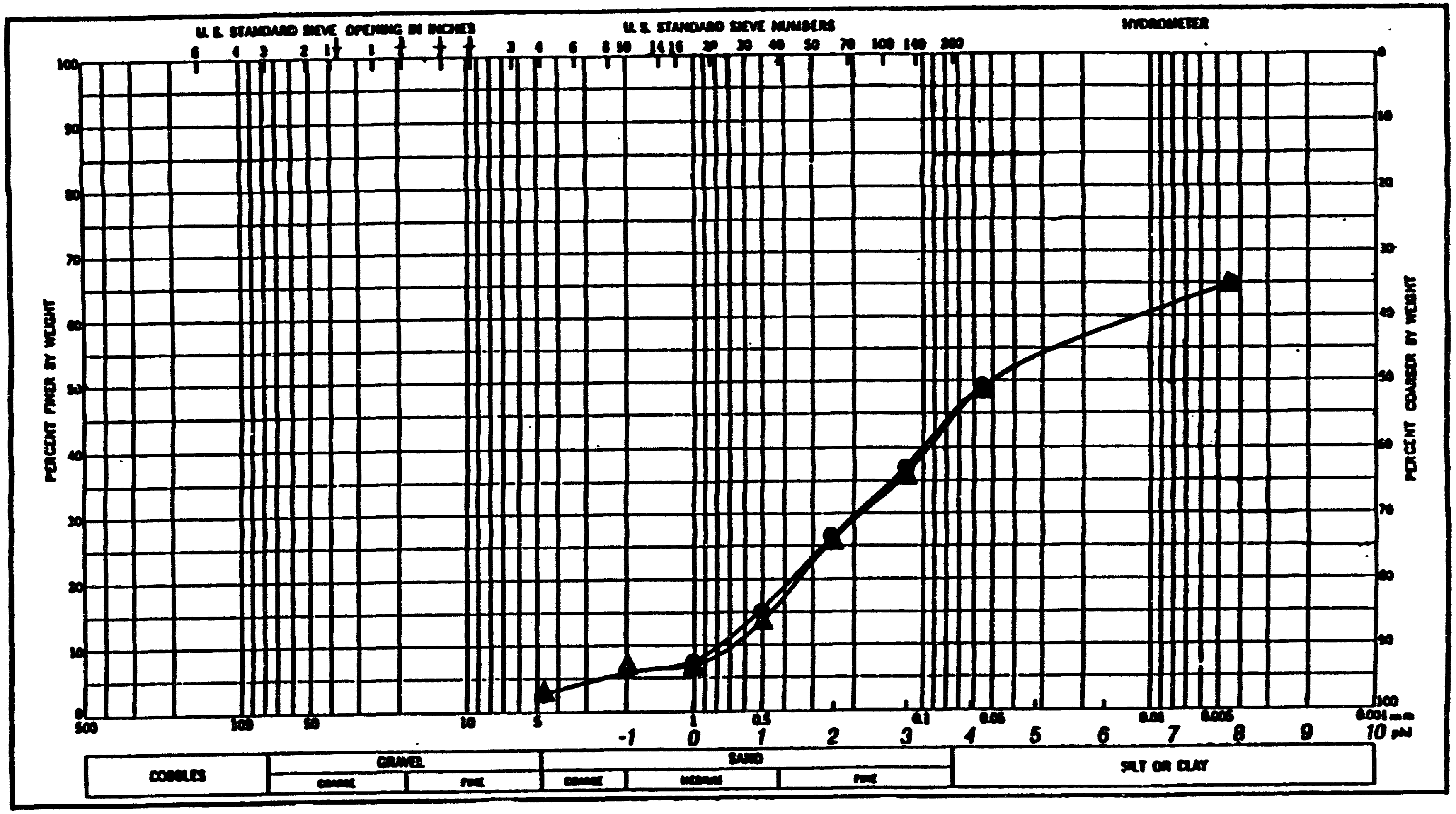


FIGURE C.4 Gradation Curve — Cameron Station, Sample CA-75A&B, Argonne National Laboratory

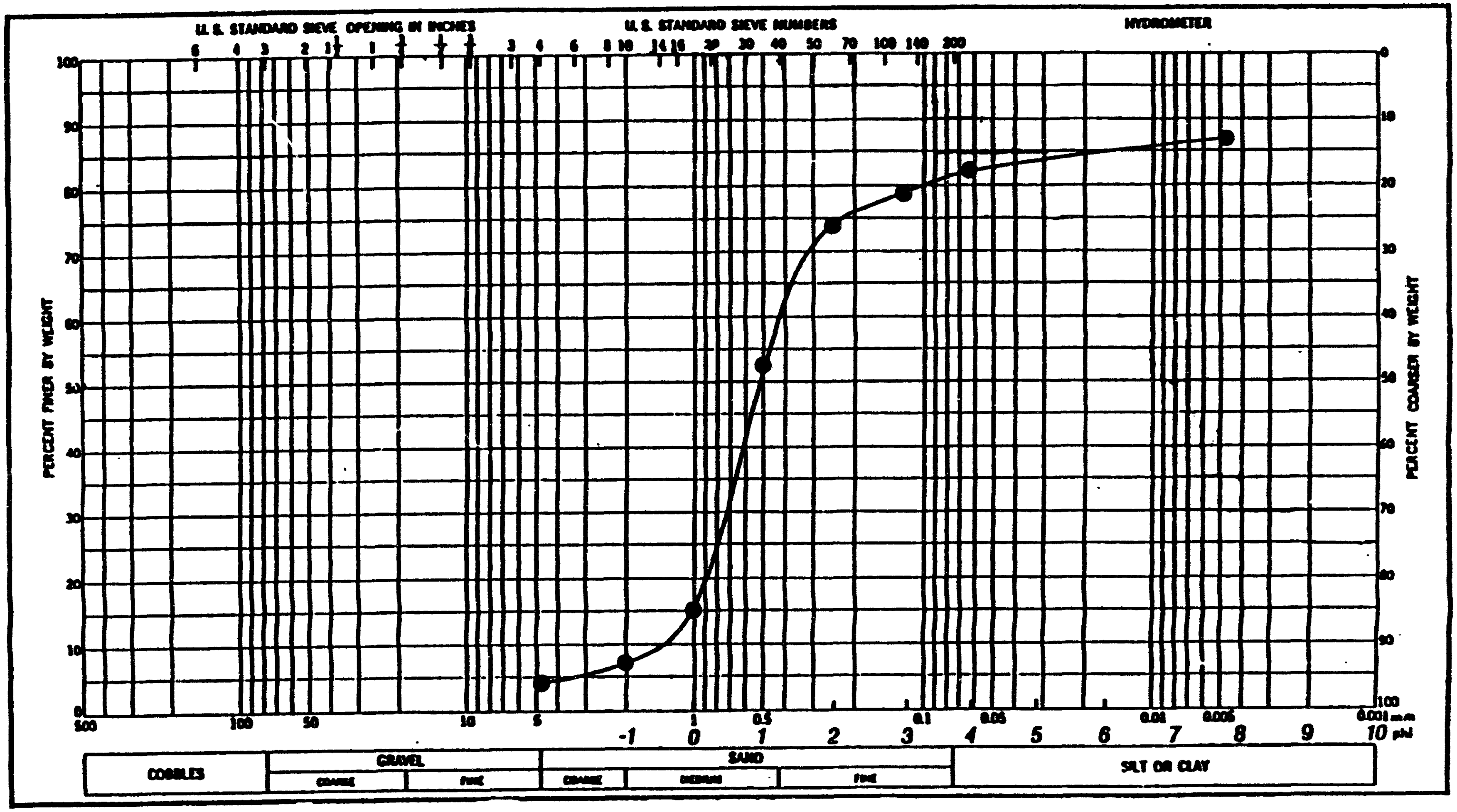


FIGURE C.5 Gradation Curve — Cameron Station, Sample CA-100, Argonne National Laboratory

)

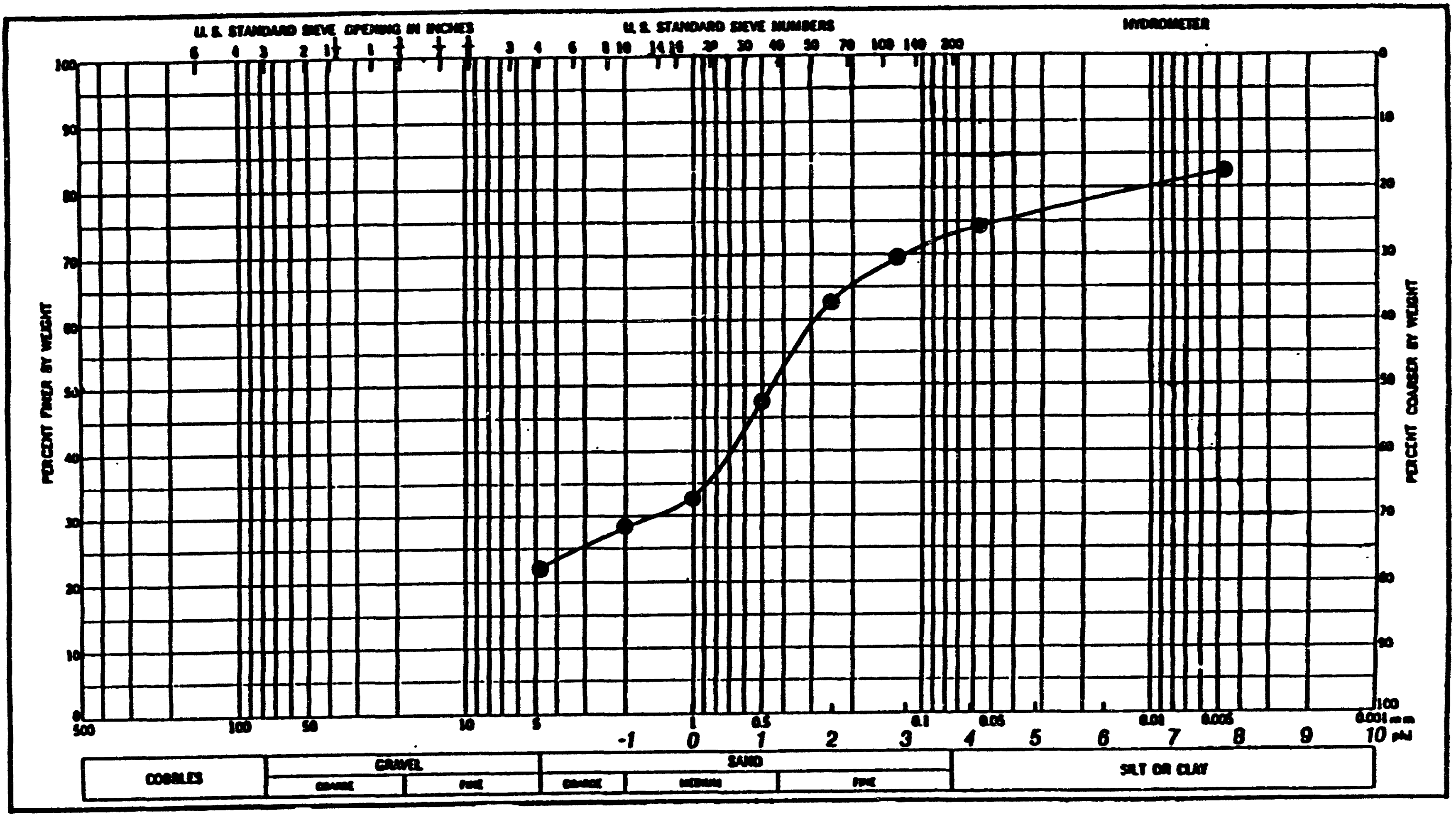


FIGURE C.6 Gradation Curve — Cameron Station, Sample CA-125, Argonne National Laboratory

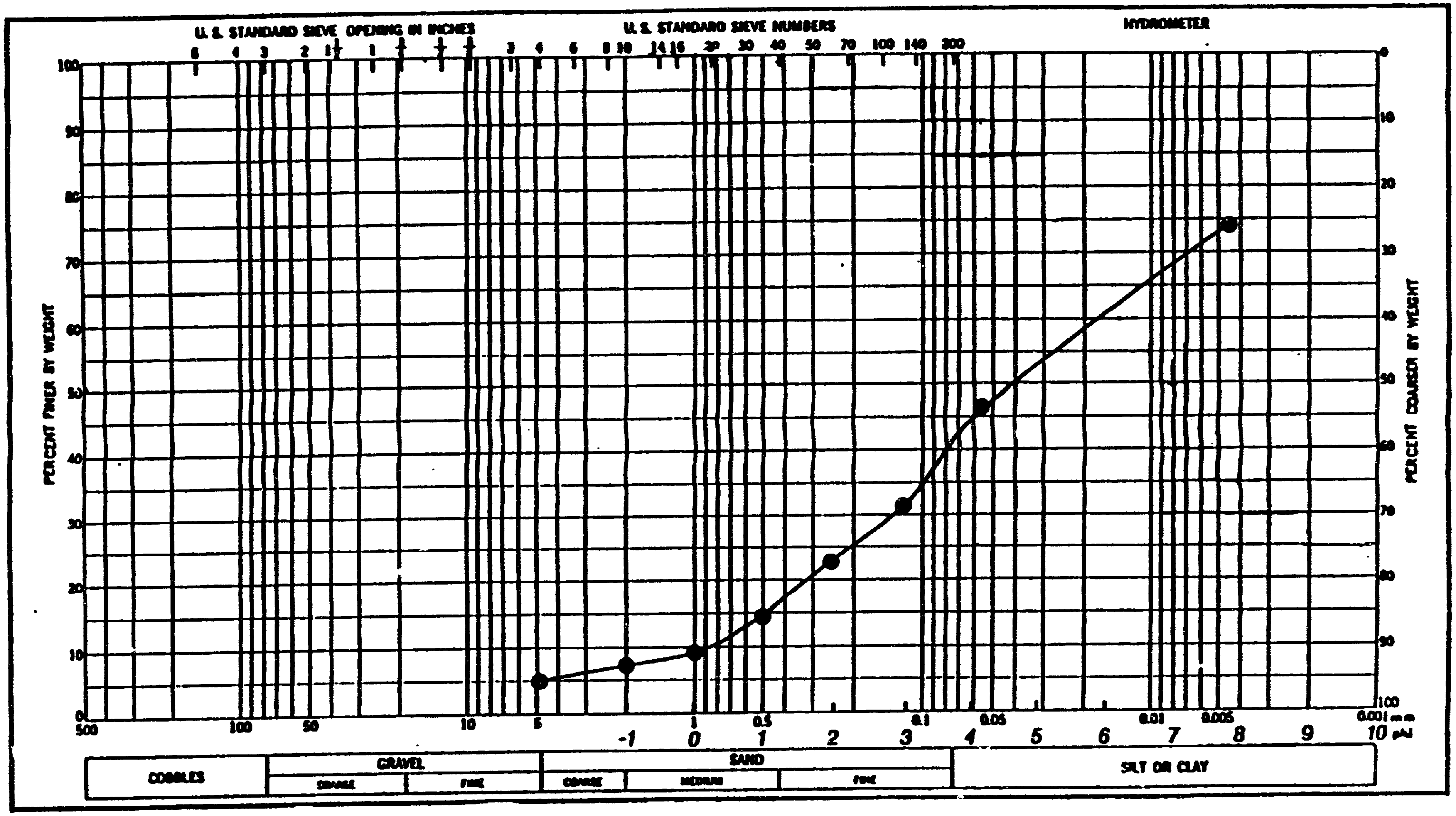


FIGURE C.7 Gradation Curve — Cameron Station, Sample CA-140, Argonne National Laboratory

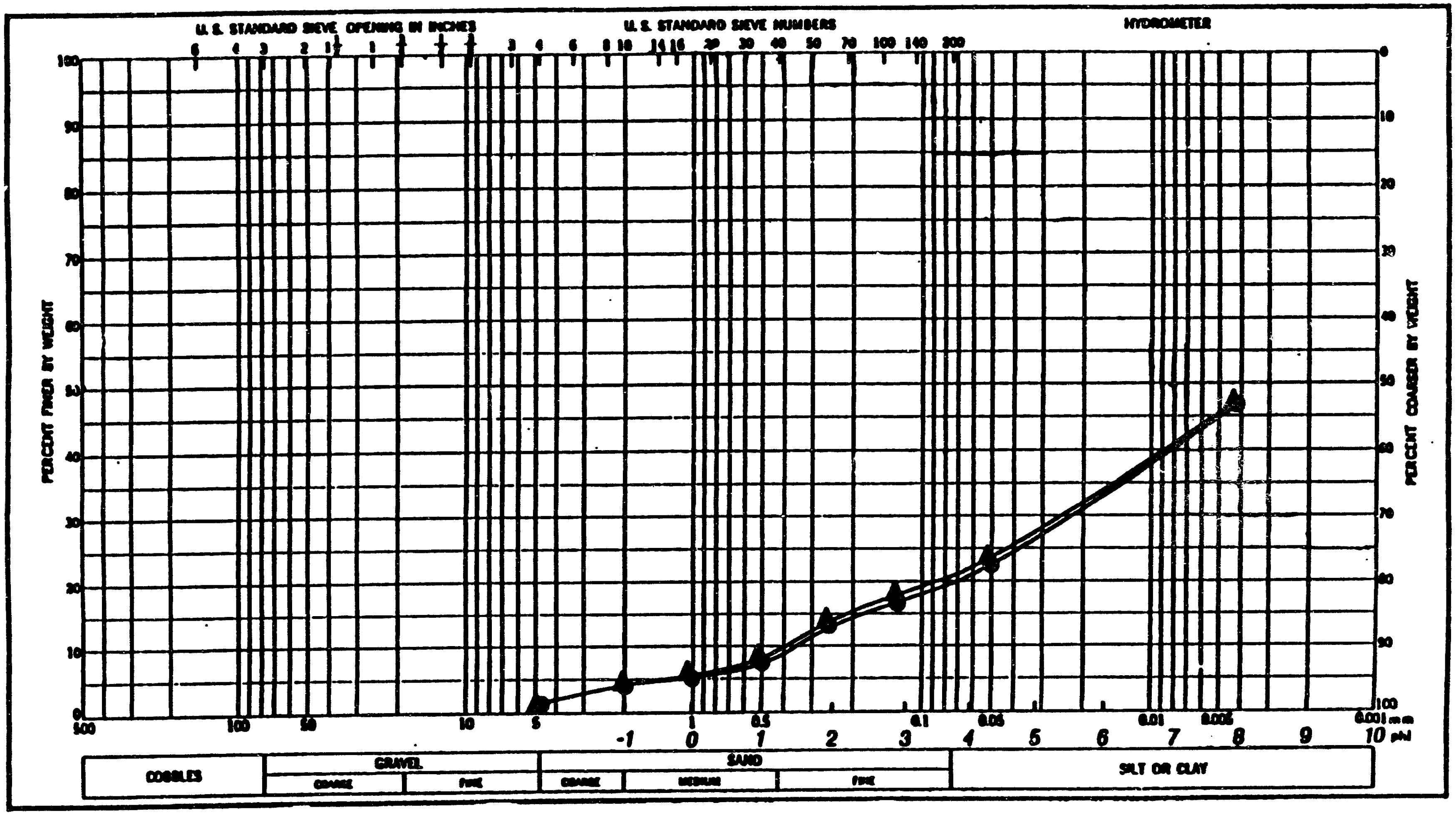


FIGURE C.8 Gradation Curve — Cameron Station, Sample CA-160A&B, Argonne National Laboratory

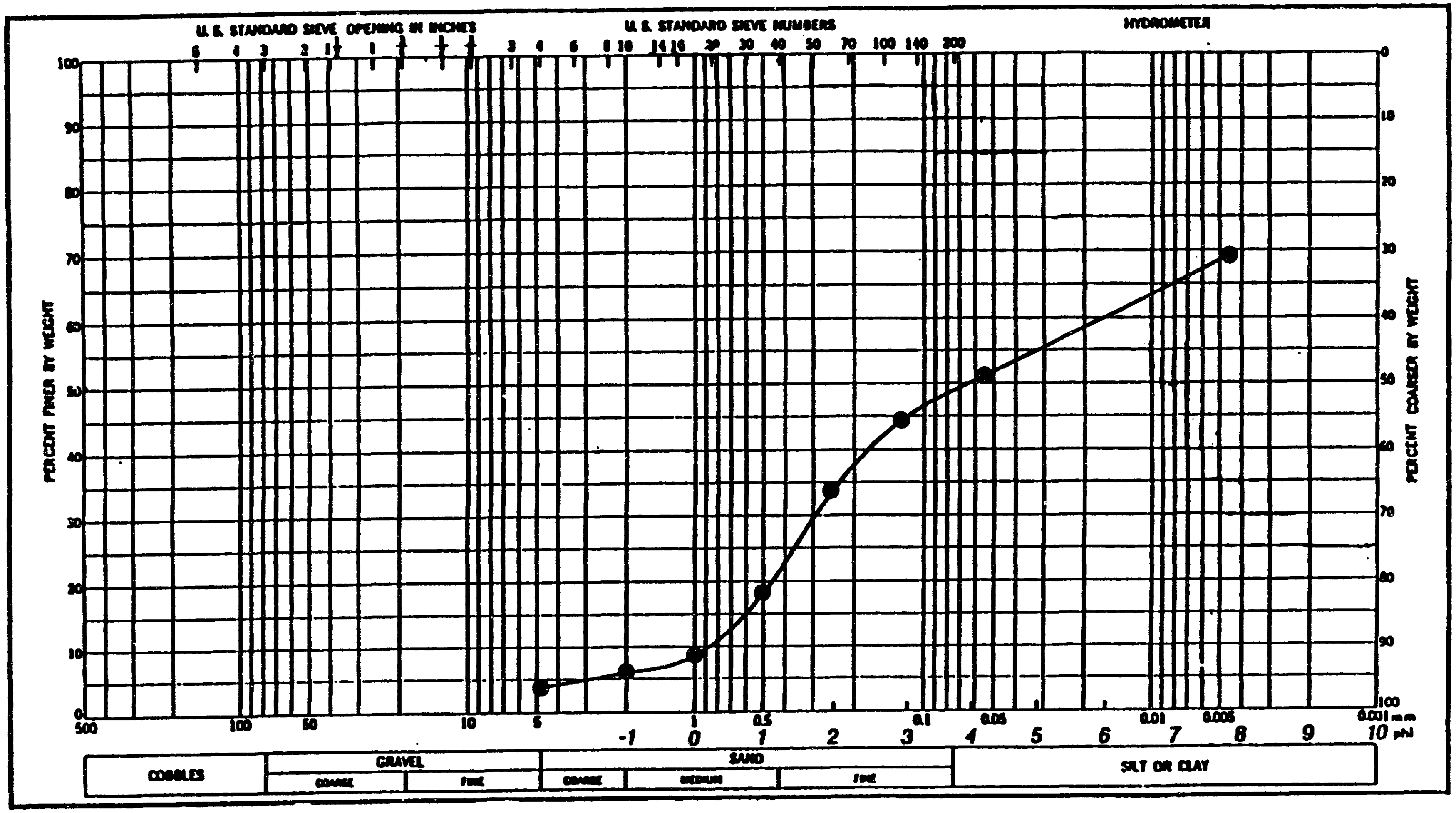


FIGURE C.9 Gradation Curve — Cameron Station, Sample CA-205, Argonne National Laboratory

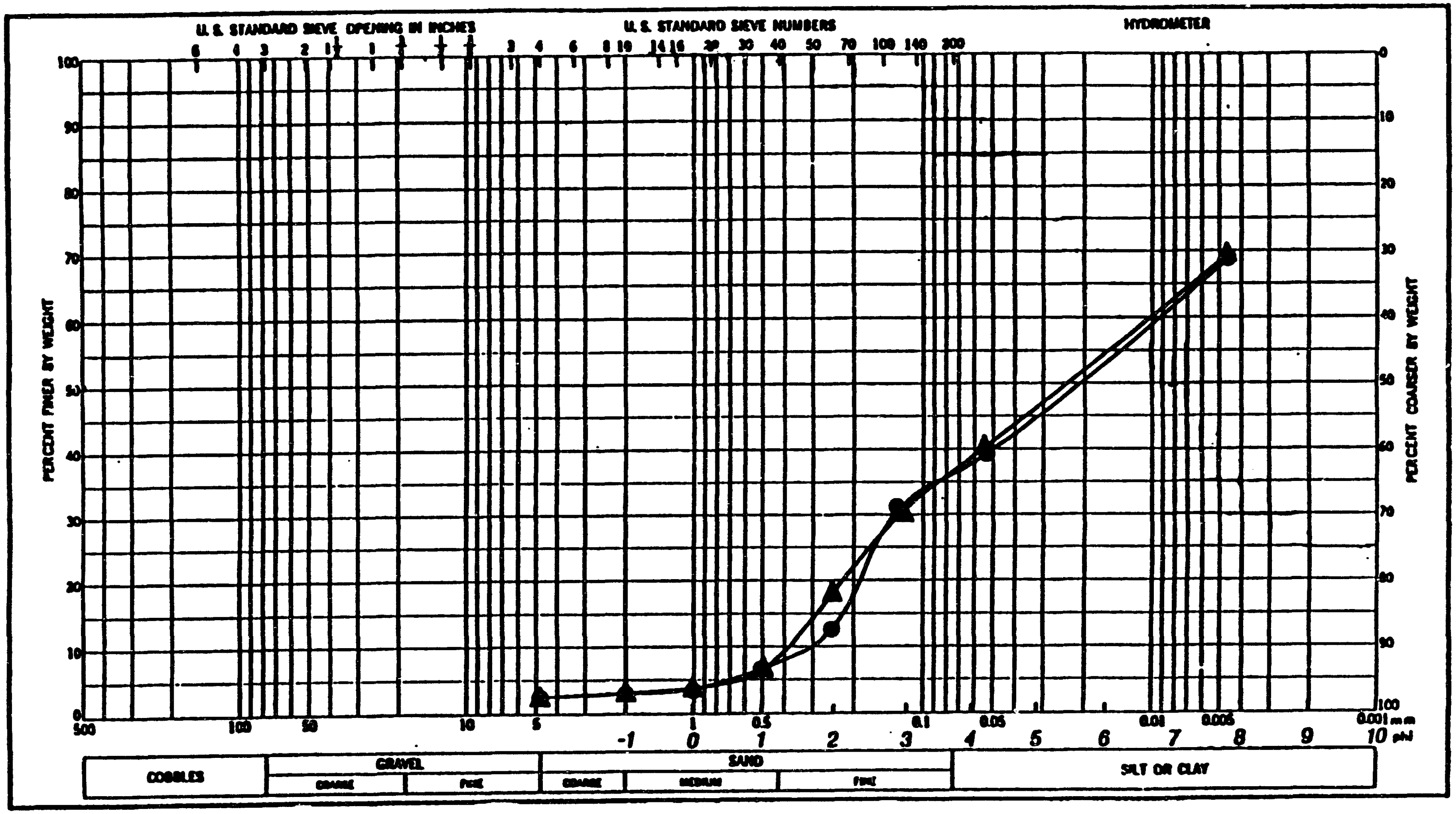


FIGURE C.10 Gradation Curve — Cameron Station, Sample CA-225A&B, Argonne National Laboratory

Appendix D:

Database for Laboratory Samples

TABLE D.1 Database for Laboratory Samples

Linear Distance (ft)	Depth (ft)	APB* (cells/g)	Aerobe (cells/g)	Anaerobe (cells/g)	NH_3-N (µg/g)	Product Vapor (ppm)	Low Range Formic Acid (ppm)	High Range Formic Acid (ppm)	Chloride (ppm)	Sulfate (ppm)
13.000	-6.000	10.166	10.166	10.166	5.500	244.000	7.810	15.630	28.910	1.750
25.000	-8.000	7.937	10.240	10.240	4.000	5.300	8.450	16.900	29.490	7.920
50.000	-5.000	12.429	14.732	10.127	5.000	260.000	7.650	15.310	9.820	2.580
75.000	-8.000	15.363	15.363	15.363	16.000	306.000	14.290	28.570	21.570	7.860
100.000	-9.000	10.597	15.202	10.597	10.000	629.000	12.190	24.390	15.200	2.520
123.000	-7.000	10.597	10.597	10.597	7.000	465.000	12.050	24.090	59.520	2.850
140.000	-8.000	10.692	8.389	10.692	29.000	419.000	13.390	26.780	21.470	2.900
160.000	-8.000	6.469	6.477	11.082	27.000	286.000	19.480	38.960	36.100	5.130
205.000	-8.000	10.240	14.845	14.845	32.000	5.300	8.450	16.900	99.350	6.110
225.000	-8.000	9.999	14.604	15.790	15.000	0.000	6.560	13.130	199.930	4.130

Linear Distance (ft)	TPH** (ppm)	Toluene (ppm)	Ethyl Benzene (ppm)	Xylene (ppm)	K (ppm)	Ca (ppm)	Pb (ppm)	Fe (ppm)	Mn (ppm)
13.000	ND	0.084	0.028	0.180	17932.400	2989.470	14.249	25868.790	33.970
25.000	26.000	ND	ND	ND	9609.980	1182.880	2.955	28553.520	23.240
50.000	ND	0.580	0.690	7.700	17006.350	1345.320	21.285	28992.300	129.700
75.000	180.000	ND	ND	ND	12570.770	1825.470	12.661	44741.060	819.850
100.000	ND	0.180	0.081	0.750	18546.370	1121.440	10.771	17469.970	50.043
123.000	320.000	ND	ND	ND	16111.530	1794.380	28.183	30450.460	201.335
140.000	ND	53.000	57.000	480.000	16963.330	2501.700	19.041	50868.230	104.560
160.000	27.000	ND	ND	ND	15614.150	2537.890	21.810	49533.340	199.150
205.000	ND	0.002	0.004	0.004	12814.890	2176.550	15.049	37905.140	940.480
225.000	0.000	ND	ND	ND	12642.110	2065.460	19.232	36087.242	1270.177

* APB - Acid-Producing Bacteria.

** TPH - Total Petroleum Hydrocarbon.

Appendix E:

Description of the Degradation of Straight-Chain and Cyclic Petroleum Products

Appendix E:

Description of the Degradation of Straight-Chain and Cyclic Petroleum Products

Section 4.2.3.3 contains a brief contrast/comparison of the aerobic and anaerobic degradation of straight-chained and cyclic hydrocarbons. Many of these activities are performed aerobically by *Pseudomonas sp.* and other aerobes. The anaerobes that perform these degradations often require a specific community composition.

E.1 Degradation of Straight-Chain Hydrocarbons

The anaerobic degradation of straight-chain hydrocarbons has been demonstrated, but it is poorly defined. The aerobic breakdown of long-chained alkanes occurs via a terminal oxidation, whereby the alkane is converted into the corresponding (nonhydrocarbon) alcohol, aldehyde, and finally the monocarboxylic acid.[1] The monocarboxylic acid would be converted, carbon-by-carbon, to acetyl coenzyme A. This coenzyme is an important intermediate in carbon metabolism in bacteria because it is a convenient way to shuttle single carbon structures needed in biosynthesis. One possible fate of acetyl coenzyme A is carbon dioxide gas.

Degradation can also occur from both ends of the alkane, resulting in the production of dicarboxylic acids. However, the end products of this particular degradation are acetate and succinate.[1] Again, these end products could be rapidly utilized by a variety of bacteria. This latter pathway is significant because the organisms in a soil environment are in the presence of organic acids and may be primed for acetate metabolism. In addition, conversion of hydrocarbon fractions (octane, nonane, decane, etc.), beyond chain-length reduction, could result in the increase in the nonhydrocarbon components. These nonhydrocarbon fractions would then serve as nutrients needed to maintain the viability of the community. The end result would be a decrease in the hydrocarbon fractions, followed by an eventual decrease in the nonhydrocarbon fraction in the local environment.

E.2 Degradation of Aromatic Compounds

Biodegradation of aromatic compounds has generally been regarded to be an aerobic process. However, studies performed on the steps in the degradation of chlorinated and fluorinated aromatics have determined that degradation of the aromatic rings can occur once the compound is dehalogenated. In all cases, anaerobic degradative processes tend to be slower than the aerobic counterpart. However, ring cleavage can occur. The anaerobic and aerobic mechanisms appear to be very similar. For example, the degradation of *p*-cresol proceeds through an alcohol, aldehyde, and carboxylic acid step. The final step is the formation of benzoate, which is then degraded to carbon dioxide.[2] Other alkylated benzenes were shown to have anaerobic degradative pathways that shared steps described for the aerobic degradation.[3] (See Figure E.1.) However, describing a mechanism for the first-step formation of the alcohol, where the methyl group is hydroxylated in the absence of molecular oxygen and an oxygenase, has been elusive. Therefore, the results have been described, but the mechanism has not been defined.

E.3 Composition of the Microbial Community

Kobayashi and Rittman[4] described the community necessary for the anaerobic decomposition of organic matter to carbon dioxide and methane. The community should contain the components listed below.

1. Hydrolytic bacteria, such as the clostridia, that decompose the major complex components of biomass (e.g., saccharides, proteins, and lipids).

2. Hydrogen-producing APB that break down the products of the above group into organic acids and neutral products (alcohols and diols).

3. Homoacetogenic bacteria that break down multicarbon compounds into acetic acid.

4. Methanogenic bacteria.

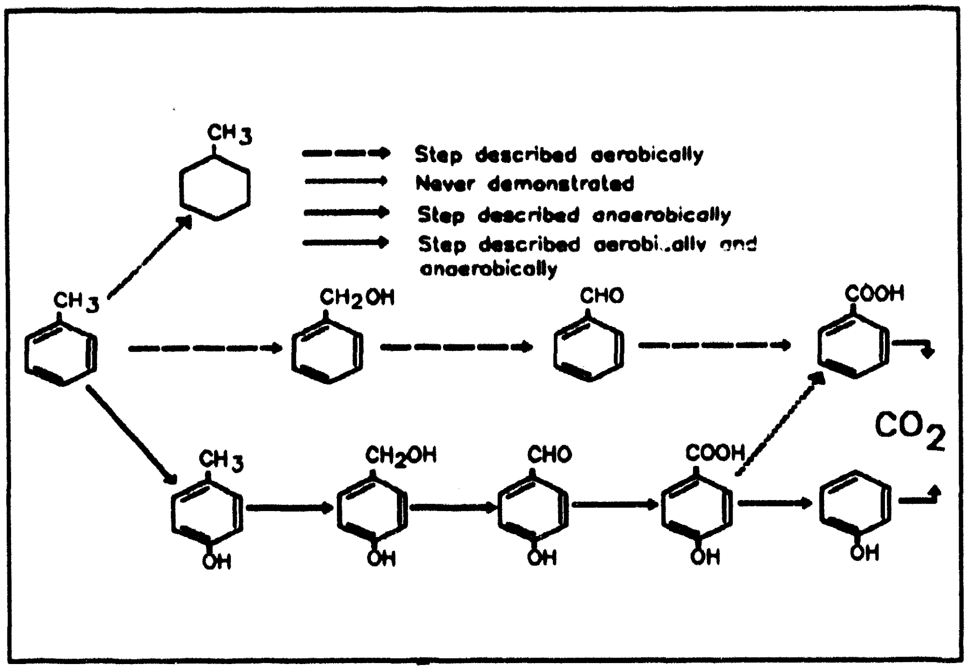


FIGURE E.1 Proposed Pathways for the Degradation of Toluene

E.4 References

1. Crueger, W., and A. Crueger, 1982, Chapter 16, Section 16.2, *Biotechnology*, Sinauer Associates, Inc., Sunderland, Md., pp. 268–269.

2. Smolenski, W.J., and J.M. Suflita, 1987, *Biodegradation of Cresol Isomers in Anoxic Aquifers*, Applied and Environmental Microbiology *53*:710-716.

3. Kuhn, E.P., et al., 1988, *Anaerobic Degradation of Alkylated Benzenes in Denitrifying Laboratory Aquifer Columns*, Applied and Environmental Microbiology *54*:490-496.

4. Kobayashi, H., and B.F. Rittman, 1982, *Microbial Removal of Hazardous Organic Compounds*, Environmental Science and Technology *16*:170A-183A.

Appendix F:

Basic Data for Groundwater Monitoring Wells, Individual Probes, Probe Clusters, and Flow-Enhancement Borings Installed by Argonne at Cameron Station

Appendix F: Basic Data for Groundwater Monitoring Wells, Individual Probes, Probe Clusters, and Flow-Enhancement Borings Installed at Cameron Station

Groundwater Monitoring Well (PX, MWS), Probe (A-D), Probe Cluster (E-M), or Boring (B)	Map Grid Coordinates		Individual Probe in Cluster	Z Depth Below Asphalt/ Ground Surface		Inside Diameter of PVC* Well or Probe Pipe (in.)	Diameter of Boring (in.)
	X	Y		Top of Screen (in.)	Bottom of Screen (in.)		
PX-4	75	250	—	62.0	237.2	3.998	8.25
PX-5	53	140	—	63.1	238.3	3.998	8.25
PX-6	0	190	—	63.2	238.4	3.998	8.25
PX-8	186	81	—	64.2	239.4	3.998	8.25
PX-9	284	256	—	64.4	239.6	3.998	8.25
PX-10	353	0	—	64.3	239.5	3.998	8.25
PX-11	419	181	—	59.9	235.1	3.998	12.0
MWS-7	101	247	—	108.5	252.0	2.049	8.25
A	205	84	—	72.0	96.0	0.608	6.25
B	358	8	—	72.0	96.0	0.608	6.25
C	364	18	—	48.0	72.0	0.608	6.25
D	409	179	—	72.0	96.0	0.608	6.25
E	389	177	—	72.0	96.0	0.608	8.25
F	202	100	F1	12.0	36.0	0.810	8.25
			F2	60.0	84.0	0.810	8.25
			F3	120.0	180.0	1.033	8.25
G	209	119	G1	12.0	36.0	0.810	8.25
			G2	60.0	84.0	0.810	8.25
			G3	120.0	180.0	1.033	8.25
H	98	156	H1	12.0	36.0	0.810	8.25
			H2	60.0	84.0	0.810	8.25
			H3	120.0	180.0	1.033	8.25
I	109	185	I1	12.0	36.0	0.810	8.25
			I2	60.0	84.0	0.810	8.25
			I3	120.0	180.0	1.033	8.25

Groundwater Monitoring Well (PX, MWS), Probe (A-D), Probe Cluster (E-M), or Boring (B)	Map Grid Coordinates		Individual Probe in Cluster	Z Depth Below Asphalt/ Ground Surface		Inside Diameter of PVC* Well or Probe Pipe (in.)	Diameter of Boring (in.)
	X	Y		Top of Screen (in.)	Bottom of Screen (in.)		
J	173	157	J1	12.0	36.0	0.608	8.25
			J2	60.0	84.0	0.608	8.25
			J3	120.0	180.0	2.049	8.25
K	174	177	K1	12.0	36.0	0.608	8.25
			K2	60.0	84.0	0.608	8.25
			K3	120.0	180.0	2.049	8.25
L	352	157	L1	12.0	36.0	0.608	8.25
			L2	60.0	84.0	0.608	8.25
			L3	120.0	180.0	2.049	8.25
M	351	177	M1	12.0	36.0	0.608	8.25
			M2	60.0	84.0	0.608	8.25
			M3	120.0	180.0	2.049	8.25
N	100	188	—	80.4	97.2	0.608**	T≠
O	189	187	—	69.0	85.8	0.608**	T
P	274	187	—	52.2	69.0	0.608**	T
Q	401	187	—	54.0	70.8	0.608**	T
				Pea Gravel Plug			
			—	Top	Bottom		
B1	187	142	—	72.0	156.0	—	8.0
B2	205	135	—	72.0	156.0	—	8.0
B3	225	127	—	72.0	156.0	—	8.0
B4	244	120	—	72.0	156.0	—	8.0

* Schedule 40.

≠ Trench installation (near top of pea gravel column, trench 18 in. wide).

** Flexible pipe to fence reading point is 0.810 in. dia., with 0.608-in. dia. couplings.

Appendix G:

Results of April 5–8, 1993, Field Tests

TABLE G.1 Vapor Flow and Vapor Property Measurements for Vapor Extracted by V4 on April 5, 1993

	Time		Temperature (°F)		Vacuum (in. water)					Concentration (%)	
						Trench 1 Probes					
Well	Turn On	Measurement	Ambient Air	Inside Pipe	Masthead	N	O	P	Q	Carbon Dioxide	Oxygen
1	15:23	15:31–15:38	48	50	10-15	-	-	-	-	0.05	20.6
2	15:41	15:47–15:55	48	49	12	-	-	-	-	0.05	20.7
3	-	16:13–16:18	48	49	-	-	-	-	-	0.05	20.6
4	-	16:20–16:30	48.3	48	15-20	0.50	0.25	-	-	-	-
5	-	16:38–	49.0	47.4	44-48	0.00	0.00	0.05	0.00	0.05	20.6

TABLE G.2 Results of Test Run 1, Pumping on Probe A and Monitoring Vacuums on Intermediate and Deep Probes at Probe Clusters F and G (see Figure 1.2) on April 6, 1993

	Vacuum (in. water)				Probe A		
	Probe G		Probe F				
Time (min)	Intermediate	Deep	Intermediate	Deep	Temperature (°F)	Vacuum (in. water)	Flow[a] (L/min)
0.17	0.00	0.00	0.00	+0.02	55	60.0	31.5
0.33	0.00	0.00	-0.07	+0.02	-	-	-
0.66	0.00	0.00	-0.05	+0.02	-	-	-
0.83	0.00	0.00	-0.03	+0.02	-	-	-
1.00	0.00	0.00	-0.01	+0.02	-	-	-
1.16	-	-	-	-	-	-	-
1.33	-0.20	0.00	+0.13	+0.02	-	-	-
1.50	-0.20	0.00	+0.12	+0.02	-	-	-
1.67	-0.20	0.00	+0.13	+0.02	-	-	-
1.83	-0.20	0.00	+0.13	+0.02	-	-	-
2.00	-0.20	0.00	+0.13	+0.02	-	-	-
2.50	-0.20	0.00	-	-	-	-	-
3.00	-0.28	0.00	+0.15	0.00	54	61.0	31.5
3.50	-0.28	+0.15	+0.19	0.00	-	-	
4.00	-0.35	+0.16	+0.19	0.00	54	62.5	31.4
4.50	-0.35	+0.16	+0.20	0.00	-	-	
5.00	-0.38	+0.16	+0.21	0.00	53	75.0	28.8
6.00	-	-	-	-	-	-	
8.00	-0.47	+0.16	+0.25	0.00	53	77.5	29.2
10.00	-0.62	+0.16	+0.26	0.00	53	75.5	27.2
13.50	-0.70	+0.16	+0.36	0.00	53	77.5	32.9

[a] Corrected for temperature and pressure of vapor in pump pipe.

TABLE G.3 Results of Test Run 2, Pumping on the Intermediate Depth Probe of Probe Cluster A and Monitoring Vacuums at the Intermediate and Deep Probes at Probe Clusters F and G (see Figure 1.2) on April 6, 1993

	Vacuum (in. water)				Probe L		
	Probe G		Probe F				
Time (min)	Intermediate	Deep	Intermediate	Deep	Temperature (°F)	Vacuum (in. water)	Flow[a] (L/min)
0.17	0.00	0.000	-0.01	0.00	54	19.5	11.3
0.33	-0.03	+0.020	+0.01	0.00	-	-	-
0.50	-0.03	-	+0.01	0.00	-	-	-
0.67	-0.03	+0.030	+0.01	0.00	-	-	-
0.83	-0.03	+0.030	+0.01	0.00	-	-	-
1.00	-0.03	+0.030	+0.01	0.00	54	19.5	11.3
1.17	-0.03	+0.035	+0.02	0.00	-	-	-
1.33	-0.03	+0.035	+0.01	0.00	-	-	-
1.50	-0.03	+0.035	+0.01	0.00	-	-	-
1.67	-0.03	+0.040	+0.01	0.00	-	-	-
1.83	-0.03	+0.040	+0.01	0.00	-	-	-
2.00	-0.03	+0.040	+0.01	0.00	54	19.5	9.0
2.50	-0.03	+0.040	+0.03	+0.01	-	-	-
3.00	-0.03	+0.050	+0.03	+0.01	-	-	-
3.50	-0.03	+0.050	+0.03	0.00	-	-	-
4.00	-0.03	+0.050	+0.03	+0.01	54	19.0	9.5
4.50	-0.05	+0.060	+0.01	+0.02	-	-	-
5.00	-0.05	+0.060	+0.02	+0.02	-	-	-
6.00	-0.03	+0.060	+0.03	0.00	-	-	-
8.00	-0.05	+0.060	+0.03	+0.02	54	18.5	9.5
10.00	-0.05	+0.060	+0.03	+0.02	54	18.2	9.0
30.00	-0.06	+0.005	+0.07	+0.02	54	16.9	7.7
47.00	-0.05	-0.030	+0.13	+0.02	54	20.0	9.0
80.00	+0.04	-0.050	+0.23	+0.02	54	20.0	8.7

[a] Corrected for temperature and pressure of vapor in pump pipe.

TABLE G.4 Results of Test Run 3, Monitoring Vacuums at the Intermediate and Deep Probes at Probe Clusters F and G after Pumping on the Intermediate Depth Probe of Probe Cluster L was Stopped (see Figure 1.2) on April 6, 1993

	Vacuum (in. water)			
	Probe G		Probe F	
Time (min)	Intermediate	Deep	Intermediate	Deep
0.00	+0.03	-0.05	-	-
0.17	+0.03	-0.05	-0.21	+0.02
0.33	+0.03	-0.05	-0.21	+0.02
0.67	+0.06	-0.05	-0.19	+0.02
0.83	+0.06	-0.05	-0.19	+0.02
1.00	+0.06	-0.05	-0.19	+0.02
1.17	+0.06	-0.05	-0.19	+0.02
1.33	+0.06	-0.05	-0.19	+0.02
1.50	+0.06	-0.05	-0.18	+0.02
1.67	+0.06	-0.05	-0.18	+0.02
1.83	+0.06	-0.05	-0.18	+0,02
2.00	+0.06	-0.05	-0.17	+0.02
2.50	+0.06	-0.05	-0.17	+0.02
3.00	+0.06	-0.05	-0.17	+0.02
3.50	-0.06	-0.05	-0.17	+0.02
4.00	+0.06	-0.05	-0.17	+0.02
4.50	+0.06	-0.05	-0.16	+0.02
5.00	+0.06	-0.05	-0.15	+0.02
6.00	+0.06	-0.05	-0.15	+0.02
8.00	+0.06	-0.05	-0.13	+0.02
10.00	+0.06	-0.05	-0.12	+0.02
14.00	-	-0.05	-0.07	+0.02

TABLE G.5 Results of Test Run 4, Pumping on Probe E and Monitoring Vacuums on Intermediate and Deep Probes at Probe Clusters L and M and Well 5 Probes P and Q (see Figure 1.2), April 7, 1993

	Vacuum (in. water)						Probe E		
	Probe L		Probe M						
Time (min)	Intermediate	Deep	Intermediate	Deep	Probe P	Probe Q	Temperature (°F)	Vacuum (in. water)	Flow[a] (L/min)
0.17	0.00	0.00	0.00	0.00	0.00	-	-	-	-
0.33	0.00	-0.02	0.00	0.00	0.00	-	-	-	-
0.67	0.00	-0.02	0.00	+0.02	0.00	-	-	-	-
0.83	0.00	-0.02	+0.02	+0.02	0.00	-	-	-	-
1.00	0.00	-0.02	+0.02	+0.02	0.00	-	-	-	-
1.17	0.00	-0.02	+0.02	+0.02	0.00	-	-	-	-
1.33	0.00	-0.02	+0.02	+0.03	0.00	-	-	-	-
1.50	0.00	-0.02	+0.02	+0.03	0.00	-	-	-	-
1.67	0.00	-0.02	+0.02	+0.03	0.00	-	-	-	-
1.83	0.00	-0.02	+0.02	+0.03	0.00	-	-	-	-
2.00	0.00	-0.02	+0.02	+0.03	0.00	-	52	94.5	20.7
2.50	0.00	-0.03	+0.02	+0.04	0.00	-	-	-	-
3.00	+0.02	-0.04	+0.06	+0.04	0.00	-	51	94.0	21.0
3.50	+0.02	-0.04	+0.06	0.00	0.00	-	-	-	-
4.00	+0.03	-0.04	+0.10	-0.02	0.00	-	53	94.5	20.7
4.50	+0.04	-0.05	+0.11	-0.04	0.00	-	-	-	-
5.00	+0.04	-0.06	+0.13	-0.07	0.00	-	-	-	-
6.00	+0.05	-0.06	+0.16	-0.10	0.00	-	54	94.5	20.9
8.00	+0.08	-0.02	+0.23	+0.18	0.00	-	-	-	-
10.00	+0.11	-0.02	+0.24	+0.20	0.00	-	55	94.8	20.9
15.00	+0.17	0.00	+0.48	+0.29	0.00	-	55	95.0	20.9
30.00	+0.24	+0.01	+0.57	+0.43	0.00	+0.19 (28 min)	55	95.1	20.9
45.00	+0.28	0.00	+0.64	(+0.30[b])	0.00	+0.25 (37 min)	57	95.1	20.9
60.00	+0.28	-0.06	+0.65	+0.70	0.00	+0.25	57	95.1	20.9

TABLE G.5 (Cont.)

	Vacuum (in. water)						Probe E		
	Probe L		Probe M						
Time (min)	Intermediate	Deep	Intermediate	Deep	Probe P	Probe Q	Temperature (°F)	Vacuum (in. water)	Flow[a] (L/min)
75.00	+0.29	-0.04	+0.68	+0.95	0.00	+0.25	57	95.3	20.9
90.00	+0.28	-0.15	+0.70	+1.01	0.00	+0.25	58	91.8	21.2

[a] Corrected for temperature and pressure of vapor in pump pipe.

[b] Change over to U-tube.

TABLE G.6 Results of Test Run 5, Pumping on the Intermediate-Depth Probe of Probe Cluster L and Monitoring Vacuums at the Shallow and Deep Probes at Probe Cluster L and the Shallow, Intermediate, and Deep Probes at Probe Cluster M (see Figure 1.2) on April 7, 1993

	Vacuum (in. water)					Probe L		
	Probe L		Probe M					
Time (min)	Shallow	Deep	Shallow	Intermediate	Deep	Temperature (°F)	Vacuum (in. water)	Flow[a] (L/min)
0.17	0.00	+0.03	0.00	0.00	0.00	-	-	-
0.33	0.00	+0.03	0.00	0.00	0.00	-	-	-
0.67	-0.05	+0.03	0.00	0.00	0.00	-	-	-
0.83	-0.05	+0.03	0.00	0.00	0.00	-	-	-
1.00	-	-	0.00	0.00	0.00	59	22.3	29.7
1.17	-0.05	+0.03	0.00	0.00	0.00	-	-	-
1.33	-0.05	+0.03	0.00	0.00	0.00	-	-	-
1.50	-0.05	+0.06	+0.02	+0.02	0.00	-	-	-
1.67	0.00	+0.06	+0.02	+0.02	0.00	-	-	-
1.83	0.00	+0.06	+0.02	+0.03	0.00	-	-	-
2.00	-	-	+0.02	+0.03	0.00	58	22.2	29.3
2.50	+0.02	+0.06	+0.02	+0.04	0.00	-	-	-
3.00	+0.05	+0.06	0.00	+0.06	0.00	58	23.5	29.7
3.50	+0.07	+0.06	0.00	+0.07	0.00	-	-	-
4.00	+0.09	+0.06	0.00	+0.08	0.00	58	24.0	29.6
4.50	+0.09	+0.06	0.00	+0.10	0.00	-	-	-
5.00	+0.10	+0.06	-0.02	+0.10	0.00	58	25.0	29.6
6.00	+0.10	+0.04	-0.03	+0.11	0.00	58	25.0	29.6
8.00	+0.13	+0.04	-0.05	+0.14	0.00	57	24.5	29.6
10.00	+0.15	+0.04	-0.04	+0.16	0.00	57	24.8	29.2
15.00	+0.17	+0.04	+0.02	+0.19	0.00	57	24.5	29.6
30.00	+0.25	+0.03	-0.07	+0.31	0.00	57	25.2	29.2
45.00	+0.31	-0.03	-0.07	+0.34	0.00	56	30.0	28.7
60.00	+0.35	-0.03	-0.07	+0.38	0.00	57	30.0	29.1
75.00	+0.38	-0.05	-0.07	+0.37	0.00	58	30.0	29.1
90.00	+0.38	-0.08	-0.07	+0.38	0.00	57	30.0	29.5

[a] Corrected for temperature and pressure of vapor in pump pipe.

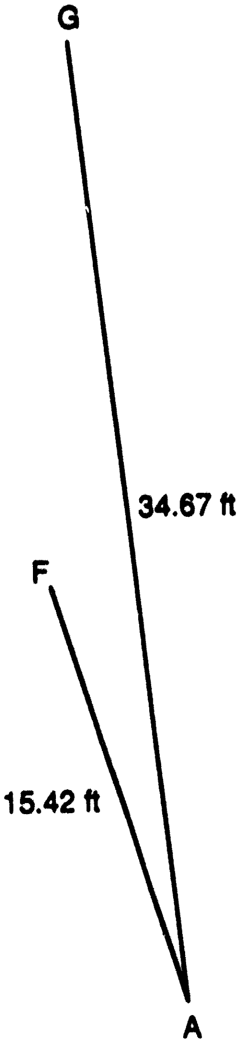


FIGURE G.1
Horizontal
Distances (ft)
between Probe A
and Probe Clusters
F and G

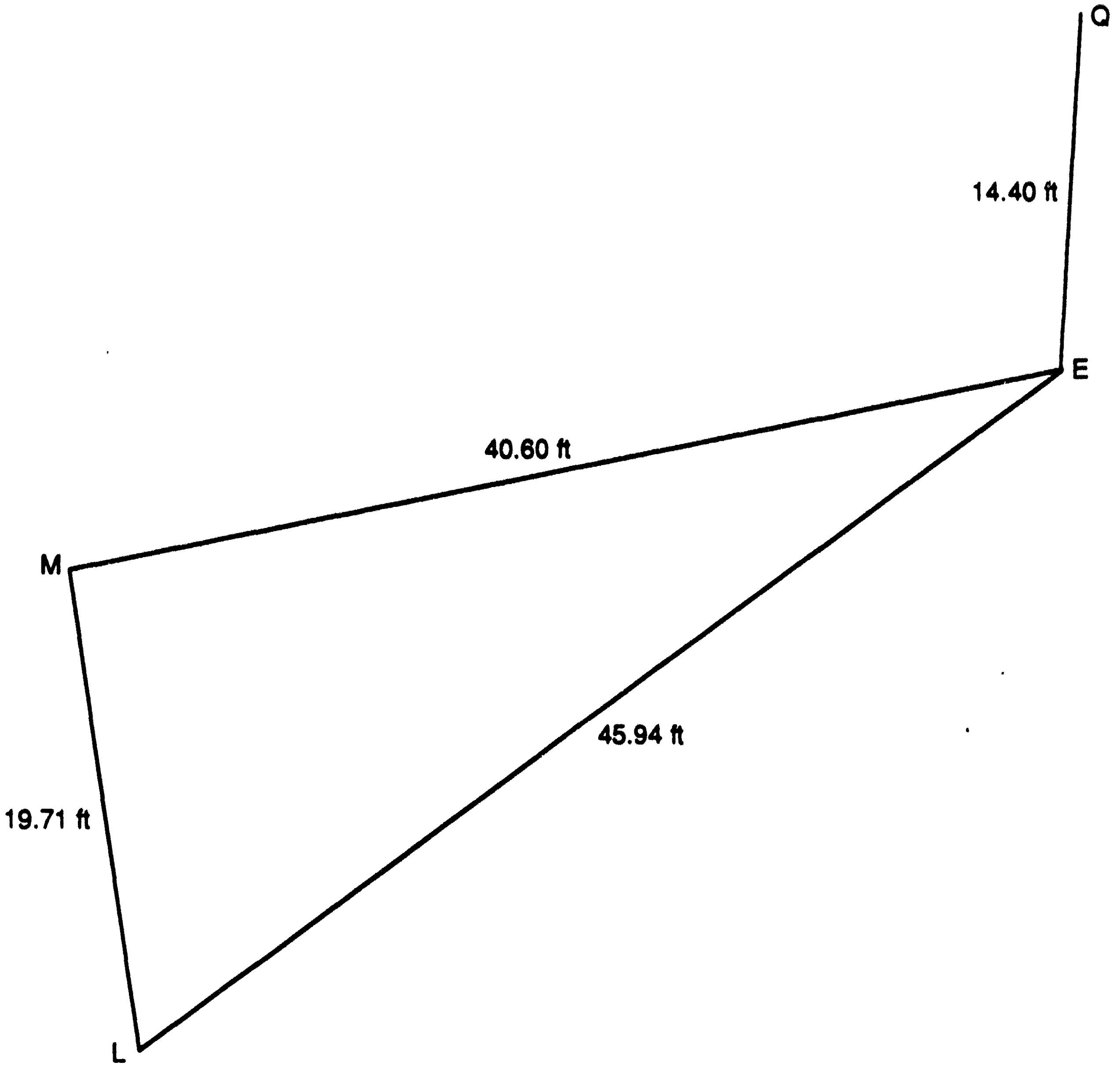


FIGURE G.2 Horizontal Distances (ft) between Probe Clusters, L and M, and Probes E and Q

TABLE G.7 Measurement of Total Petroleum Hydrocarbons (TPH), Oxygen, and Carbon Dioxide in Vapor Extracted by V4 from Horizontal Wells 1–5 on April 8, 1993

		Ambient			Vapor						
Well	Time (min)	Temperature (°F)	Pressure (mbar)	Weather	Temperature (°F)	Vacuum (in. water)	Differential Pressure (in. water)	Flow (scfm)	Oxygen (%)	Carbon Dioxide (%)	TPH[a] (ppm)
5	9:10	49.0	1018	sunny	51.4	14.5	0.35	12.8	20.8	0.06	35
4	9:33	56.4	1018	sunny	52.7	10.5	0.30	11.8	20.8	0.07	22
3	10:22	58.7	-	sunny	53.8	13.5	0.50	15.2	20.1	0.05	13
2	10:33	58.7	-	sunny	54.4	13.5	0.35	12.7	20.5	0.05	22
1	10:48	61.0	-	sunny	55.5	13.0	0.65	17.3	20.0	0.03	35

[a] TPH = Total petroleum hydrocarbon.

DATE
FILMED
10/13/94

END