AR Doc # 1157

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 377TH AIR BASE WING (AFMC)

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15 April 1998

MEMORANDUM FOR MR. BENITO GARCIA, CHIEF
HAZARDOUS & RADIOACTIVE MATERIALS BUREAU
NEW MEXICO ENVIRONMENT DEPARTMENT
PO BOX 26110
SANTA FE NM 87502

FROM: 377 ABW/EMR
2050 Wyoming Blvd SE, Ste 125
Kirtland AFB NM 87117-5270

Appen III

SUBJECT: Bioventing Feasibility Site Characterization Report, SWMU ST-341, Condensate Holding Tank and Evaporation Pond (ST-341)

1. We are forwarding a copy of the Bioventing Site Characterization Report, SWMU ST-341, Condensate Holding Tank and Evaporation Pond. Additional copies without appendices are being sent to Mr. Steve Pullen of your staff and Ms. Julie Jacobs with the Groundwater Quality Bureau.

2. Kirtland AFB is currently conducting a pilot study as part of an interim corrective measure (ICM) at SWMU ST-341. We are evaluating passive and enhanced bioventing at this site. This report presents the results of a characterization project primarily intended to provide site details required for design of the ICM.

3. Please call me at (505) 846-0053 if you have any questions regarding this document. Although this document is part of an FY97 project, it meets most of the requirements in the new NMED guidance for RFI reports.

CHRISTOPHER B. DEWITT, R.P.G.
Chief, Restoration Branch
Environmental Management Division

cc:
NMED-HRMB (Mr. Pullen)
NMED-GWQB (Ms. Jacobs)
EPA Region 6 (Ms. Morlock)
HQ AFMC/CEVC (Capt Weiss)

CERTIFICATION

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

JAMES S. LEATHERWOOD, GS-14
Director
Environmental Management Division

PREFACE

This Site Characterization Report discusses the activities performed during 1997 at one solid waste management unit (SWMU) ST-341, Condensate Holding Tank and Evaporation Pond of the RCRA Part B Permit for Kirtland Air Force Base (AFB). The report addresses the requirements of the U.S. Army Corps of Engineers statement of work, dated June 26 1997.

This report was prepared by Tetra Tech NUS (Tt NUS) in November 1997. Mr. Ronald L. Witcofski of the U.S. Corps of Engineers was the Contracting Officer and Mr. Steven M. Rowe served as the Technical Manager.

Jeffrey W. Johnston
Tt NUS Program Manager

R. Reid Olson for
Mark Garman
Tt NUS Project Manager

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TABLES

ACRONYMS

AFB	Air Force Base
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, total xylenes
cfm	cubic feet per minute
cfu/gm	colony forming unit/gram of soil
CLP	Contract Laboratory Program
CMD/I	Corrective Measures Design/Implementation
CMS	Corrective Measures Study
CPVC	chlorinated polyvinyl chloride
DRO	diesel range organics
ECP	Environmental Compliance Program
EPA	U.S. Environmental Protection Agency
GRO	gasoline range organics
HHRB	human health risk-based
HSA	hollow-stem auger
IRP	Installation Restoration Program
mg/kg	milligram/kilogram
MP	monitor point
NMED	New Mexico Environment Department
PID	photo ionization detector
ppm-v	parts per million-volume
psi	pounds per square inch
QC	quality control
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
SWMU	solid waste management unit
SVOCs	semi-volatile organic compounds
TKN	total Kjeldahl nitrogen
TPH	total petroleum hydrocarbons
TOC	total organic carbon
Tt NUS	Tetra Tech NUS

ACRONYMS (CONTINUED)

μg/L	micrograms per liter
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
UST	underground storage tank
VOCs	volatile organic compounds

EXECUTIVE SUMMARY

This Bioventing Feasibility Site Characterization Report presents the results of the first phase of a bioremediation feasibility study for hydrocarbon-impacted soils at solid waste management unit (SWMU) ST-341, Condensate Holding Tank and Evaporation Pond (ST-341), Kirtland Air Force Base (AFB), New Mexico. The purpose of the site characterization was to collect sufficient data to determine the feasibility of in-situ bioremediation at SWMU ST-341. Site characterization data will be used in determining the technical approach and design of the pilot study phase of the Corrective Measures Design/Implementation (CMD/I) at ST-341.

Site characterization field work was conducted September 9 through October 8, 1997. Site characterization activities included a soil gas survey, soil gas permeability test, in-situ respiration test, and soil characterization sampling. Soil gas samples were analyzed for numerous parameters including: benzene, toluene, ethylbenzene, xylenes, petroleum hydrocarbons, and fixed gases. Soil samples were analyzed for benzene, toluene, ethylbenzene, xylenes, petroleum hydrocarbons, microbial populations, nutrient conditions, and physical properties. Permeability test and in-situ respiration test field data were used in calculations to determine intrinsic soil permeability and biodegradation rates.

Site characterization vapor and soil chemical analyses indicate that petroleum hydrocarbon contamination extends laterally beyond the berm of the evaporation pond but is encompassed by the soil venting well array at the site. Petroleum hydrocarbon contamination extends vertically to a depth of approximately 75 ft below ground surface (bgs). Vapor phase petroleum hydrocarbons are more widespread than the petroleum hydrocarbons sorbed to soil. Decreasing oxygen concentrations and increasing carbon dioxide concentrations toward the center of the petroleum hydrocarbon plume indicate that biodegradation is occurring at the site.

Soil gas permeability test results indicate that permeability to vapor flow at the site is in excess of 0.1 darcy, therefore conducive to bioventing. In-situ respiration test results exhibited oxygen utilization rates in excess of 1 % per day indicating favorable conditions for aerobic biodegradation of petroleum hydrocarbons.

Soil microbial population and physical properties analyses indicate that aerobic microbial populations are present at the site and that the physical properties of the soil are conducive to bioventing. Soil moisture contents at the site are below the optimal range for biodegradation. Soil nutrient conditions analyses indicate that the site is deficient in phosphorous, an important nutrient for microbial populations. The phosphorous deficiency may be compounded by the alkalinity of site soils.

Overall, site characterization results indicate that bioventing is a feasible remedial alternative at SWMU ST-341. The pilot study design will include three phases: 1) passive (barometric) bioventing, 2) active bioventing, and 3) active bioventing combined with phosphorous and moisture injection. Results from the three phases will be compared to identify optimum conditions for in-situ bioremediation.

Section 1

1. INTRODUCTION

This Site Characterization Report presents the results of the first phase of a bioremediation feasibility study for hydrocarbon-impacted soils at solid waste management unit (SWMU) ST-341, Condensate Holding Tank and Evaporation Pond (ST-341), Kirtland Air Force Base (AFB), New Mexico. It summarizes the activities conducted at one SWMU listed in Appendix III to Module IV of the Kirtland AFB Resource Conservation and Recovery Act (RCRA) Part B Permit. Contamination at this site was identified during the Appendix III RCRA Facility Investigation (RFI) (USAF, 1995a and 1997a). The site characterization field work was performed from September 9 through October 10, 1997. This report was prepared to meet the requirements of the Corps of Engineers Statement of Work dated June 26, 1997 and is considered a deliverable under Contract Number DACA 01-95-D-0017, Delivery Order 0023.

1.1 Description of the Site Characterization

Based on the results from Phase 1 and Phase 2 RFIs at this SWMU, a Corrective Measures Study (CMS) and a Corrective Measures Design/Implementation (CMD/I) were recommended for this site. The CMD/I consists of two phases: a Site Characterization Phase summarized in this report, and a Pilot Study Phase. The Site Characterization Phase consisted of four characterization tasks:

- A soil gas survey performed from September 9 through September 22, 1997.
- A soil gas permeability test performed on September 25, 1997.
- An in-situ respiration test was performed from September 29 through October 4, 1997.
- Soil sampling conducted from October 6 through October 8, 1997.

The report is organized into seven sections plus appendices, which are contained in a separate volume. Section 1 outlines the study, scope, and objectives of the site characterization. Section 2 presents background information about the site and summarizes the results of previous investigations. Sections 3 through 6 discuss each of the site characterization tasks, the methods used during the field investigation, and the results of the characterization tasks. Section 7 discusses the feasibility of in-situ bioremediation at this site and recommendations for implementation of the pilot study phase of the project. Reference citations in this report are presented in the last, unnumbered section. Appendices are submitted under separate cover and include:

Appendix A Corps of Engineers Statement of Work

Appendix B Surveying Data

Appendix C Field Data Sheets, Well Completion Forms, Boring Logs

Appendix D Chain-of-Custody Forms

Appendix E Laboratory Analytical Reports

Appendix F Validation Memoranda

Appendix G Calculations

1.2 Project Objectives

The objective of the site characterization was to collect sufficient data to determine the feasibility of in-situ bioremediation at SWMU ST-341. Site characterization data will be used in determining the technical approach and design of the pilot study phase of the CMS at ST-341.

1.3 Scoping Documents

The following project scoping documents were used to implement the Site Characterization Study at ST-341:

- Bioventing Feasibility Site characterization Work Plan for SWMU ST-341, Condensate Holding tank and Evaporation Pond (ST-341), Kirtland Air Force Base, New Mexico (USAF, 1997b)
- Kirtland AFB Base-Wide Plans for Installation Restoration Program (IRP) (U.S. Air Force [USAF], 1995b)
- U.S. Army Corps of Engineers (USACE) Omaha District General Chemistry Supplement to the Scope of Services (USACE, 1996a)
- USACE Omaha District General Health and Safety Supplement to the Scope of Services (USACE, 1996b)
- Manual, Bioventing Principles and Practice, Volume I: Bioventing Principles (U.S. Environmental Protection Agency [EPA], 1995a)
- Manual, Bioventing Principles and Practice, Volume II: Bioventing Design (EPA, 1995b).

Section 2

2. BACKGROUND INFORMATION

This SWMU is located near Building 1033 in the fuel management section, west of the New Mexico Air National Guard Complex, in the western portion of Kirtland AFB (Figure 2-1). It includes a condensate holding tank / underground storage tank (UST), a 240-ft overflow pipe, and an unlined evaporation pond. The pond is the subject of the CMS (Figure 2-2). The condensate holding tank is used to collect a fuel/water mixture from fuel pump water condensers. The buried steel overflow pipe extends about 240 ft southwest from the UST to the unlined evaporation pond. During a December 1993 site inspection, there were no visible soil stains, but the surface soil under the pipe outfall exhibited visible evidence of ponding of liquids. In July 1996, the 250-gallon condensate holding tank was removed and replaced with a self-contained 300-gallon vaulted-below storage tank. The 240-ft overflow line was disconnected from the condensate collection system and abandoned in place.

This site is located in the industrial land use area. Three production wells are within a mile of the evaporation pond: KAFB-2 is 2,700 ft southwest; KAFB-7 is 3,900 ft southeast; and KAFB-14 is 5,100 ft west-northwest. Depth to groundwater is estimated to be 350 to 400 ft bgs at SWMU ST-341 (USAF, 1995a).

2.1 Results of Previous Investigations

This site was previously investigated under the Phase 1 and Phase 2 Appendix III RFIs (USAF, 1995a, 1996, 1997). During Phase 1, the investigation was limited to Geoprobe soil sampling in the vicinity of the condensate holding tank from ground surface to approximately 12 ft below grade, and one borehole at the evaporation pond which extended to 58 ft below grade. The purpose of soil sampling during the Phase 2 investigation was to define the vertical and lateral extent of contamination at the site. During the Phase 2 investigation, eight Geoprobe and eight hollow-stem auger borings were drilled at the site. Three boreholes were drilled along the overflow pipe, three boreholes were drilled at the condensate holding tank location, and nine boreholes were drilled in the area of the unlined evaporation pond (Figure 2-1). Five of the boreholes in the vicinity of the unlined evaporation pond and two boreholes in the vicinity of the condensate holding tank were completed as soil venting wells (Figure 2-2). Complete analytical results are presented in the Phase 1 and Phase 2 Appendix III RFI Reports (USAF, 1995a, 1997). The nature and extent of contamination based on soil sampling conducted during Phases 1 and 2 of the Appendix III RFI are summarized below.

Appendix III Phase 1 Results

- Five volatile organic compounds (VOCs) were detected in samples collected from this site; all concentrations were below human health risk-based (HHRB) action levels (EPA, 1996).

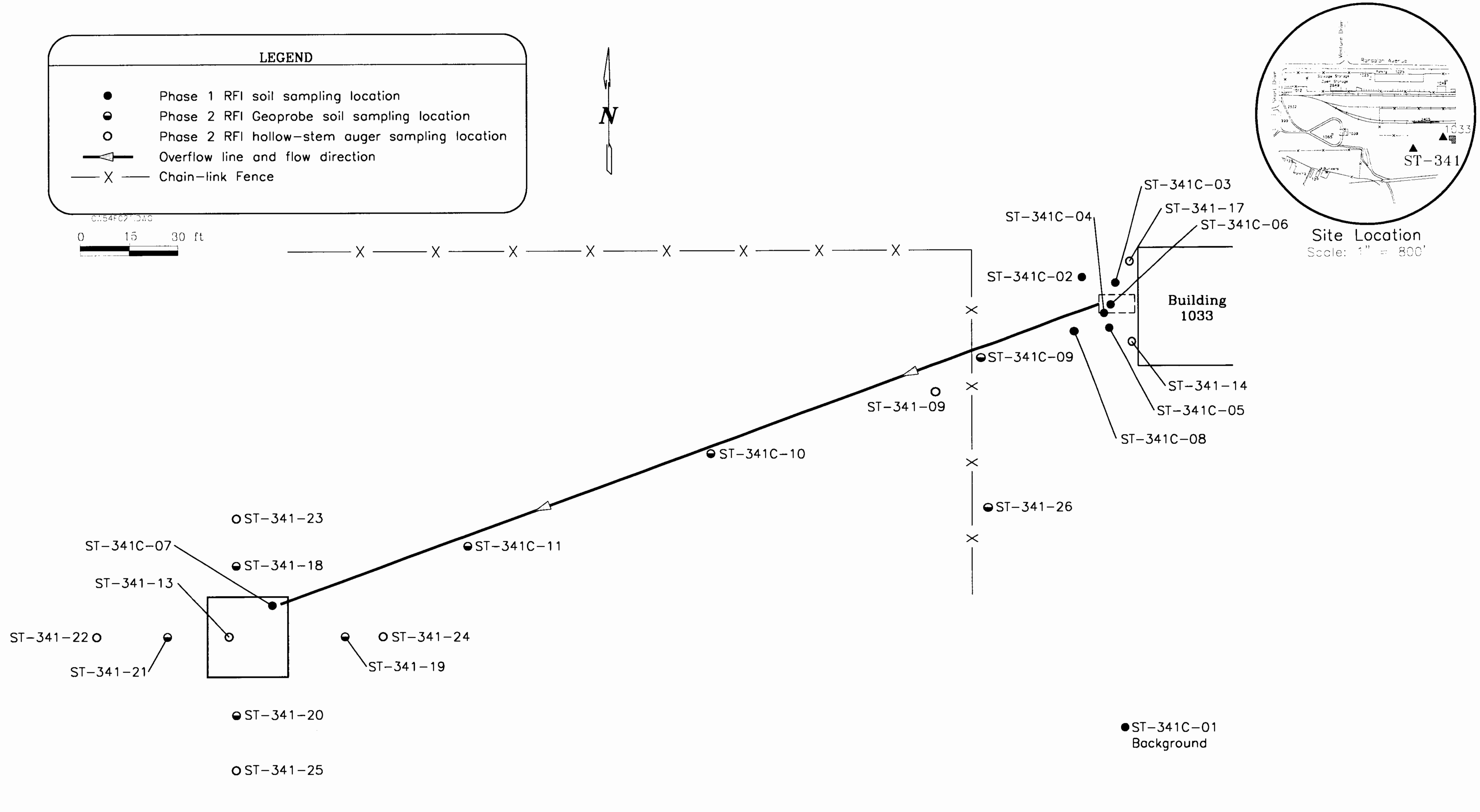

Figure 2-1.
Site Map for SWMU ST-341

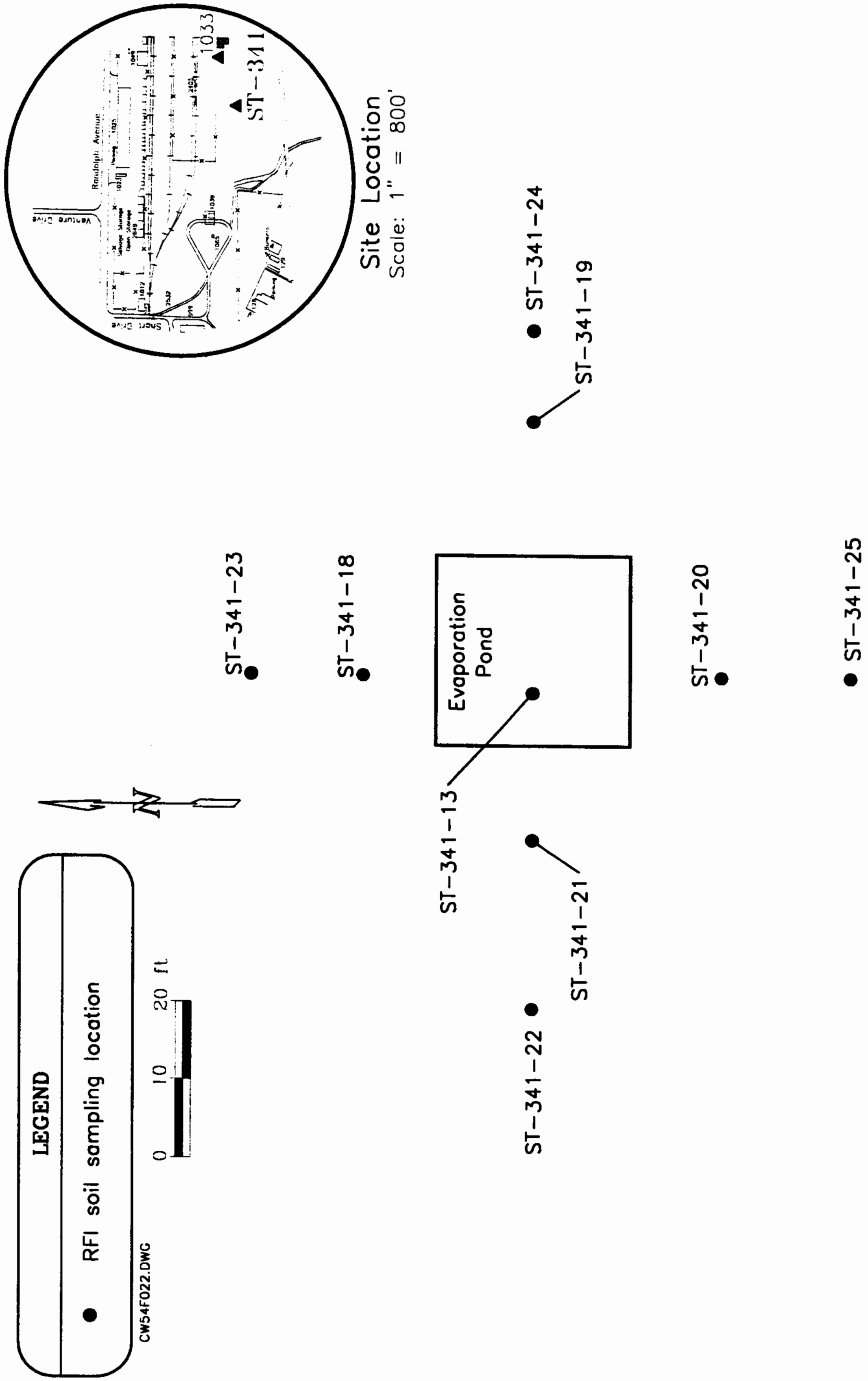

Figure 2-2. SWMU ST-341, Evaporation Pond RFI Boring Locations

- Twenty-two semi-volatile organic compounds (SVOCs) were detected in samples collected at this site. Four were at concentrations equal to or above the HHRB action levels: benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, and indeno(1,2,3-c,d)pyrene. The detections exceeding HHRB action levels are summarized in Table 2-1.

- Diesel range organics (DRO) were detected in 18 samples; the concentrations detected in 15 samples (ranging from 110 to 10,000 milligrams per kilogram (mg/kg)) exceeded the New Mexico Environment Department (NMED) action level for total petroleum hydrocarbons (TPH) of 100 mg/kg. (NMED, 1995).

- Gasoline range organics (GRO) were detected in 21 samples; the concentrations detected in 11 samples (ranging from 102 to 360,000 mg/kg) exceeded the NMED action level for TPH of 100 mg/kg.

Appendix III Phase 2 Results

- Thirteen VOCs were detected in samples collected from this site; concentrations were below HHRB action levels for all of the detected VOCs.

- Eighteen SVOCs were detected in samples collected at this site. Only one SVOC, benzo(a)pyrene, was detected at a concentration exceeding the HHRB action level. The detection exceeding the HHRB action levels is listed in Table 2-1.

- Diesel range hydrocarbons were detected in eight samples; the concentrations detected in six samples (ranging from 890 to 1,700 mg/kg) exceeded the 100 mg/kg NMED action level for TPH.

- Gasoline range hydrocarbons were detected in 29 samples; the concentrations detected in 15 samples (ranging from 100 to 12,000 mg/kg) exceeded the 100 mg/kg NMED action level for TPH.

- Jet Fuel A, which overlaps with gasoline and diesel range hydrocarbons, was detected in 21 samples; the concentrations detected in 15 samples exceeded the 100 mg/kg NMED action level for TPH. The maximum detected concentration was 15,000 mg/kg.

Table 2-1. RFI Analytical Results For Compounds Exceeding HHRB[1] Action Levels at SWMU ST-341

CHEMICAL CLASS	ANALYTE	SAMPLE I.D.	DETECTION (mg/kg)	HHRB ACTION LEVEL (mg/kg)
PHASE 1				
SVOC	Benzo(a)anthracene	ST-341C-03-0910	4.9	0.6
		ST-341C-08-0506	2.6	0.6
	Benzo(a)pyrene	ST-341C-03-0910	1.8	0.06
		ST-341C-05-0809	0.30	0.06
		ST-341C-08-0506	0.85	0.06
	Benzo(b)fluoranthene	ST-341C-03-0910	2.4	0.6
		ST-341C-08-0506	1.5	0.6
	Indeno(1,2,3-c,d)pyrene	ST-341C-03-0910	0.88	0.6
PHASE 2				
SVOC	Benzo(a)pyrene	ST-341-09-0507	0.10	0.06

(1) EPA Region VI HHRB screening levels (EPA, 1996)

Based on the results of the Phase 1 and Phase 2 Appendix III RFIs, a CMS and a CMD/I were recommended for this SWMU. The CMS was divided into two phases; the site characterization described in this report, and a subsequent pilot study. The pilot study phase will evaluate the effectiveness of in-situ bioremediation and identify the conditions that maximize the biodegradation of petroleum hydrocarbons at ST-341.

2.2 Scope of the Site Characterization

The site characterization consisted of four field investigation tasks:

- Soil gas survey
- Soil gas permeability test
- In-situ respiration test
- Soil characterization sampling.

Soil gas survey boring locations, permeability test well locations, the in-situ respiration test nested well location, and the soil characterization boring locations are depicted in Figure 2-3. Sections 3 through 6 discuss each of the site characterization tasks.

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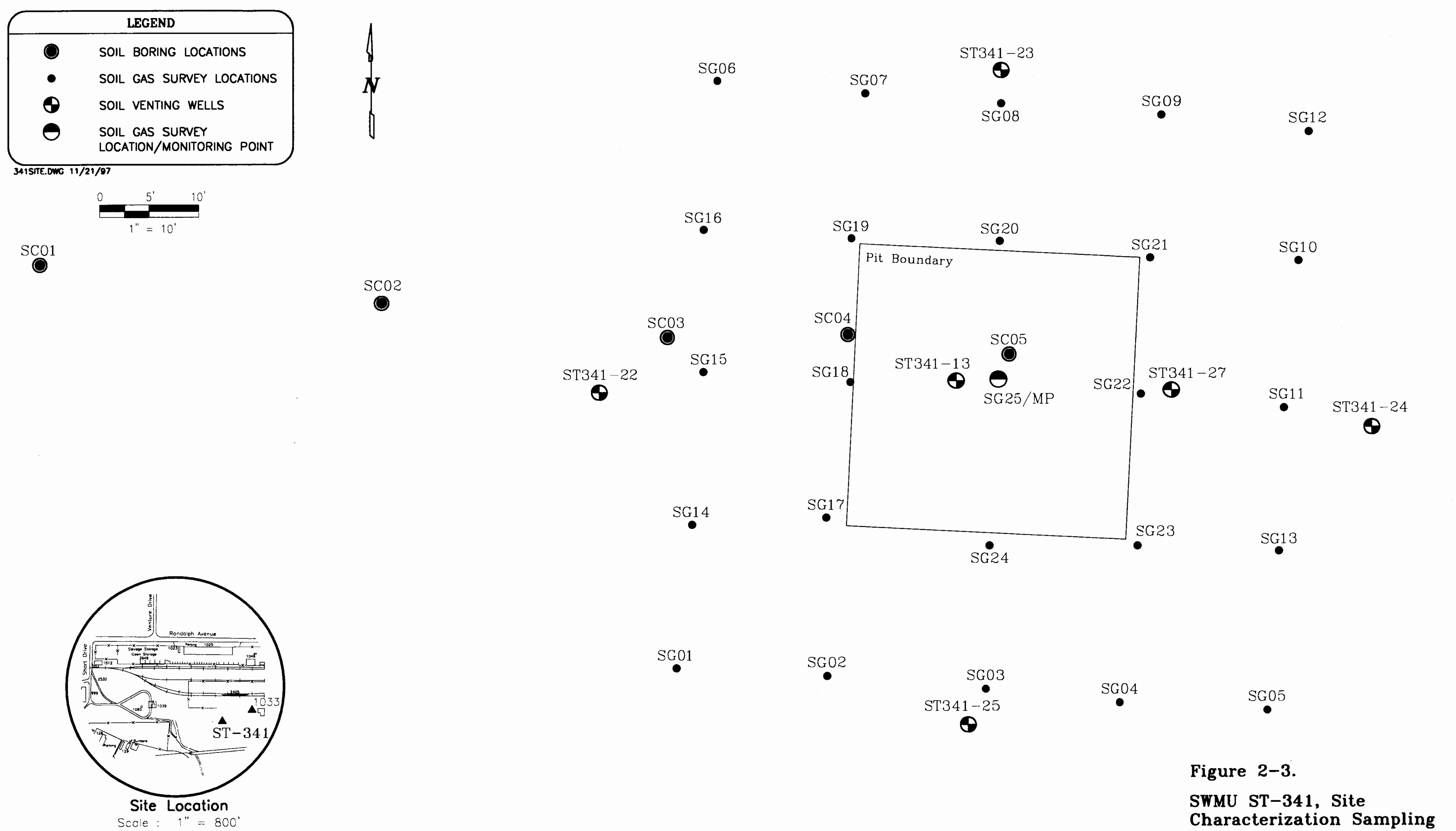

Figure 2-3.

SWMU ST-341, Site Characterization Sampling Locations

Section 3

3. SOIL GAS SURVEY

The soil gas survey was designed to delineate the extent of the contaminant plume at ST-341 evaporation pond, and to establish ambient concentrations of naturally occurring (permanent) soil gases, which are influenced by biological activity. The soil gas survey was performed from September 9 through September 22, 1997.

3.1 Methodology

A total of 25 soil borings (SG01 through SG25) were drilled on a 60 x 60 ft grid (15-ft centers) encompassing the ST-341 evaporation pond. Soil gas survey borings were advanced using a combination of direct push (Geoprobe) and hollow-stem auger (HSA) drilling techniques. The locations of the borings are shown on Figure 3-1. Soil gas samples were collected at 15, 30, 45, and 60 ft below ground surface (bgs) in each boring except for borings SG02 and SG03. Instead of collecting a sample at the 60 ft interval, samples were collected at 54 ft and 53 ft bgs in borings SG02 and SG03, respectively.

Due to the density of subsurface soils at the site, Geoprobe drilling generally reached refusal at a depth of approximately 39 ft bgs. HSA drilling was used to reach the 45 and 60 ft sample intervals in twenty of the borings. Five borings (SG01, SG02, SG03, SG08, and SG25) were successfully completed using only Geoprobe drilling methods. When HSA drilling was used, the augers were advanced to approximately five ft above the desired sample interval and the Geoprobe was used to advance the remaining five ft and collect the soil gas sample.

A total of 125 soil gas samples (including replicates and confirmatory samples) were collected using the Geoprobe Post-Run Tubing System and Retractable Drive Point. Soil gas samples were collected at each sample interval in the following manner:

- The retractable drive point was advanced to the desired depth using the Geoprobe rig.
- The retractable drive point was disengaged by pulling up the probe rods approximately 6 in. Extension rods were inserted within the probe rods to confirm disengagement of the retractable drive point.

Post-run tubing was inserted within the probe rods and threaded onto the retractable drive point to form a vacuum-tight connection.

- The post-run tubing was connected to a GasTech GA-90 oxygen/carbon dioxide meter and purged until oxygen and carbon dioxide readings stabilized. Dura-clamp valves were used to seal the post-run tubing after oxygen/carbon dioxide screening.

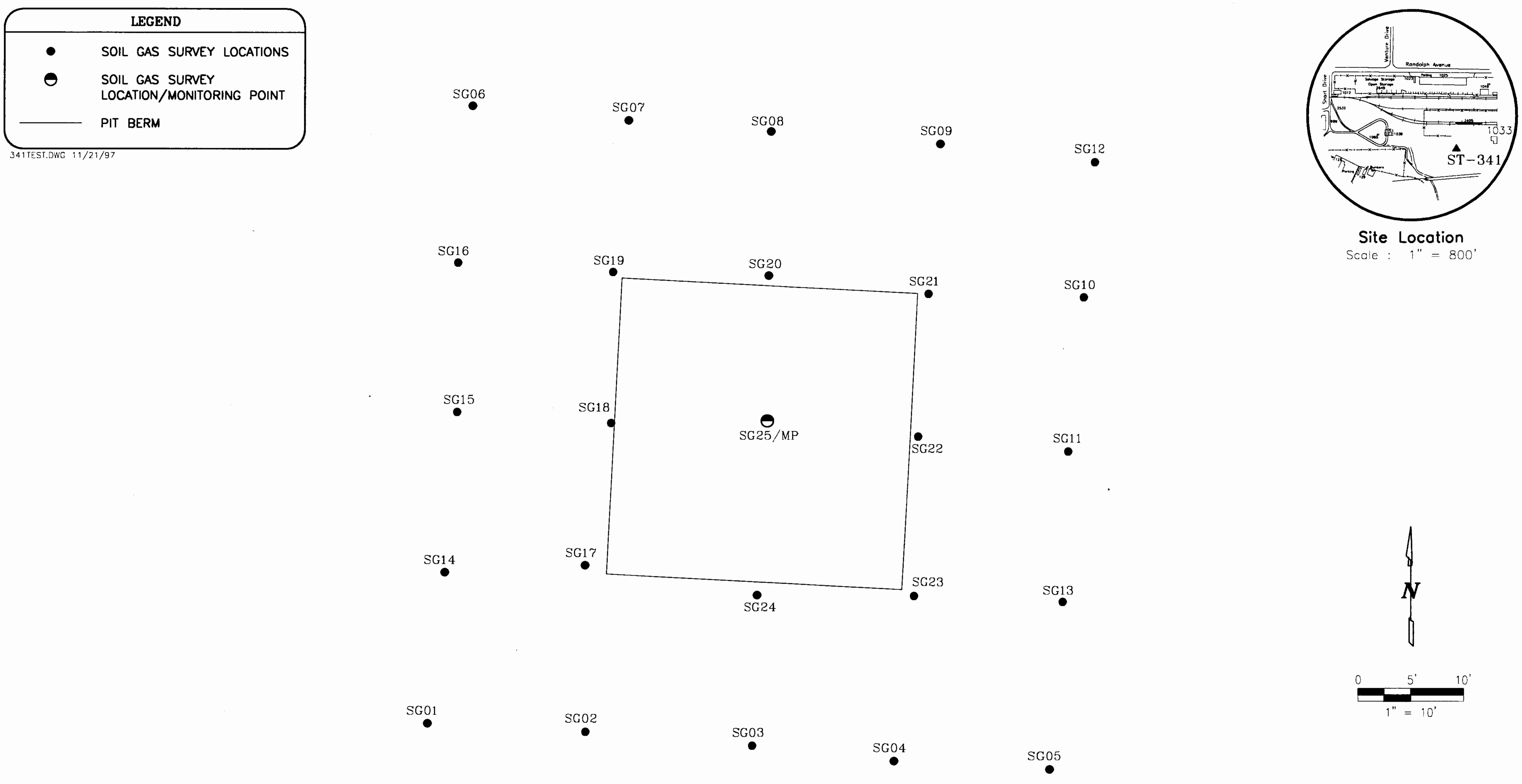

Figure 3-1.
SWMU ST-341, Soil Gas Survey Grid

- The post-run tubing was connected to a vacuum chamber inlet port linked to an enclosed Tedlar bag. A vacuum pump was connected to the outlet port of the vacuum chamber. As vacuum was initiated, the dura-clamp valve was released to allow the soil gas sample to flow from the post-run tubing into the Tedlar bag. Once the Tedlar bag was filled, the dura-clamp valve was closed to seal the post-run tubing. The vacuum was then released, the vacuum chamber opened, and the Tedlar bag valve closed.

- After collection of the soil gas sample, the post-run tubing was connected to a Photovac or Mini-Rae photoionization detector (PID) for volatile organics screening. Following PID screening, the dura-clamp valve was removed from the post-run tubing, and the post-run tubing was removed from the drive point for disposal.

After sample collection, soil gas samples were immediately delivered to an on-site mobile laboratory for analyses. Each soil gas sample was analyzed for benzene, toluene, ethylbenzene, and total xylenes (BTEX), total petroleum hydrocarbons (TPH), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), and oxygen (O_2) by the mobile laboratory. Soil gas replicate samples were collected at a frequency of 10% of the total number of samples. Confirmatory samples were collected when review and comparison of mobile laboratory results and field screening results indicated potentially erroneous readings. Erroneous readings (samples diluted with atmospheric air) were caused by short-circuiting during sample collection.

Difficulty was encountered during the soil gas survey in collecting representative soil gas samples from nearly half of the sample intervals. Field screening results were used to evaluate the representativeness of soil gas samples during collection. Short-circuiting (dilution with atmospheric air) appeared to occur because of the high vacuum required to extract samples from intervals of low permeability and/or intervals containing heavy hydrocarbon residuals. The greatest difficulty with short-circuiting during sample collection was encountered at the 30 ft- and 45 ft- sample intervals. Numerous attempts were required in an effort to obtain representative soil gas samples at these depths. It is estimated that approximately ten percent of the soil gas survey results are diluted to some extent with atmospheric air. The dilution results in lower than actual hydrocarbon and carbon dioxide concentrations, and higher than actual oxygen concentrations.

3.2 Results

Soil gas survey mobile laboratory analytical results are summarized in Table 3-1. BTEX soil gas concentrations are generally low throughout the soil gas survey grid. Higher concentrations of the BTEX compounds were generally detected in the 45 and 60 ft sample intervals. Methane was not detected in any of the soil gas samples. Trace amounts of carbon monoxide were detected in some samples. At this site, the TPH, carbon dioxide, and oxygen analytical results are the most useful data for evaluating in-situ bioremediation potential.

Isoconcentration maps of the soil gas survey grid are presented for the TPH, oxygen, and carbon dioxide analytical results in Figures 3-2 through 3-9. The maps are specific to each soil gas sampling interval. Figures 3-2, 3-4, 3-6, and 3-8 reflect carbon dioxide and oxygen concentrations in soil gas samples collected at the 15-, 30-, 45-, and 60-ft intervals, respectively. Figures 3-3, 3-5, 3-7, and 3-9 reflect TPH concentrations in soil gas samples collected at the 15-, 30-, 45-, and 60-ft intervals, respectively. Figures 3-10 through 3-13 are isoconcentration cross section maps of the soil gas grid. Carbon dioxide and

Table 3-1. Summary of Soil Gas Survey Anayltical Results at SWMU ST-341

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Sample ID	Benzene ug/L	Toluene ug/L	Ethylbenzene ug/L	M&P-Xylene ug/L	O-Xylene ug/L	TPH-Gas PPM	CO_2 %	Oxygen %	Nitrogen %	Methane %	CO %
SG-01-15	ND	ND	ND	ND	ND	ND	0.65	18.80	71.56	ND	0.37
SG-01-30	ND	ND	ND	ND	ND	ND	3.66	14.85	69.82	ND	ND
SG-01-45	ND	4.9	ND	1.9	ND	732	3.88	14.02	75.19	ND	ND
SG-01-60	ND	25.7	ND	ND	1.7	7276	5.76	12.44	71.65	ND	ND
SG-02-15	ND	ND	ND	ND	ND	23	2.19	17.04	67.25	ND	ND
SG-02-30	ND	ND	ND	ND	ND	ND	3.19	13.35	74.98	ND	ND
SG-02-45	ND	2.8	ND	ND	ND	722	7.09	10.53	71.89	ND	ND
SG-02-54	ND	3.0	ND	ND	ND	428	2.17	17.42	68.74	ND	ND
SG-03-15	ND	ND	ND	ND	ND	14	1.78	17.90	69.13	ND	ND
SG-03-15DUP	ND	ND	ND	ND	ND	ND	1.71	18.00	68.72	ND	ND
SG-03-30	ND	ND	ND	ND	ND	24	0.99	18.94	68.87	ND	ND
SG-03-45	ND	ND	ND	1.1	ND	331	3.20	18.09	71.10	ND	0.49
SG-03-53	ND	1.60	ND	2.8	ND	980	3.16	14.13	70.66	ND	ND
SG-04-15	ND	ND	ND	ND	ND	16	1.99	18.04	69.53	ND	ND
SG-04-30	ND	ND	ND	ND	ND	125	4.28	16.42	67.77	ND	ND
SG-04-45	1.0	10.7	4.5	4.2	2.8	1192	7.96	11.63	71.58	ND	ND
SG-04-60	ND	ND	1.2	ND	ND	794	4.49	15.37	72.18	ND	ND
SG-05-15	ND	ND	ND	ND	ND	ND	1.59	12.80	47.67	ND	ND
SG-05-30	ND	ND	ND	1.1	ND	224	2.57	12.00	52.96	ND	ND
SG-05-45	2.3	7.2	ND	1.1	1.3	595	6.08	12.97	81.84	ND	ND
SG-05-60	1.3	ND	3.5	ND	ND	288	2.00	19.38	79.26	ND	ND
SG-06-15	ND	ND	ND	ND	ND	ND	1.72	14.22	52.58	ND	ND
SG-06-30	3.9	ND	ND	ND	ND	282	3.46	9.64	50.31	ND	ND
SG-06-45	17.7	18.3	ND	8.0	2.2	2362	6.44	8.99	55.89	ND	0.56
SG-06-60	7.6	7.5	ND	ND	ND	1060	5.55	14.63	73.58	ND	ND
SG-06-60B	NA	NA	NA	NA	NA	NA	5.95	14.09	74.17	ND	ND
SG-07-15	ND	ND	ND	ND	ND	ND	2.81	14.6	57.28	ND	0.32
SG-07-15DUP	ND	ND	ND	ND	ND	41	2.38	13.92	58.15	ND	ND
SG-07-30	4.7	ND	ND	3.3	2.9	1571	4.71	10.76	60.40	ND	ND
SG-07-45	ND	ND	1.4	ND	ND	616	3.27	17.89	70.93	ND	ND
SG-07-45B	NA	NA	NA	NA	NA	NA	1.74	19.79	72.33	ND	ND

Table 3-1. Summary of Soil Gas Survey Anayltical Results at SWMU ST-341

page 2 of 5

Sample ID	Benzene ug/L	Toluene ug/L	Ethylbenzene ug/L	M&P-Xylene ug/L	O-Xylene ug/L	TPH-Gas PPM	CO_2 %	Oxygen %	Nitrogen %	Methane %	CO %
SG-07-60	13.8	18.5	3.1	1.2	ND	2799	9.47	9.54	74.75	ND	ND
SG-07-60DUP	16.7	23.8	5.4	2.4	ND	3156	10.23	9.51	74.11	ND	ND
SG-08-15	ND	ND	ND	ND	ND	102	3.11	13.22	59.02	ND	ND
SG-08-30	1.4	2.2	ND	8.9	8.4	2603	5.16	9.46	57.40	ND	ND
SG-08-45	ND	24.5	16.0	33.6	11.5	13939	9.21	5.52	59.50	ND	ND
SG-08-60	ND	ND	ND	23.0	5.4	15956	8.50	7.53	64.35	ND	ND
SG-09-15	ND	ND	ND	ND	ND	15	1.99	13.77	55,71	ND	0.32
SG-09-30	ND	ND	ND	ND	ND	ND	0.05	17.81	61.26	ND	ND
SG-09-45	2.5	5.0	ND	1.9	3.5	453	2.61	17.55	76.52	ND	ND
SG-09-60	10.6	14.7	2.1	3.8	6.7	2810	7.87	8.54	74.34	ND	ND
SG-09-60DUP	11.7	15.8	2.5	4.3	7.3	2717	7.91	8.86	74.74	ND	ND
SG-10-15	ND	ND	ND	ND	ND	26	2.32	15.32	62.99	ND	ND
SG-10-30	ND	ND	ND	2.0	ND	344	4.44	11.44	61.30	ND	0.12
SG-10-30DUP	ND	ND	ND	2.3	ND	387	4.66	11.89	63.45	ND	ND
SG-10-45	3.4	8.2	1.0	2.5	4.6	950	5.17	12.16	76.19	ND	ND
SG-10-60	5.9	12.5	1.8	3.2	5.3	2190	6.87	9.24	76.07	ND	ND
SG-11-15	ND	ND	ND	ND	ND	49	2.32	15.24	63.65	ND	ND
SG-11-30	ND	ND	ND	ND	ND	33	0.33	17.25	59.54	ND	0.09
SG-11-30B	ND	4.6	15.1	18.9	1.8	1173	5.73	13.11	67.60	ND	ND
SG-11-45	3.0	14.7	1.8	4.1	5.7	2025	7.36	10.00	75.28	ND	ND
SG-11-60	3.5	17.7	2.7	5.4	8.0	2984	7.87	8.72	75.55	ND	ND
SG-12-15	ND	ND	ND	ND	ND	13.00	1.98	15.46	61.5	ND	0.1
SG-12-30	1.3	ND	ND	ND	ND	372	4.16	12.18	63.72	ND	0.49
SG-12-45	12.5	26.3	ND	1.3	2.0	1141	7.00	11.49	83.27	ND	ND
SG-12-60	11.4	32.8	3.5	8.9	1.4	2099	5.90	11.42	75.13	ND	ND
SG-13-15	ND	ND	ND	ND	ND	32	1.68	17.67	71.38	ND	ND
SG-13-30	1.1	9.4	ND	1.4	ND	389	4.13	14.21	70.75	ND	ND
SG-13-45	2.1	13.2	ND	ND	2.0	1044	6.64	12.18	82.76	ND	ND
SG-13-45DUP	2.3	14.9	ND	ND	5.5	1116	6.81	11.88	82.48	ND	ND
SG-13-60	ND	4.2	ND	11.6	ND	816	2.80	15.50	75.53	ND	ND

Table 3-1. Summary of Soil Gas Survey Anayltical Results at SWMU ST-341

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Sample ID	Benzene ug/L	Toluene ug/L	Ethylbenzene ug/L	M&P-Xylene ug/L	O-Xylene ug/L	TPH-Gas PPM	CO_2 %	Oxygen %	Nitrogen %	Methane %	CO %
SG-14-15	ND	ND	ND	ND	ND	ND	1.88	17.81	70.46	ND	0.43
SG-14-30	ND	2.3	1.1	ND	ND	89	5.56	12.43	73.66	ND	0.74
SG-14-45	ND	7.5	ND	ND	ND	4327	6.85	9.62	63.41	ND	ND
SG-14-45DUP	ND	17.5	ND	12.0	2.8	5633	6.90	10.44	66.47	ND	ND
SG-14-60	ND	12.2	ND	ND	ND	9211	8.23	9.56	69.14	ND	ND
SG-15-15	ND	2.8	1.8	3.1	1.7	38	1.25	17.66	67.37	ND	ND
SG-15-30	17.0	57.0	2.7	26.0	8.5	1531	6.15	11.24	67.69	ND	ND
SG-15-30DUP	17.9	56.0	2.6	26.0	8.0	1569	5.90	10.89	65.79	ND	0.39
SG-15-45	1.4	5.7	2.2	1.6	ND	1251	8.06	11.95	75.53	ND	ND
SG-15-60	3.0	12.7	4.6	8.5	2.0	2992	10.31	9.63	74.34	ND	ND
SG-16-15	ND	1.8	ND	ND	ND	42	2.12	16.50	67.54	ND	ND
SG-16-30	1.3	1.4	ND	2.3	ND	359	4.51	12.57	68.04	ND	0.42
SG-16-45	ND	48.8	5.2	37.5	8.1	9418	8.60	10.92	77.04	ND	ND
SG-16-60	24.5	66.4	1.3	4.8	3.3	12366	9.86	12.64	81.54	ND	ND
SG-17-15	ND	ND	ND	ND	ND	27	1.73	17.45	70.66	ND	ND
SG-17-30	ND	ND	ND	1.1	ND	18	0.17	19.34	66.21	ND	0.27
SG-17-30B	ND	8.5	ND	6.4	6.9	3992	7.92	10.77	67.97	ND	ND
SG-17-45	1.6	17.8	2.0	1.2	ND	2476	10.59	9.02	76.01	ND	ND
SG-17-60	ND	5.7	ND	4.6	ND	2071	5.74	15.00	73.99	ND	ND
SG-18-15	ND	ND	ND	ND	ND	ND	0.37	18.75	65.66	ND	ND
SG-18-15B	ND	ND	ND	1.1	2.8	185	6.26	12.13	65.69	ND	ND
SG-18-30	ND	3.5	1.5	6.0	4.0	910	1.38	17.79	69.14	ND	ND
SG-18-30B	ND	12.9	ND	ND	1.4	7180	10.43	7.71	69.47	ND	ND
SG-18-45	ND	40.7	13.1	17.9	4.3	12655	5.13	15.11	72.25	ND	ND
SG-18-60	ND	27.3	2.3	8.2	6.9	21825	10.92	7.30	66.76	ND	ND
SG-19-15	ND	2.3	ND	1.4	ND	38	1.42	17.48	67.68	ND	0.14
SG-19-15B	ND	ND	ND	ND	ND	189	4.89	14.62	67.85	ND	ND
SG-19-30	ND	1.0	ND	19.5	6.5	332	1.14	18.30	67.37	ND	0.16
SG-19-30DUP*	ND	3.1	1.4	51.4	17.3	2476	5.55	11.33	70.75	ND	ND
SG-19-45	ND	6.4	ND	ND	ND	533	3.16	17.73	65.98	ND	ND

Table 3-1. Summary of Soil Gas Survey Anayltical Results at SWMU ST-341

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Sample ID	Benzene ug/L	Toluene ug/L	Ethylbenzene ug/L	M&P-Xylene ug/L	O-Xylene ug/L	TPH-Gas PPM	CO_2 %	Oxygen %	Nitrogen %	Methane %	CO %
SG-19-45B	ND	28.3	2.8	2.4	6.2	4216	9.47	9.41	73.23	ND	ND
SG-19-60	4.9	14.8	5.6	1.9	1.2	3443	9.58	9.09	72.34	ND	ND
SG-20-15	ND	ND	ND	ND	ND	ND	9.65	10.75	79.19	ND	ND
SG-20-30	1.8	ND	ND	ND	ND	14	0.16	23.55	80.38	ND	ND
SG-20-30B	ND	ND	ND	ND	ND	780	3.31	15.61	68.86	ND	ND
SG-20-45	ND	ND	ND	2.6	ND	327	0.49	20.28	70.89	ND	ND
SG-20-45B	ND	ND	1.4	2.8	7.7	735	2.89	17.93	68.50	ND	ND
SG-20-45C	ND	15.3	ND	1.1	2.7	1447	14.61	4.36	73.24	ND	ND
SG-20-60	ND	1.5	3.4	2.1	2.3	2921	11.45	6.27	65.47	ND	ND
SG-20-60DUP	ND	2.2	4.3	3.0	4.9	3164	12.34	6.76	70.82	ND	ND
SG-21-15	ND	ND	ND	ND	ND	10	0.71	21.77	79.80	ND	ND
SG-21-15B	ND	2.2	ND	10.3	6.1	279	5.30	14.00	67.23	ND	ND
SG-21-30	ND	1.6	ND	2.2	2.0	312	6.63	12.82	79.93	ND	ND
SG-21-45	ND	1.1	ND	ND	ND	30	0.15	20.99	73.54	ND	ND
SG-21-45B	ND	3.4	5.6	3.0	1.1	839	3.93	11.50	54.00	ND	ND
SG-21-60	ND	16.7	1.0	2.5	2.9	2794	10.06	8.34	70.94	ND	ND
SG-22-15	ND	ND	ND	ND	2.7	ND	8.25	11.96	78.92	ND	ND
SG-22-30	64.3	34.6	5.4	11.6	10.2	970	12.59	5.05	81.27	ND	ND
SG-22-45	ND	ND	1.9	ND	ND	183	0.42	21.09	69.30	ND	ND
SG-22-60	ND	2.2	ND	3.4	1.1	3998	12.19	6.82	73.69	ND	ND
SG-23-15	ND	2.1	ND	1.1	4.3	83	3.08	17.26	74.97	ND	ND
SG-23-30	ND	10.3	2.3	6.3	9.1	556	5.21	13.24	74.60	ND	ND
SG-23-45	ND	1.1	1.5	2.2	ND	1751	9.37	9.26	71.53	ND	ND
SG-23-60	ND	21.3	ND	1.1	3.2	2485	10.79	8.36	70.29	ND	ND
SG-24-15	ND	ND	3.6	ND	ND	54	5.54	15.40	69.55	ND	ND
SG-24-30	ND	1.5	ND	ND	ND	539	4.90	14.47	71.91	ND	ND
SG-24-45	ND	10.7	ND	1.6	ND	3831	10.70	8.21	73.78	ND	ND
SG-24-60	ND	113.2	2.8	1.2	ND	9687	9.22	11.20	74.98	ND	ND
SG-24-60DUP	ND	179.0	1.5	6.2	ND	13763	9.10	11.41	72.73	ND	ND

Table 3-1. Summary of Soil Gas Survey Anayltical Results at SWMU ST-341

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Sample ID	Benzene ug/L	Toluene ug/L	Ethylbenzene ug/L	M&P-Xylene ug/L	O-Xylene ug/L	TPH-Gas PPM	CO_2 %	Oxygen %	Nitrogen %	Methane %	CO %
SG-25-15	ND	37.1	40.4	9.0	9.1	3624	20.86	1.61	73.12	ND	ND
SG-25-30	NA	NA	NA	NA	NA	NA	3.09	18.06	75.13	ND	ND
SG-25-30B	ND	48.5	1.6	26.4	6.3	2615	7.78	11.51	74.12	ND	ND
SG-25-45	ND	52.6	7.3	23.0	5.2	4788	15.08	2.62	76.17	ND	ND
SG-25-60	ND	68.4	ND	3.7	ND	15633	10.84	3.76	76.70	ND	ND

Footnotes:

Complete laboratory analytical results and method detection limits are presented in Appendix E

ND - NOT DETECTED

DUP - Replicate Sample

B - Resample (Based on Questionable Initial Result)

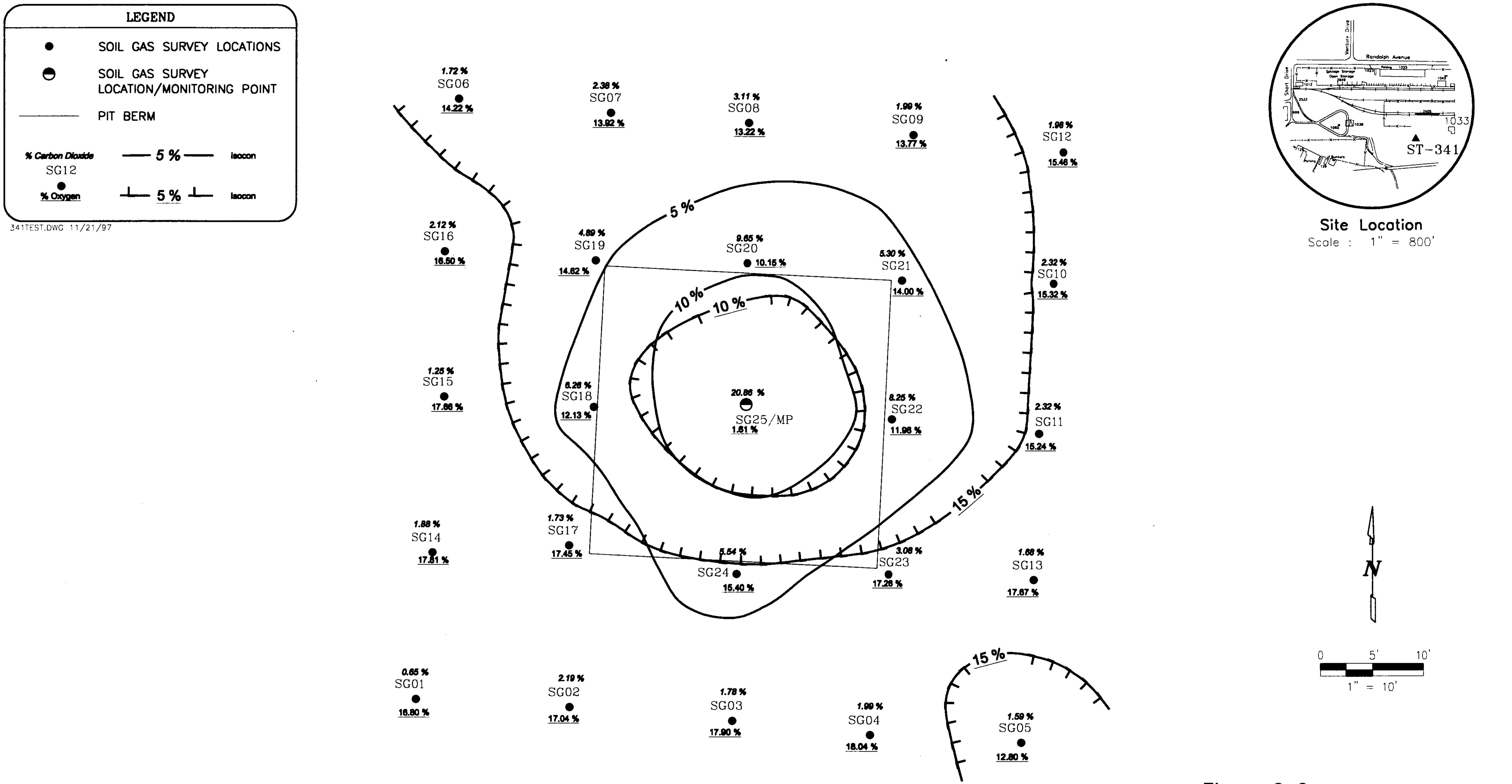

Figure 3-2.

Soil Gas Survey – 15ft Interval, Carbon Dioxide/Oxygen Concentrations

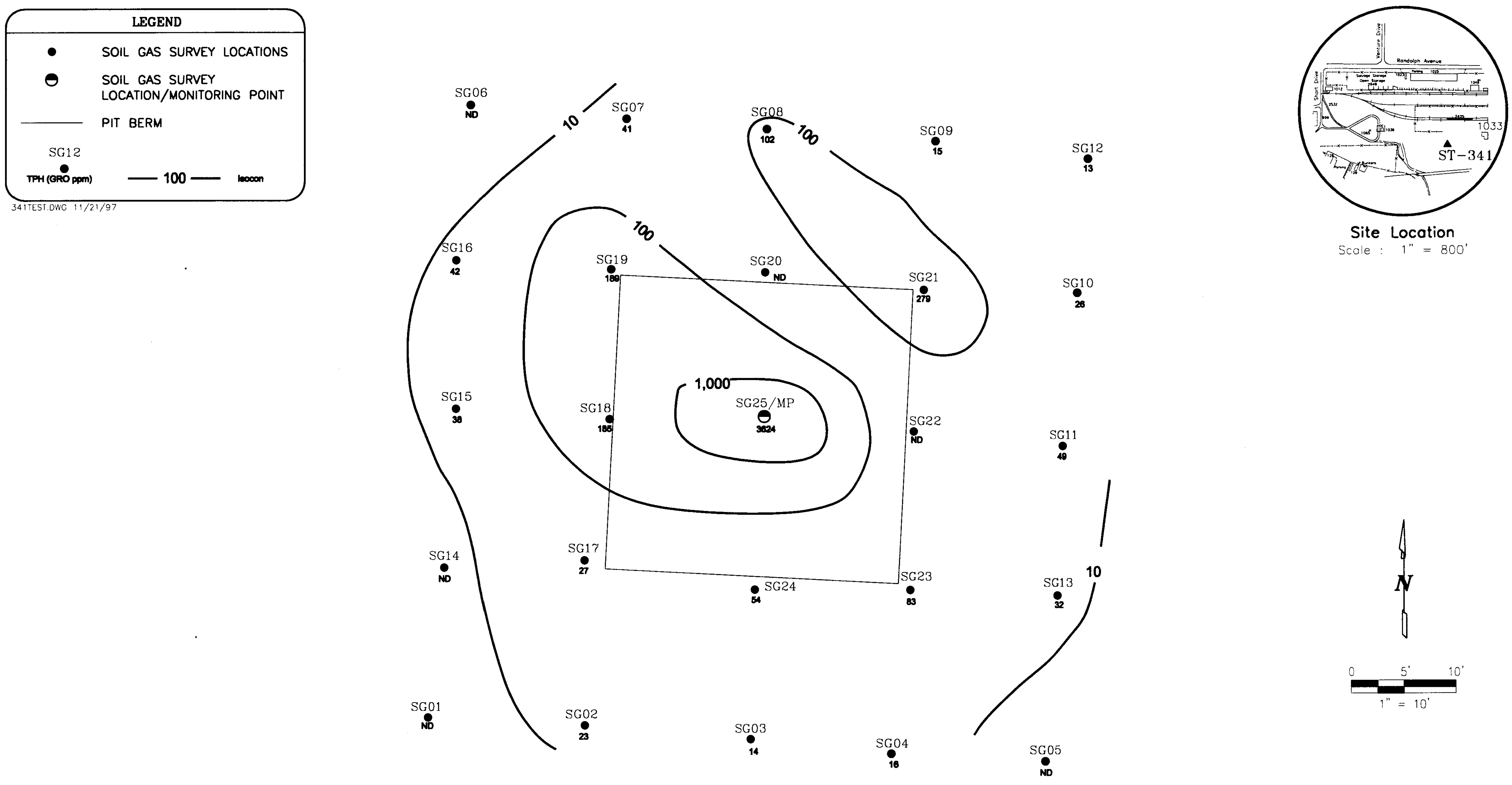

Figure 3-3.

Soil Gas Survey - 15ft Interval, TPH (GRO) Concentrations

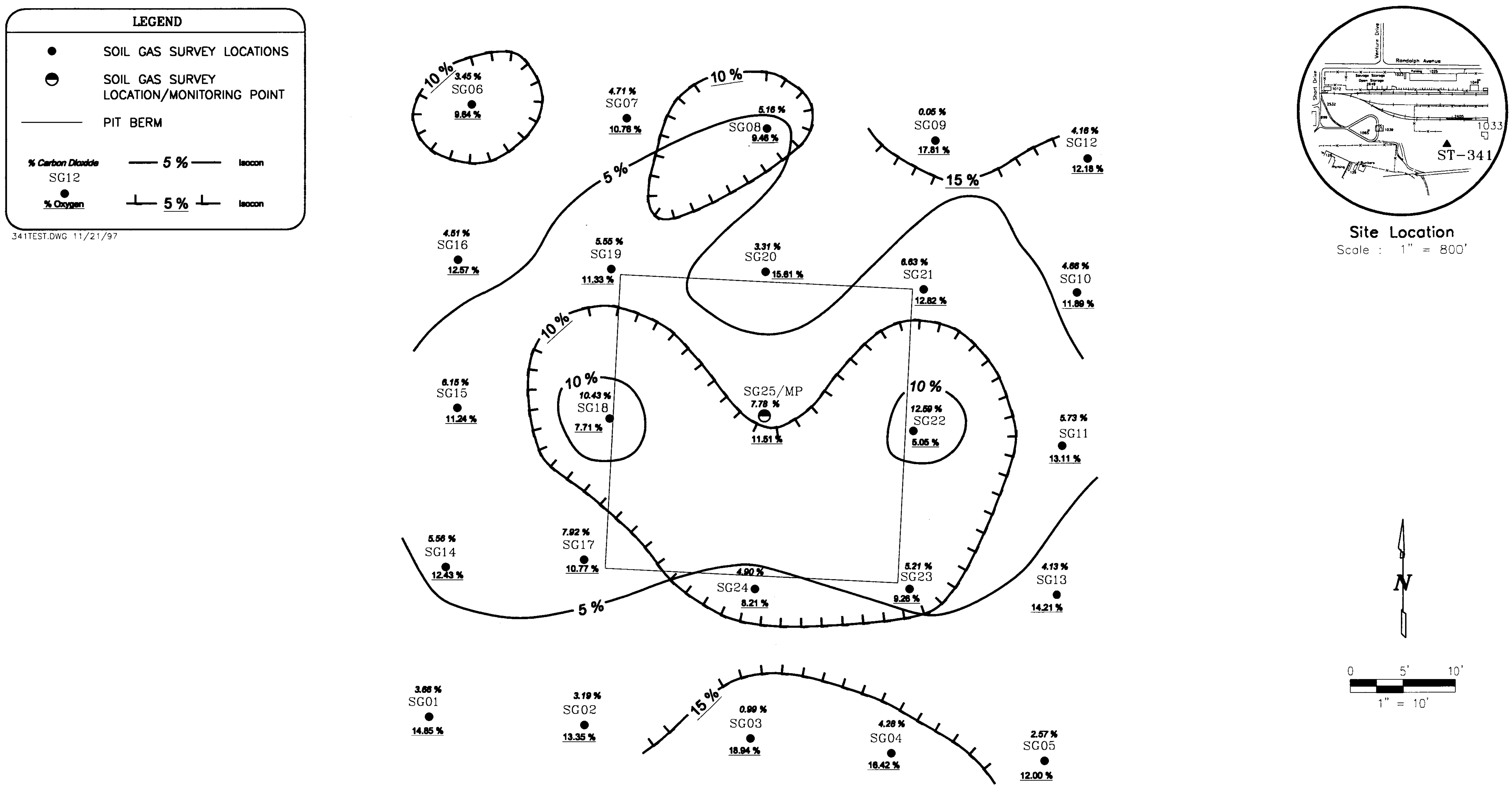

Figure 3-4.

Soil Gas Survey – 30ft Interval, Carbon Dioxide/Oxygen Concentrations

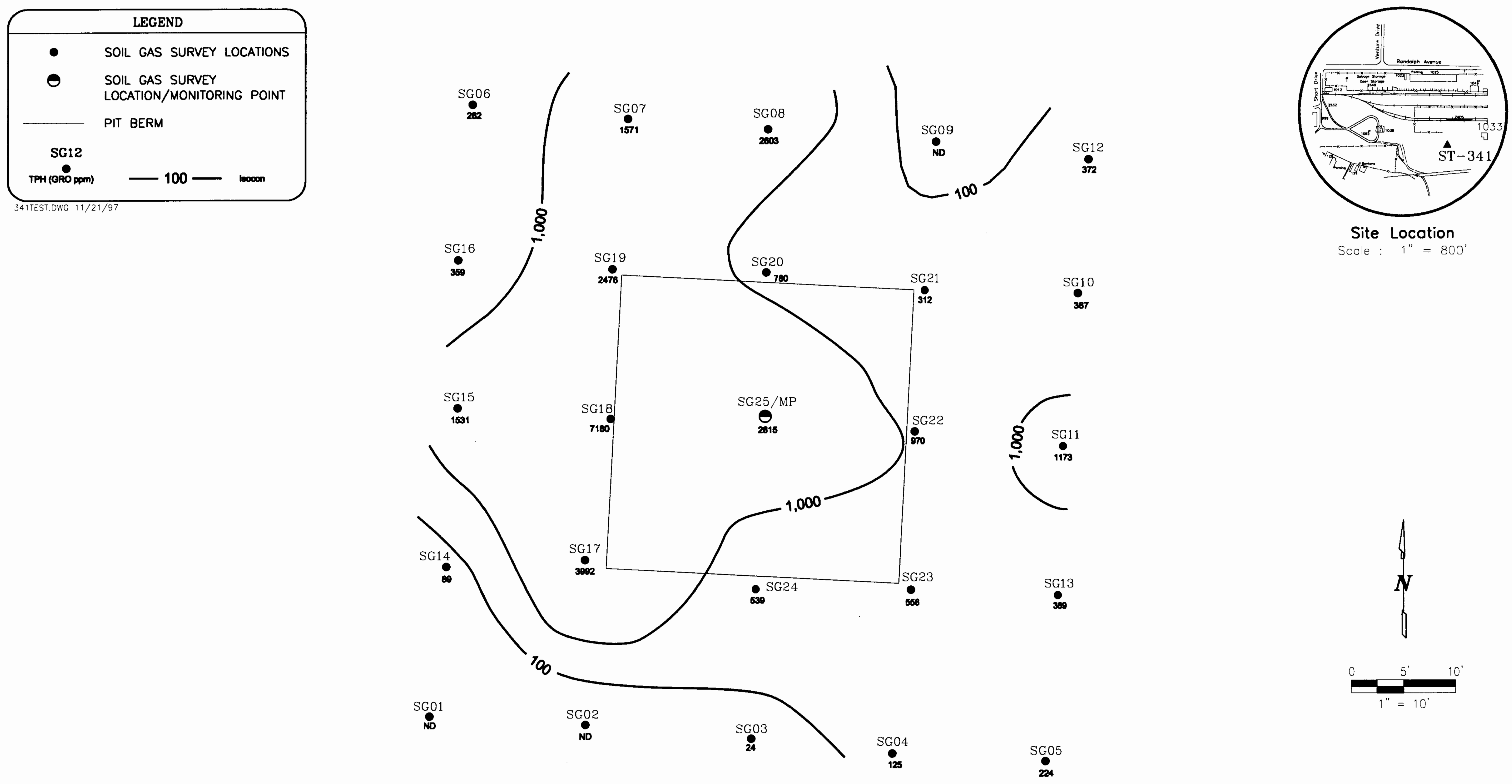

Figure 3-5.

Soil Gas Survey – 30ft Interval, TPH (GRO) Concentrations

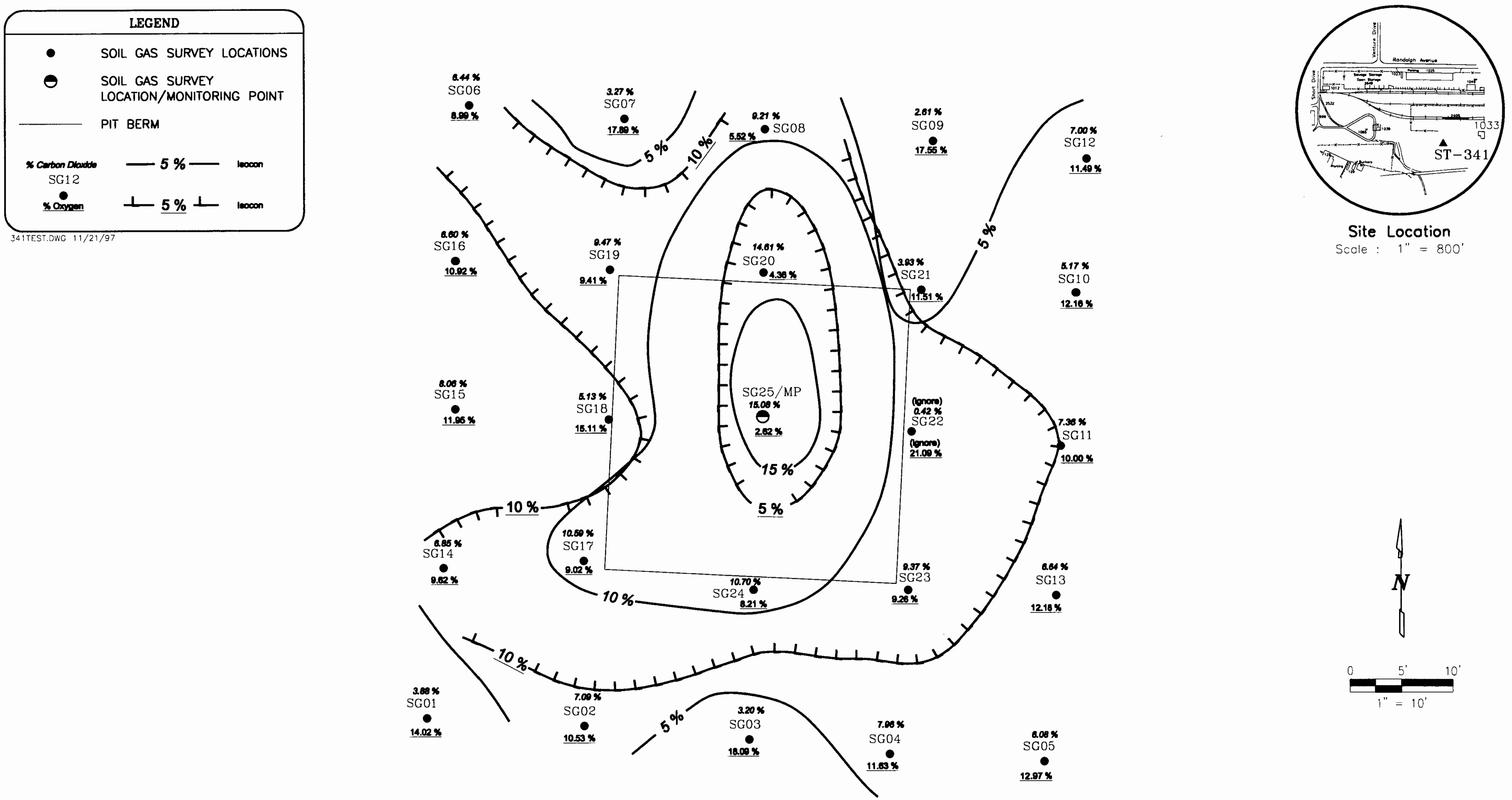

Figure 3-6.

Soil Gas Survey – 45ft Interval, Carbon Dioxide/Oxygen Concentrations

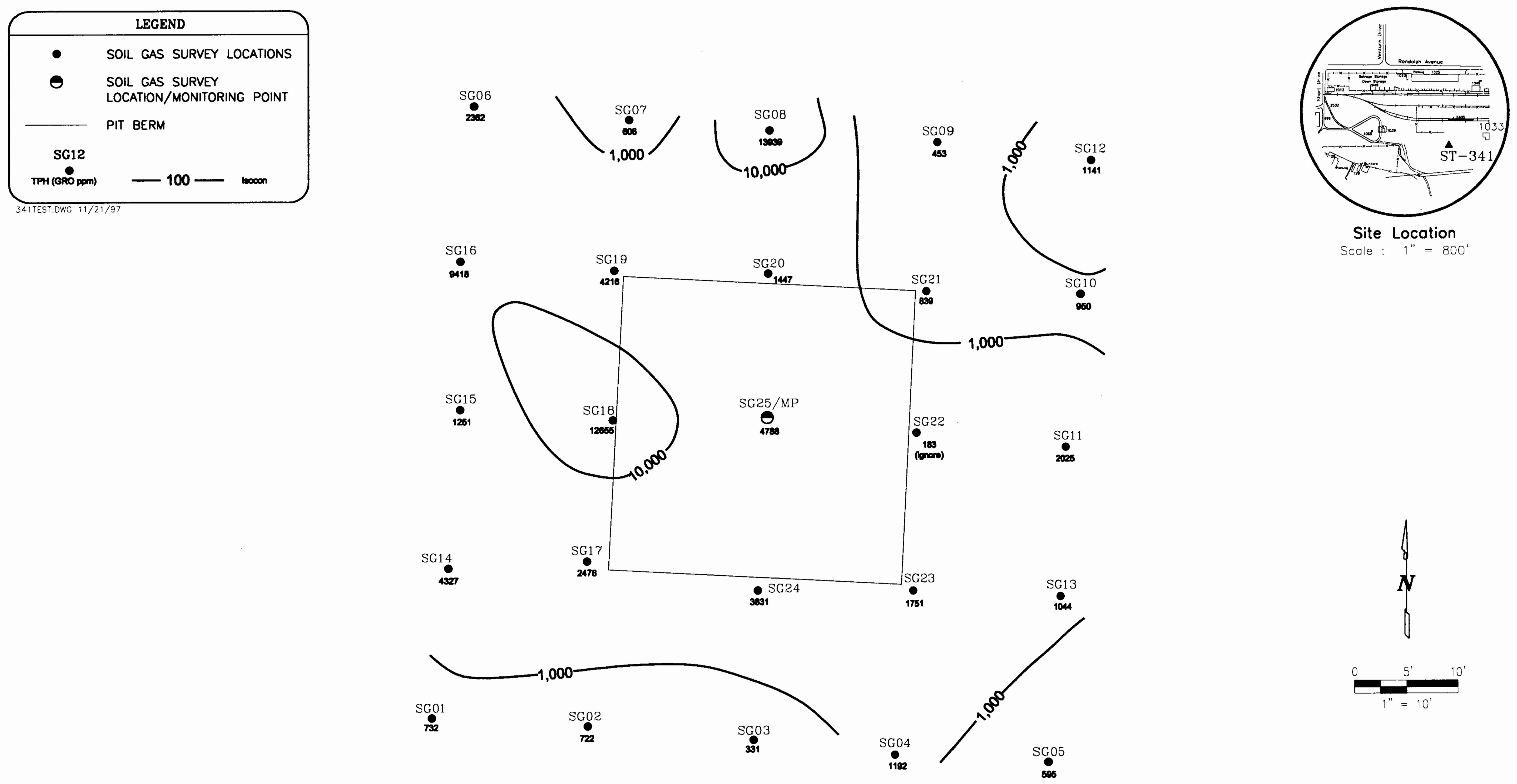

Figure 3-7.

Soil Gas Survey – 45ft Interval, TPH (GRO) Concentrations

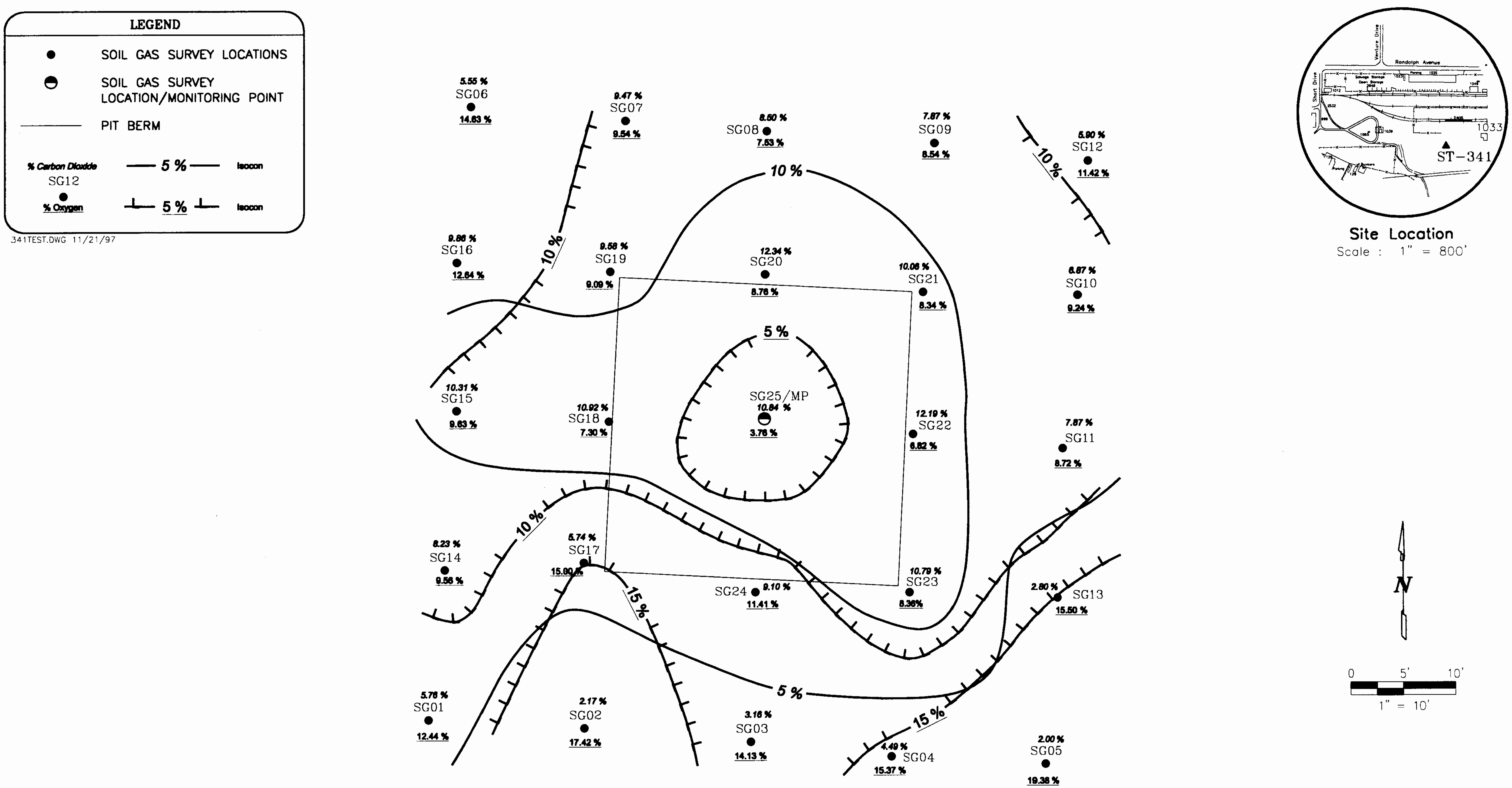

Figure 3-8.

Soil Gas Survey – 60ft Interval, Carbon Dioxide/Oxygen Concentrations

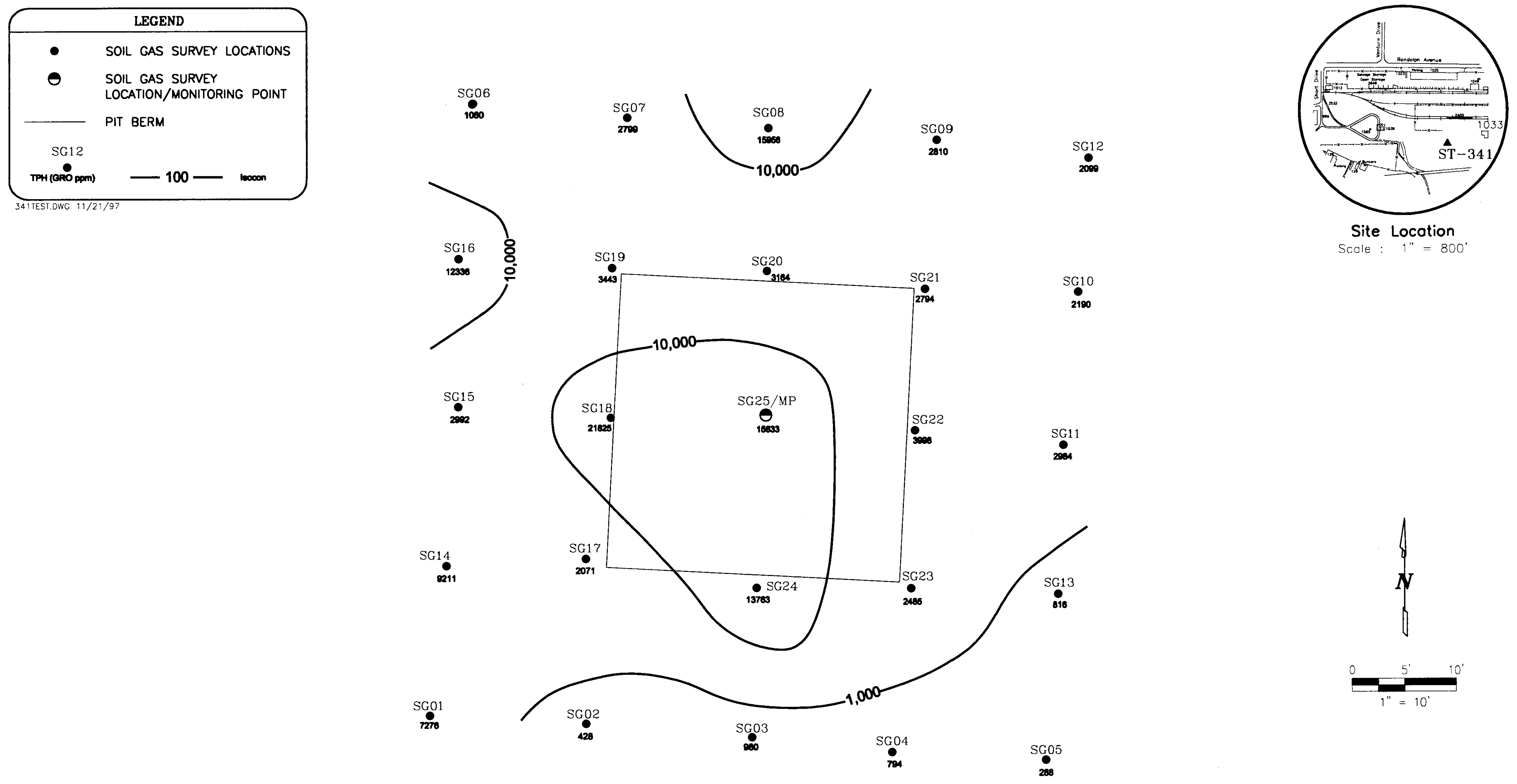

Figure 3-9.

Soil Gas Survey – 60ft Interval, TPH (GRO) Concentrations

oxygen concentrations are presented in Figure 3-10 (north-south cross section) and Figure 3-12 (east-west cross section). TPH concentrations are presented in Figure 3-11 (north-south cross section) and Figure 3-13 (east-west cross section).

Vapor phase TPH was detected in every boring in the soil gas survey grid. TPH soil gas concentrations are highest near the center of the evaporation pond and generally increase with depth. The TPH plume also appears to expand laterally with increasing depth. However, The lateral extent of TPH is not defined for the vapor phase. Carbon dioxide concentrations are highest near the center of the evaporation pond with some variation according to depth. Oxygen concentrations are lowest at the center of the evaporation pond with some variation according to depth. The relationship of carbon dioxide and oxygen concentrations to TPH concentrations indicate that aerobic biodegradation is occurring at the site, resulting in oxygen depletion and carbon dioxide production at the center of the plume. The results of the soil gas survey indicate that subsurface oxygen concentrations at the site are a limiting condition for hydrocarbon biodegradation. Aeration through air injection is the preferred method for increasing subsurface oxygen concentrations (EPA, 1995a and b). Air injection results in minimal discharge of volatile organics to the atmosphere and aerobic biodegradation by creating an in situ bioreactor. If the contaminants are volatile, some will migrate in the gas phase into the surrounding soil where they can biodegrade. Chapter 4 discusses the feasibility of air injection as a method of oxygen delivery at the site.

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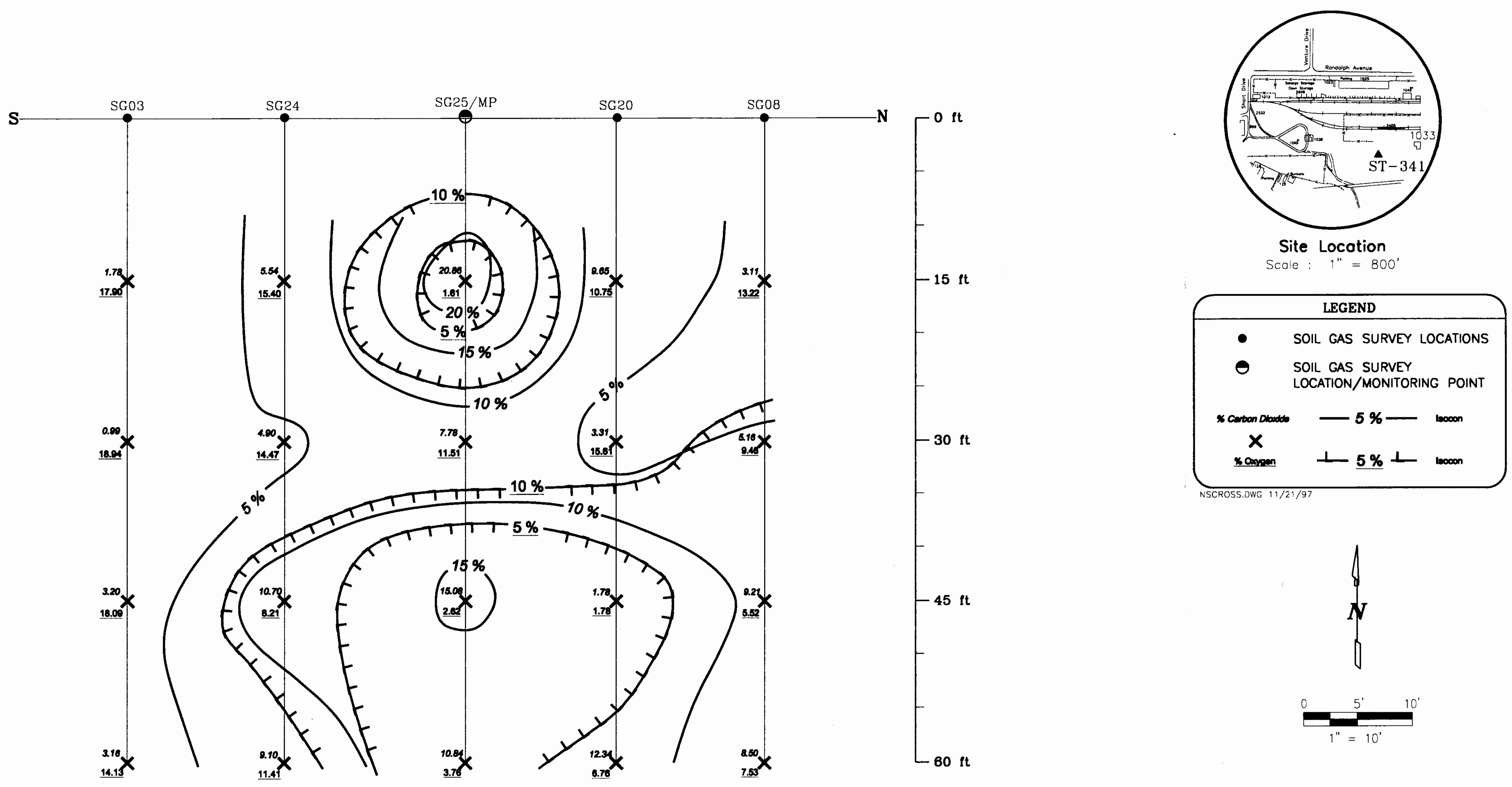


Figure 3-10.

Soil Gas Survey - North-South Cross Section, Carbon Dioxide/Oxygen Concentrations

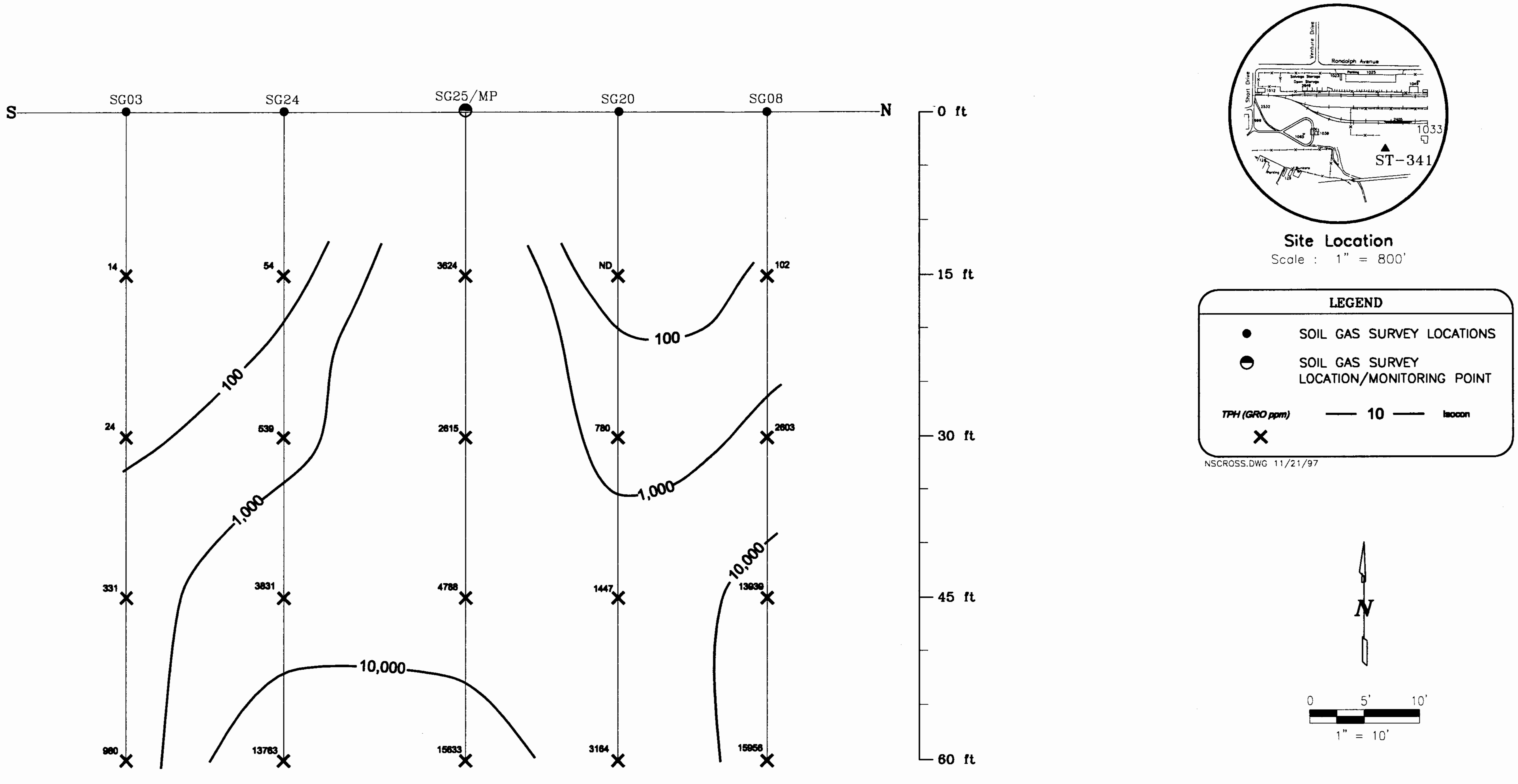


Figure 3-11.

Soil Gas Survey – North-South Cross Section, TPH (GRO) Concentrations

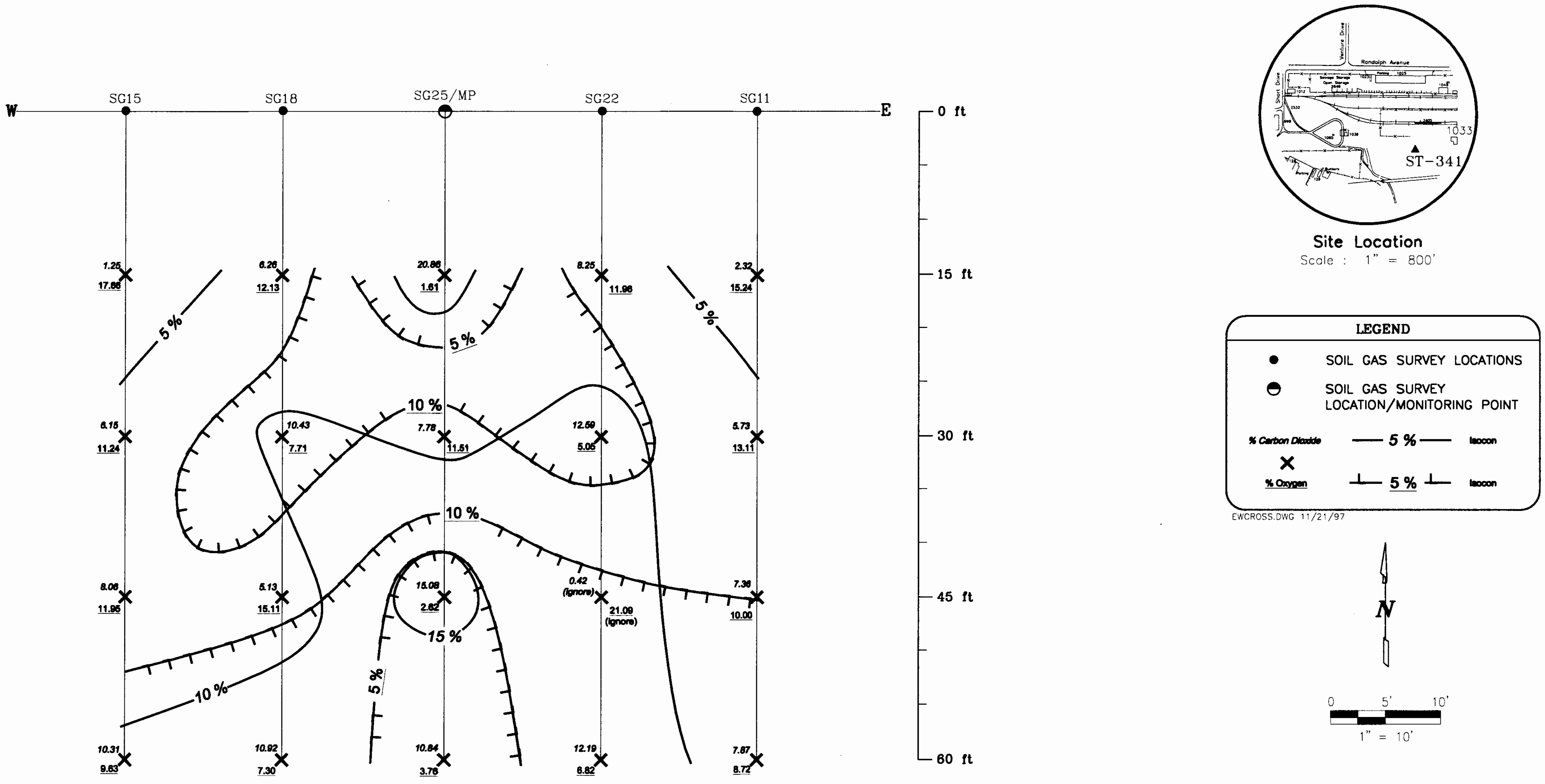


Figure 3-12.

Soil Gas Survey – East-West Cross Section, Carbon Dioxide/Oxygen Concentrations

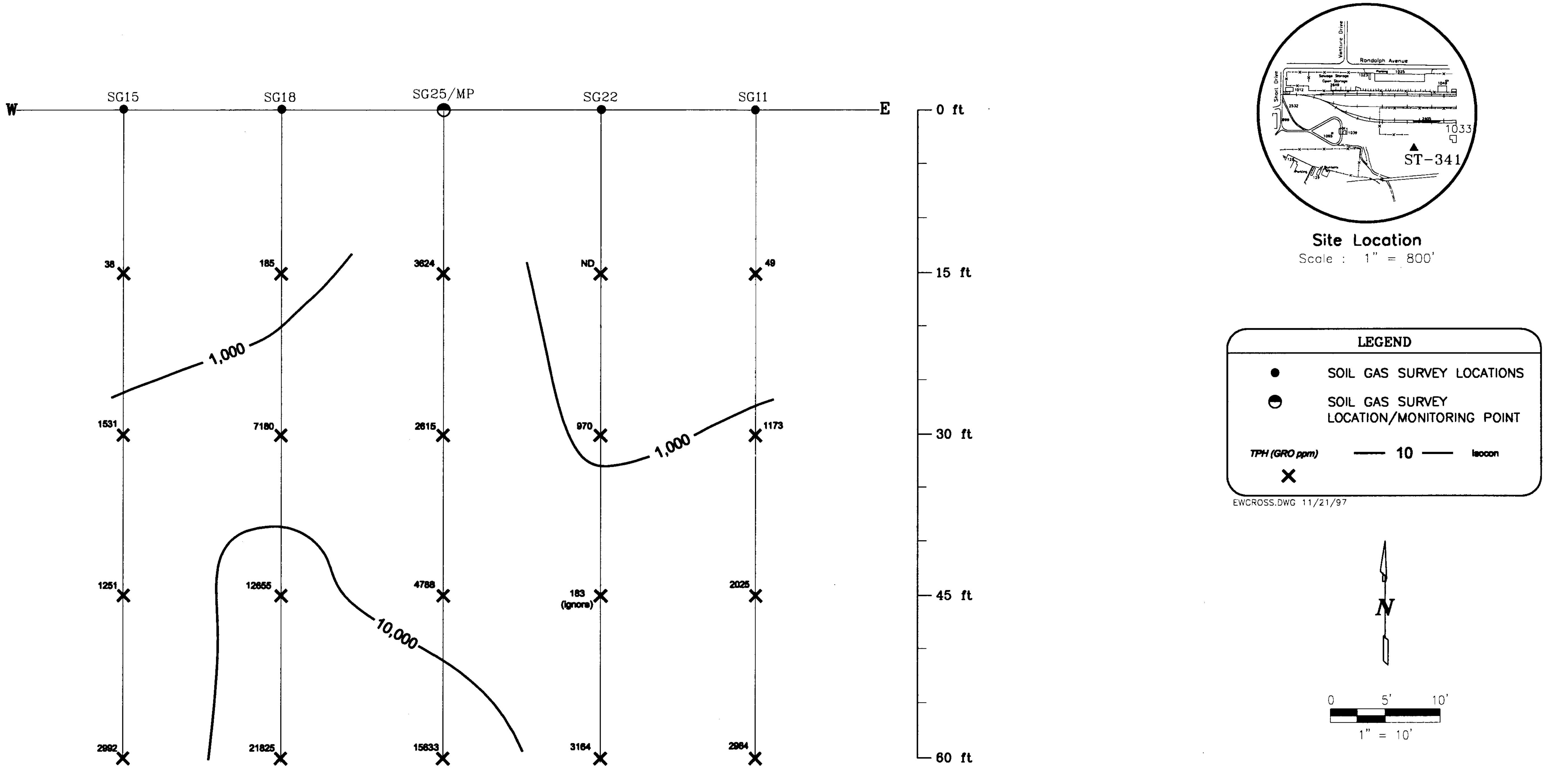


Figure 3-13.

Soil Gas Survey – East-West Cross Section, TPH (GRO) Concentrations

Section 4

4. SOIL GAS PERMEABILITY TEST

The soil gas permeability test was designed to determine the site pressure radius of influence, which has been found at Bioventing Initiative sites, to represent a conservative measure of the oxygen radius of influence (EPA, 1995a,b). The soil gas permeability test also provided data necessary to calculate the intrinsic permeability at the site. The radius of influence and intrinsic permeability are critical design parameters for the bioventing pilot study.

4.1 Methodology

The soil gas permeability test utilized the five existing soil venting wells (ST341-13 and ST341-22 through ST341-25) and two additional wells (ST341-27 and MP) shown on Figure 4-1. The two additional wells (ST341-27 and MP) were installed on September 23, 1997 using conventional HSA drilling techniques. Vapor monitoring well ST341-27 was installed approximately 20 ft west of the air injection well (ST341-24) to provide short distance pressure influence data during the test. It is constructed of 2 in. diameter Schedule 40 PVC screened from 25 to 65 ft bgs with 0.01 slot well screen. The borehole annulus contains 10/20 silica sandpack surrounding the well screen and bentonite chips surrounding the blank PVC casing. Nested well MP was installed in the center of the evaporation pond primarily for use in the in-situ respiration test. However, it was utilized during the soil gas permeability test to provide pressure influence data at the discrete depth intervals of 15, 30, 45, and 60 ft bgs. Nested well MP contains four individual vapor implants constructed of 0.5 ft long, 0.5 in. diameter stainless steel screen attached to 0.25 in. diameter polyethylene tubing. The screened intervals are designated MP15, MP30, MP45, and MP60 and are installed at 15, 30, 45, and 60 ft bgs, respectively. The borehole annulus surrounding each screened interval contains 1.5 ft of 8/12 silica sandpack; the sand pack intervals are segregated from one another by 12.5 ft intervals of bentonite chips. Well installation diagrams for vapor monitoring well ST341-27 and nested well MP are included in Appendix C.

The soil gas permeability test was performed on September 25, 1997. Two 1.5 horsepower Rotron DR454 regenerative blowers were connected in parallel to air injection well ST341-24. The inlet to air injection well ST341-24 was fitted with a thermometer to monitor injected air temperature and a flowmeter to regulate airflow. The inlet was also ported to monitor the air injection pressure. The vapor monitor wells (ST341-13, -22, -23, -25, and -27) and the nested MP wells (MP15, MP30, MP45, and MP60) were sealed and ported for pressure monitoring. Magnehelic pressure gauges capable of accurately measuring an overall range of 0 to 100 in H_2O were used to monitor pressure.

The soil gas permeability test was performed using stepped air injection rates. Air was injected into well ST341-24 at three stepped flow rates of 20, 60, and 120 cfm (0.5, 1.5, and 3 cfm per foot of well screen). Air-flow rates, injected air temperature, and pressure were monitored for the duration of the test. Readings were recorded frequently during the first 30 minutes of each step (2- to 5-minute intervals); the reading frequency was decreased (10- to 15-minute intervals) as asymptotic conditions were approached. Pressure was measured at the monitoring points until steady-state conditions were reached (2 to 3 hours per test). Upon reaching asymptotic conditions during each step, the air injection rate was increased to the level designated for the subsequent test phase. The test was completed when asymptotic conditions were reached during the third test phase (120 cfm air-flow rate).

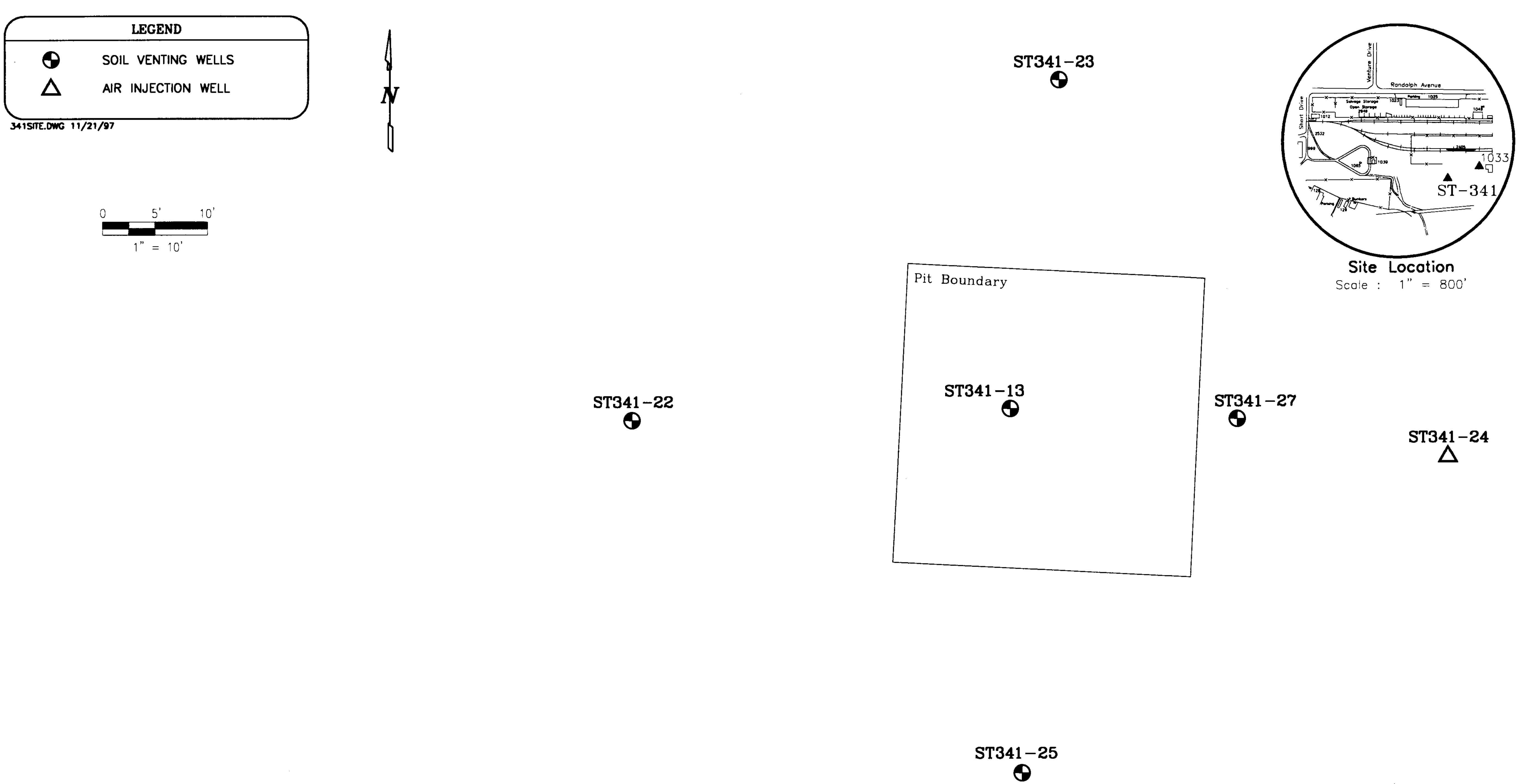


Figure 4-1.

SWMU ST-341, Soil Gas Permeability Test Well Locations

4.2 Results

Soil gas permeability test field data sheets are included in Appendix C. Semi-log plots of pressure readings versus distance from the air injection well are presented in Figure 4-2. Figure 4-2 represents the pressures measured from the vapor monitoring wells at steady state conditions during the 20 cfm, the 60 cfm, and the 120 cfm air injection test phases. It has been empirically determined at Bioventing Initiative sites that the distance at which the resulting pressure-distance curve intersects a pressure of 0.1 inches H_2O is the radius of influence (EPA, 1995a,b). As shown on Figure 4-2, the pressure radius of influence at the site is approximately 95 ft at an air injection flow rate of 20 cfm, 242 ft at an air injection rate of 60 cfm, and 258 ft at an air injection rate of 120 cfm. Figures 4-3, 4-4, and 4-5 present semi-log plots of pressure changes over time during the 20 cfm, 60 cfm, and 120 cfm steps of the soil gas permeability test, respectively.

Data from the soil gas permeability test was also used to calculate the intrinsic permeability at the site. Analysis of the test data was performed using the methodology described by Johnson et. al., 1990. The flow rate and transient pressure distribution data can be used to estimate the soil permeability to vapor flow. The expected change in the subsurface pressure distribution with time $P'(r,t)$ is predicted by equation 1:

$$(1) \qquad P' = \frac{Q}{4\pi m(k/u)} \int_{\frac{r^2 \varepsilon \mu}{4kP_{atm}t}}^{\infty} \frac{e^{-x}}{x} dx$$

For $\left(r^2 \varepsilon \mu / 4kP_{atm}t\right) < 0.1$, the equation can be approximated by equation 2:

$$(2) \qquad P' = \frac{Q}{4\pi m(k/u)} \left[-0.5772 - \ln\left(\frac{r^2 \varepsilon \mu}{4kP_{atm}} \right) + \ln(t) \right]$$

where:

P'	= gauge pressure measured at distance r and time t
m	= stratum thickness
r	= radial distance from vapor extraction well
k	= soil permeability to air flow
μ	= viscosity of air = 1.8×10^{-4} g/cm-s
ε	= air-filled soil void fraction
t	= time
Q	= volumetric vapor flow rate from extraction well
P_{atm}	= ambient atmospheric pressure = 1.0 atm = 1.013×10^6 g/cm-s^2

Figure 4-2. Soil Gas Permeability Test, Pressure-Distance Relationship at Asymptoptic Conditions at SWMU ST-341

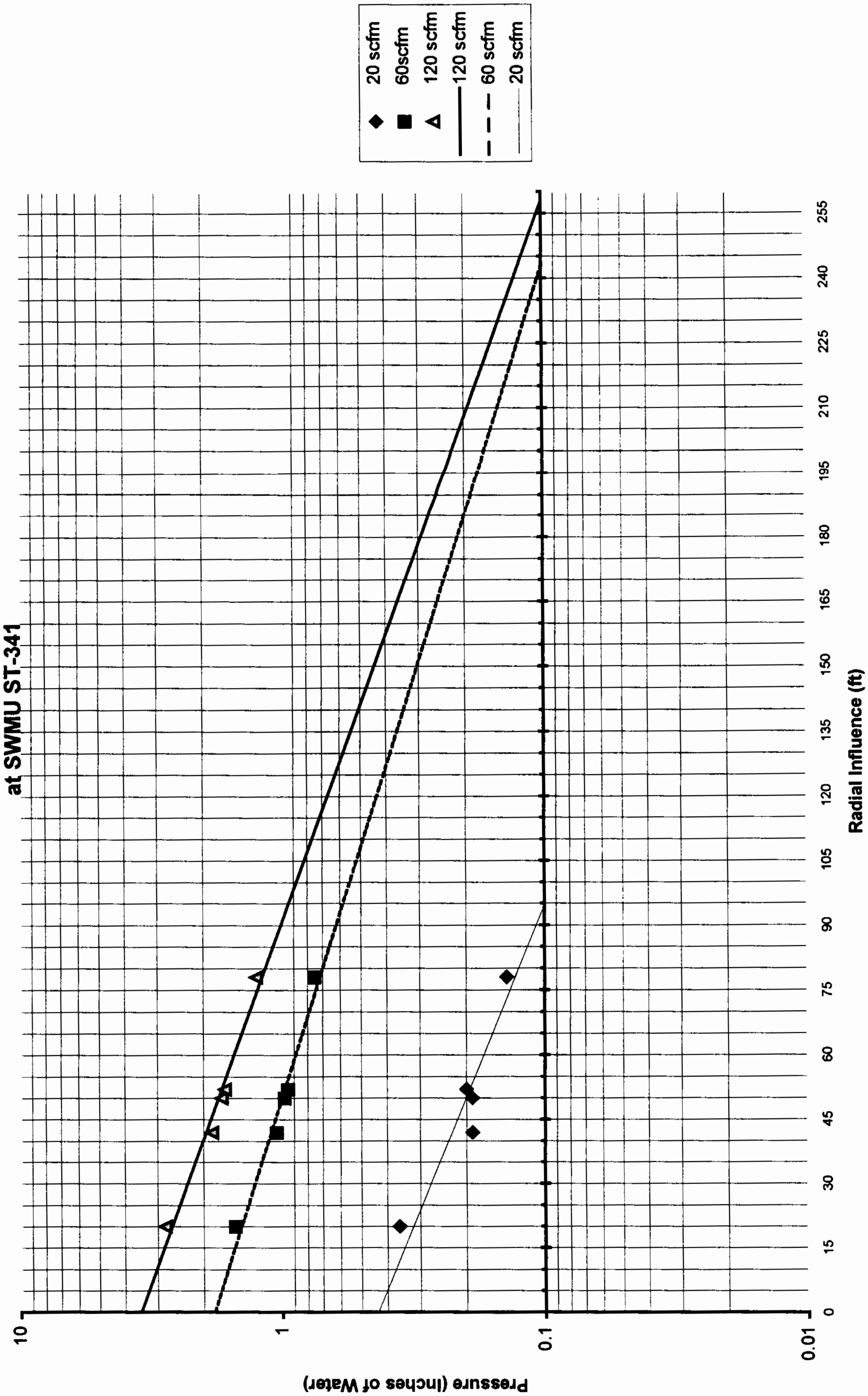


Figure 4-3. Soil Gas Permeability Test, Pressure-Time Relationship at 20 scfm at SWMU ST-341

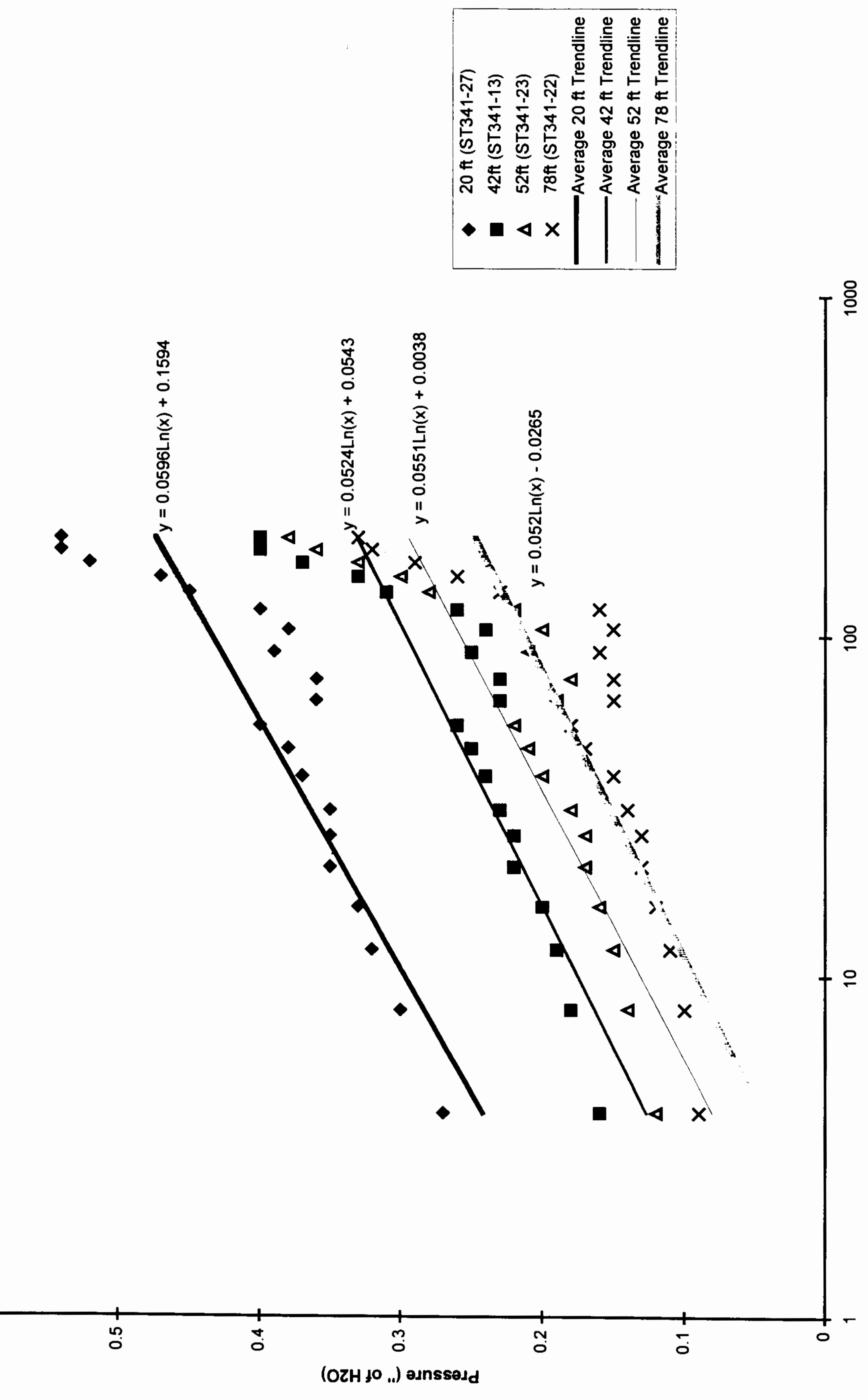


Figure 4-4. Soil Gas Permeability Test, Pressure-Time Relationship at 60 scfm at SWMU ST-341

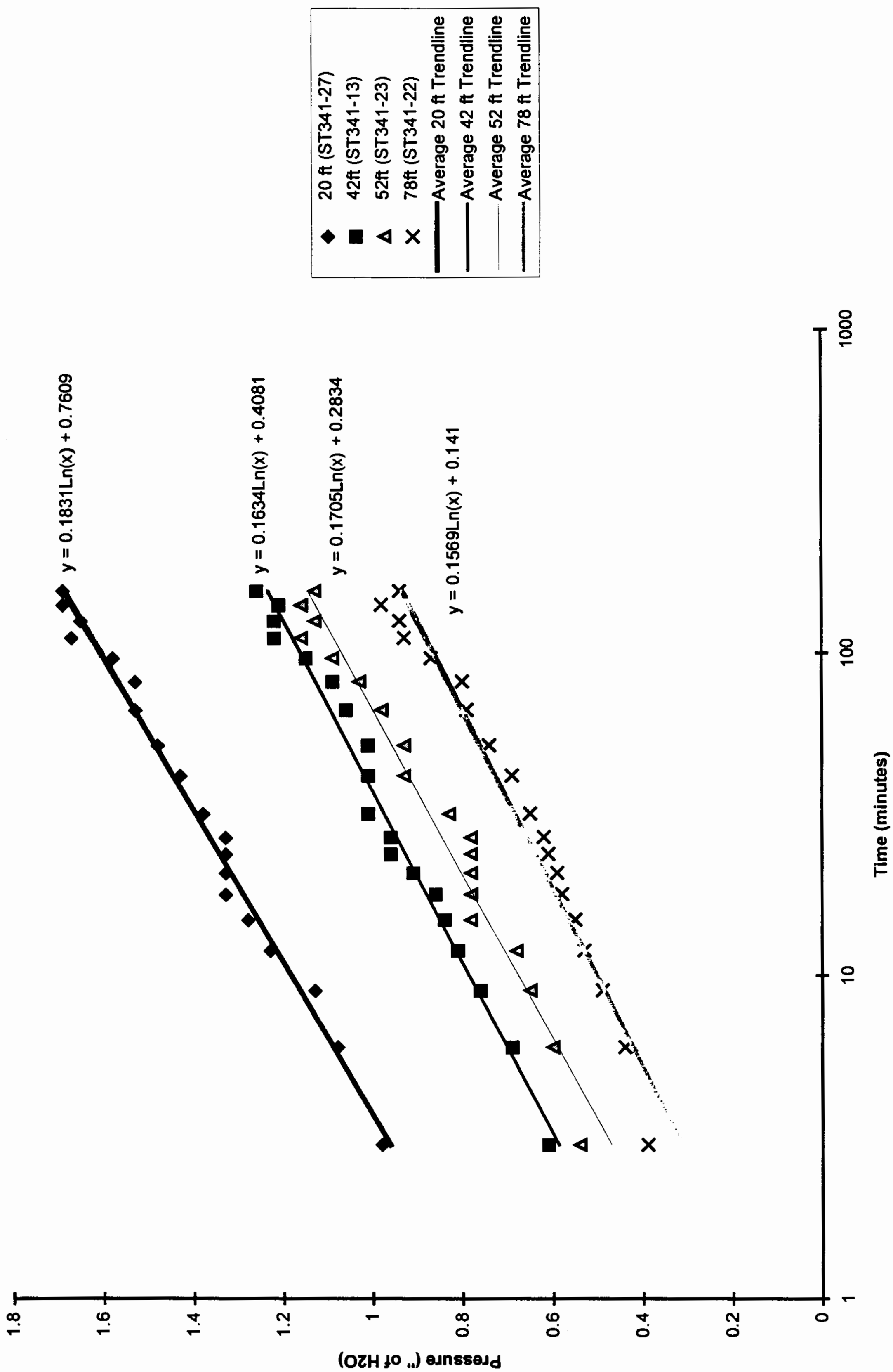
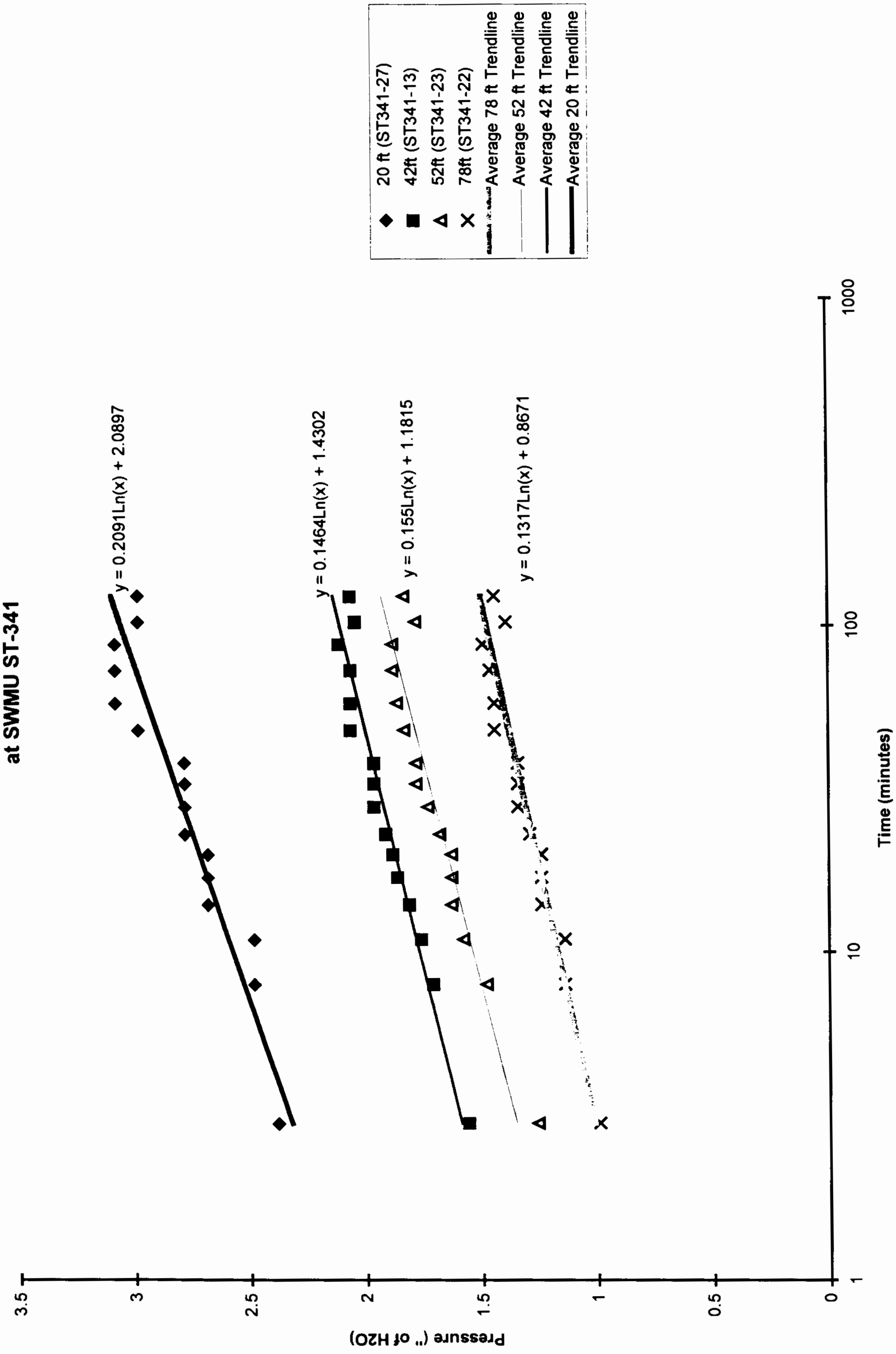


Figure 4-5. Soil Gas Permeability Test, Pressure-Time Relationship at 120 scfm at SWMU ST-341



Equation 2 predicts a plot of *P'* vs *ln*(*t*) should be a straight line with slope *A* and *y*-intercept *B* equal to:

(3) $$A = \frac{Q}{4\pi m(k/u)}$$

(4) $$B = \frac{Q}{4\pi m(k/u)}\left[-0.5772 - \ln\left(\frac{r^2 \varepsilon \mu}{4kP_{atm}}\right)\right]$$

When *Q* and *m* are known, as they are for this test, permeability to vapor flow can be calculated using the following equation:

(5) $$k = \frac{Q\mu}{4A\pi m}$$

Where:

k	= soil permeability to air flow
Q	= volumetric vapor flowrate from injection well
μ	= viscosity of air = 1.8 x 10^{-4} g/cm-s
A	= calculated slope
m	= stratum thickness

Intrinsic permeability can be calculated from the soil permeability to air flow using the following equation (Freeze and Cherry, 1979):

(6) $$K = \frac{k\mu}{\rho g}$$

where:

K	= intrinsic permeability
k	= soil permeability to air flow
μ	= viscosity of air = (1.8 x 10^{-4} g/cm-s)
ρ	= density of air (1.205 x 10^{-3}g/cm^3)
g	= gravitational acceleration (9.8 x 10^{-2}g/cm/S^2)

Values of intrinsic permeability flow were calculated for the 60 and 120 cfm flow rate steps of the permeability test. Soil permeability was not calculated for the 20 cfm flow rate because of a barometric pressure change which occurred between 55 and 130 minutes of that air injection step (Figure 4-3). For the 60 cfm flow rate, the intrinsic permeability had a calculated range of 4.21 x 10^{-6}cm^2 to 7.66 x 10^{-6}cm^2 or to 4.25 x 10^2 darcy to 7.74 x 10^2 darcy. For the 120 cfm flow rate, the intrinsic permeability had a calculated range of 9.83 x 10^{-6}cm^2 to 1.83 x 10^{-5}cm^2 or 9.48 x 10^2 darcy to 1.85 x 10^3 darcy. The calculations of soil permeability are presented in Appendix G.

The intrinsic permeability at SWMU ST-341 evaporation pond is well in excess of the 0.1 darcy threshold for sufficient air exchange. Therefore, this site is suitable for applying bioventing technology in terms of soil air permeability.

Section 5

5. IN-SITU RESPIRATION TEST

The in-situ respiration test was designed to provide the data necessary to calculate the oxygen utilization rate of microbial populations at the site. The test was performed in accordance with Bioventing Initiative guidelines for in-situ respiration testing (EPA 1995a,b). Helium was injected as a tracer gas in conjunction with the oxygen. The helium data collected during the test provides confirmation whether measured oxygen utilization rates are actually caused by microbial utilization or by other effects such as leakage or diffusion (EPA, 1995a,b). The helium diffuses out of the soil column about three times faster than oxygen. Therefore, the helium is considered a conservative tracer. The oxygen utilization rate will be used in the bioventing pilot study design.

Respiration testing is based on the principle that biodegradation is fundamentally an electron transfer process. Biological energy is obtained through the oxidation of reduced materials. Microbial enzymes catalyze the electron transfer. Electrons are removed from organic substrates to capture the energy that is available through the oxidation process. The electrons are moved through respiratory or electron transfer chains (metabolic pathways) composed of a series of compounds to terminal electron acceptors. A large proportion of the microbial population in soil depends upon oxygen as the terminal electron acceptor for metabolism. Loss of oxygen induces a change in the activity and composition of the soil microbial population. Biodegradation can occur under both aerobic (oxygen present) and anaerobic (oxygen absent) conditions; aerobic biodegradation is typically more efficient (WDNR, 1994).

A wide variety of organic materials are easily degraded under aerobic conditions. In aerobic metabolism, O_2 is the terminal electron acceptor. When biodegradation follows this pattern, microbial populations quickly adapt and reach high densities. As a result, the rate of biodegradation quickly becomes limited by rate of supply of oxygen, not the inherent microbial capacity to degrade the contaminant. The ultimate products of aerobic metabolism are carbon dioxide and water.

Respiration testing measures oxygen depletion/carbon dioxide production in the soil and provides a measure of the biological activity. A given amount of oxygen is provided to the soil and the levels of oxygen carbon dioxide are measured over time. Increased oxygen depletion/carbon dioxide production in the contaminated area indicates that aerobic biodegradation is occurring.

5.1 Methodology

The in-situ respiration test utilized the nested well monitor point (MP) vapor implants described in Section 4.1 as the four air injection/vapor monitoring points. Nested well MP was installed in the center of the evaporation pond because soil gas survey field screening results indicated that the center of the evaporation pond was the area of most significant oxygen depletion and highest hydrocarbon concentrations. Difficulty was encountered during the soil gas survey in collecting representative soil gas samples at the 30 ft- and 45 ft- intervals of this location (SG25) because of short-circuiting during sample collection. The short-circuiting was thought to occur because of the high vacuum required to extract samples from these intervals containing heavy hydrocarbon residuals and fine-grained soils.

Nested well MP contains four individual vapor implants constructed of 0.5 ft long, 0.5 in. diameter stainless steel screen attached to 0.25 in. diameter polyethylene tubing. The screened intervals are designated MP15, MP30, MP45, and MP60 and are installed at 15, 30, 45, and 60 ft bgs, respectively.

The borehole annulus surrounding each screened interval contains 1.5 ft of 8/12 silica sandpack; the sand pack intervals are segregated from one another by 12.5 ft intervals of bentonite chips. Each vapor implant was equipped with a thermocouple to monitor in-situ soil temperature. Well installation diagrams for nested well MP are included in Appendix C.

The in-situ respiration test was performed from September 29 through October 4, 1997. During the air injection phase, a 185 cubic feet per minute (cfm) compressor was used to supply approximately 45 pounds per square inch (psi) of air to a two in. diameter chlorinated polyvinyl chloride (CPVC) mixing chamber/manifold. The mixing chamber/manifold was equipped with a pressure gauge, temperature gauge, helium inlet port, sample port, and four outlet ports to the vapor implants. Helium was added to the injected air stream at the helium inlet port. The helium flow was controlled using a pressure regulator and flowmeter at the helium tank source. The concentration of helium was monitored through the sample port, using a Marks Model 9821 helium detector, to maintain a helium concentration of approximately three percent. Each of the four outlet ports was equipped with a flowmeter to maintain an airflow of approximately 1.4 cfm to each vapor implant (MP15, MP30, MP45, and MP60). An in-situ respiration test equipment process diagram is included in Appendix C.

Prior to initiating the in-situ respiration test, baseline field screening measurements of oxygen and carbon dioxide concentrations were taken from each monitoring point using the GASTECH GA-90 carbon dioxide/oxygen detector. Beginning September 29, 1997 at 1130 hours, air containing helium (an inert tracer gas) was injected into the vapor implants for approximately 24 hours. The helium concentration was maintained at approximately 3 percent and the injection flow rate was maintained at 1.4 cfm to each vapor implant until air injection was terminated at 1350 hours on September 30, 1997.

Upon the completion of air injection, soil gas samples were extracted from the vapor implants at intervals: immediately upon termination of air injection, every 2 hours for the first 10 hours, and at 5-hour intervals thereafter for 5 days. Temperature readings were taken at the same intervals as soil gas sample collection. The final soil gas samples and temperature readings were collected at 98 hours after termination of air injection. A total of 104 soil gas samples (including replicates) were collected during the in-situ respiration test. Soil gas samples were collected from each vapor implant in the following manner:

- The vapor implant tubing was sealed at all times (when not in use) with dura-clamp valves.

- The vapor implant tubing was connected to the GasTech GA-90 oxygen/carbon dioxide meter and the dura-clamp valve was released. Soil gas was purged until oxygen and carbon dioxide readings stabilized. The dura-clamp valve was resealed and the vapor implant tubing removed from the GasTech GA-90 oxygen/carbon dioxide meter. The vapor implant tubing was connected to the Marks Model 9821 helium detector and the dura-clamp valve was released. Soil gas was purged until helium readings stabilized. The dura-clamp valve was resealed and the vapor implant tubing removed from the Marks Model 9821 helium detector.

- The vapor implant tubing was connected to a vacuum chamber inlet port linked with an enclosed Tedlar bag. A vacuum pump was connected to the outlet port of the vacuum chamber. As vacuum was initiated, the dura-clamp valve was released to allow the soil gas sample to flow from the vapor implant tubing into the Tedlar bag. Once the Tedlar bag was filled, the dura-clamp valve was closed to seal the vapor implant tubing. The vacuum was then released, the vacuum chamber opened, and the Tedlar bag valve closed. The Tedlar bag sample was labeled and delivered to the fixed-base laboratory for oxygen and carbon dioxide analyses.

- A 60 milliliter (ml) syringe equipped with a three-way valve was attached to the vapor implant tubing. The dura-clamp valve was released, and 60 ml of soil gas were drawn into the syringe. The syringe contents were purged to the atmosphere using the three-way valve. The purging step was repeated and a third 60 ml volume of soil gas drawn into the syringe. After drawing the third 60 ml volume of soil gas, the three-way syringe valve was closed and the dura-clamp valve was closed to seal the vapor implant tubing. The syringe three-way valve was fitted with a needle; the needle was inserted into the septa of a 15 ml double-walled steel canister. The syringe valve was opened and the soil gas sample injected into the steel canister. The steel canister was labeled and delivered to the fixed-base laboratory for helium analysis. The syringe and needle were purged with three 60 ml volumes of atmospheric air prior to reuse.

5.2 Results

In-situ respiration test soil gas analytical results are summarized in Table 5-1. In-situ respiration test field screening data sheets are included in Appendix C. The percent values of soil gas (oxygen, carbon dioxide, and helium) concentrations over time at each vapor implant interval (15-, 30-, 45-, and 60-ft bgs) are presented graphically in Figure 5-1 through 5-4. The figures illustrate that the rate of oxygen depletion is much greater than the helium diffusion rate at all four soil vapor implants. This implies that aerobic biodegradation of hydrocarbons is occurring at all four depths. Increasing carbon dioxide levels are also evident in Figures 5-1 through 5-4. However, the levels of carbon dioxide in the soil gas may be buffered by the alkaline soils at the site. Carbon dioxide can form carbonates rather than gaseous carbon dioxide, particularly in soils with a pH over 7.5 and high reserve alkalinity (Leeson and Hinchee, 1997). Using the oxygen data from Figures 5-1 through 5-4, the oxygen utilization rate is calculated as the zero-order relationship between percentage of oxygen versus time. Hexane is used as the representative hydrocarbon to estimate biodegradation rates of hydrocarbon from the oxygen utilization rates. Based on the oxygen rates, the biodegradation rate (in terms of mg hexane-equivalent per kg of soil per day) is estimated using the following equation:

$$-k_B = \frac{\frac{ko}{100}\theta_a \frac{1\,L}{1{,}000\,cm^3}\rho_{O_2} C}{\rho_k\left(\frac{1\,kg}{1{,}000\,g}\right)} = \frac{-k_O\theta_a\rho_{O_2}C\,(0.01)}{\rho_k}$$

Where:

k_B	= biodegradation rate (mg/kg-day)
k_O	= oxygen utilization rate (%/day)
θ_a	= gas-filled pore space (volumetric content at the vapor phase, cm^3 gas/cm^3 soil)
ρ_{O2}	= density of oxygen = 1,330 mg/L
C	= mass ratio of hydrocarbons to oxygen required for mineralization (1:3.5)
ρ_k	= soil bulk density (g/cm^3)

Table 5-1. In-Situ Respiration Test Data Analytical Results at SWMU ST-341

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Sample Date/Time and Sample I.D.	Analytical Parameters CO2, O2, He	Analytical Results Vapor Implant ST341-MP15	Vapor Implant ST341-MP30	Vapor Implant ST341-MP45	Vapor Implant ST341-MP60
9-30-97 / 1400	**CO2:**	ND	ND	ND	ND
ST341-MP##-00	**O2:**	19.01	19.08	19.03	15.93
	Helium:	1.49	0.5	2.34	2.27
9-30-97 / 1600	**CO2:**	ND	ND	ND	ND
ST341-MP##-02	**O2:**	18.29	17.41	18.18	18.82
	Helium:	1.02	1.53	2.52	1.40
9-30-97 / 1800	**CO2:**	ND	ND	ND	ND
ST341-MP##-04	**O2:**	18.32	18.44	18.50	18.58
	Helium:	1.25	1.11	1.93	2.87
9-30-97 / 2000	**CO2:**	ND	ND	ND	ND
ST341-MP##-06	**O2:**	17.12	17.97	17.33	16.35
	Helium:	1.69	1.19	1.21	2.80
9-30-97 / 2200	**CO2:**	ND	ND	ND	ND
ST341-MP##-08	**O2:**	16.78	17.59	16.74	17.62
	Helium:	1.02	2.45	2.44	3.49
9-30-97 / 2400	**CO2:**	ND	ND	ND	ND
ST341-MP##-10	**O2:**	15.64	16.06	16.66	17.35
	Helium:	2.41	2.95	2.63	3.60
10-01-97 / 0500	**CO2:**	ND	ND	0.11	ND
ST341-MP##-15	**O2:**	14.68	14.02	14.60	15.58
	Helium:	1.09	1.03	1.16	1.38
10-01-97 / 1000	**CO2:**	0.21	0.13	ND	ND
ST341-MP##-20	**O2:**	12.45	11.61	14.23	17.03
	Helium:	1.63	1.00	2.90	1.83
10-01-97 / 1500	**CO2:**	0.24	ND	0.96	ND
ST341-MP##-25	**O2:**	11.67	11.36	11.83	16.71
	Helium:	2.73	3.49	1.80	3.18
10-01-97 / 2000	**CO2:**	0.24	0.22	0.13	ND
ST341-MP##-30	**O2:**	8.41	8.43	13.44	16.77
	Helium:	0.90	2.86	2.82	3.09
10-01-97 / 2000	**CO2:**	0.28	0.12	ND	ND
ST341-MP##-99	**O2:**	8.83	9.91	14.00	16.91
(Field Replicate)	**Helium:**	2.08	3.53	3.19	1.31
10-02-97 / 0100	**CO2:**	ND	0.22	0.13	ND
ST341-MP##-35	**O2:**	19.08	6.99	13.06	17.43
	Helium:	2.16	1.00	2.89	1.68
10-02-97 / 0600	**CO2:**	0.32	0.29	0.12	ND
ST341-MP##-40	**O2:**	4.97	5.78	10.69	17.20
	Helium:	0.87	3.04	2.37	0.95

Table 5-1. In-Situ Respiration Test Data Analytical Results at SWMU ST-341
page 2 of 2

Sample Date/Time and Sample I.D.	Analytical Parameters CO2, O2, He	Analytical Results Vapor Implant ST341-MP15	Vapor Implant ST341-MP30	Vapor Implant ST341-MP45	Vapor Implant ST341-MP60
10-02-97 / 1100	**CO2:**	0.31	0.18	0.12	ND
ST341-MP##-45	**O2:**	3.82	5.99	11.56	15.24
	Helium:	1.25	1.97	0.95	2.64
10-02-97 / 1600	**CO2:**	0.33	0.19	0.17	ND
ST341-MP##-50	**O2:**	3.14	5.08	12.00	16.97
	Helium:	1.53	2.77	2.30	2.77
10-02-97 / 2100	**CO2:**	0.43	0.31	0.20	0.12
ST341-MP##-55	**O2:**	3.72	3.91	10.91	15.45
	Helium:	1.05	2.36	2.25	2.55
10-03-97 / 0200	**CO2:**	0.46	0.25	0.25	0.11
ST341-MP##-60	**O2:**	3.52	4.21	10.67	15.47
	Helium:	1.62	1.43	2.82	1.49
10-03-97 / 0700	**CO2:**	0.39	0.29	0.22	0.13
ST341-MP##-65	**O2:**	5.82	6.40	10.39	15.59
	Helium:	0.88	2.52	1.01	2.32
10-03-97 / 1200	**CO2:**	0.19	0.32	0.21	0.13
ST341-MP##-70	**O2:**	1.03	4.05	10.53	14.97
	Helium:	0.85	1.89	1.29	2.01
10-03-97 / 1700	**CO2:**	0.46	0.35	0.26	0.18
ST341-MP##-75	**O2:**	3.15	3.22	9.82	15.51
	Helium:	0.84	1.54	0.62	1.91
10-03-97 / 2200	**CO2:**	0.52	0.34	0.21	0.18
ST341-MP##-80	**O2:**	3.35	3.75	9.46	14.09
	Helium:	0.37	0.73	2.08	1.59
10-03-97 / 2200	**CO2:**	0.42	0.28	0.23	0.18
ST341-MP##-99	**O2:**	3.61	3.28	9.28	14.57
(Field Replicate)	**Helium:**	0.81	0.54	1.93	1.31
10-04-97 / 0300	**CO2:**	0.45	0.38	0.26	0.26
ST341-MP##-85	**O2:**	3.43	3.10	8.90	12.99
	Helium:	0.93	1.80	1.63	0.79
10-04-97 / 0800	**CO2:**	0.55	0.33	0.25	0.26
ST341-MP##-90	**O2:**	3.33	3.60	7.50	13.04
	Helium:	0.84	1.80	2.00	1.56
10-04-97 / 1300	**CO2:**	0.41	0.36	0.28	0.30
ST341-MP##-95	**O2:**	3.86	3.56	7.86	13.46
	Helium:	0.76	0.74	2.00	1.73
10-04-97 / 1600	**CO2:**	0.46	0.30	0.30	0.31
ST341-MP##-98	**O2:**	4.11	3.59	8.44	13.15
	Helium:	0.90	1.30	1.97	1.78

Figure 5-1. In-Situ Respiration Test, Analytical Results for Vapor Implant MP15 at SWMU ST-341

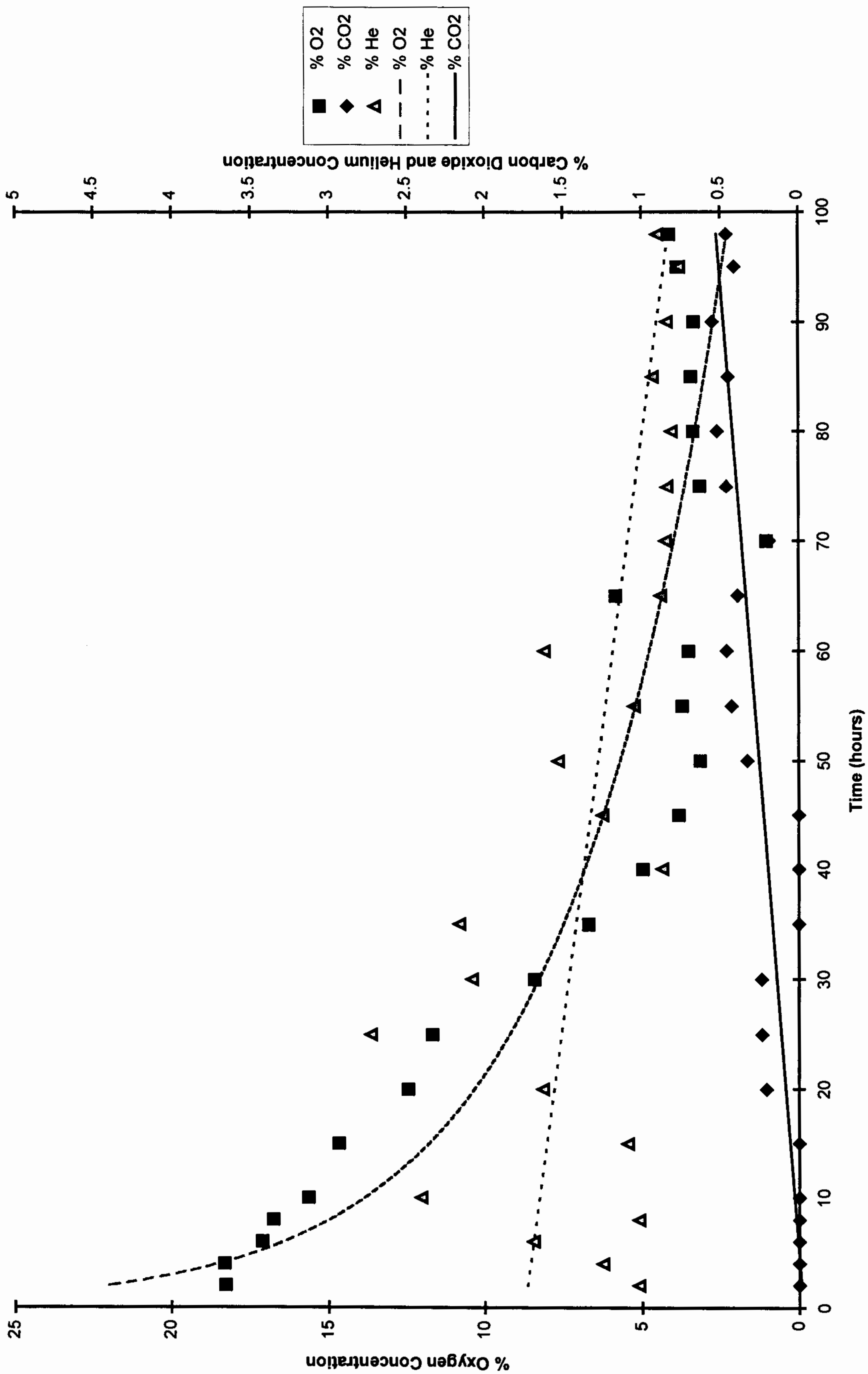


Figure 5-2. In-Situ Respiration Test, Analytical Results for Vapor Implant MP30 at SWMU ST-341

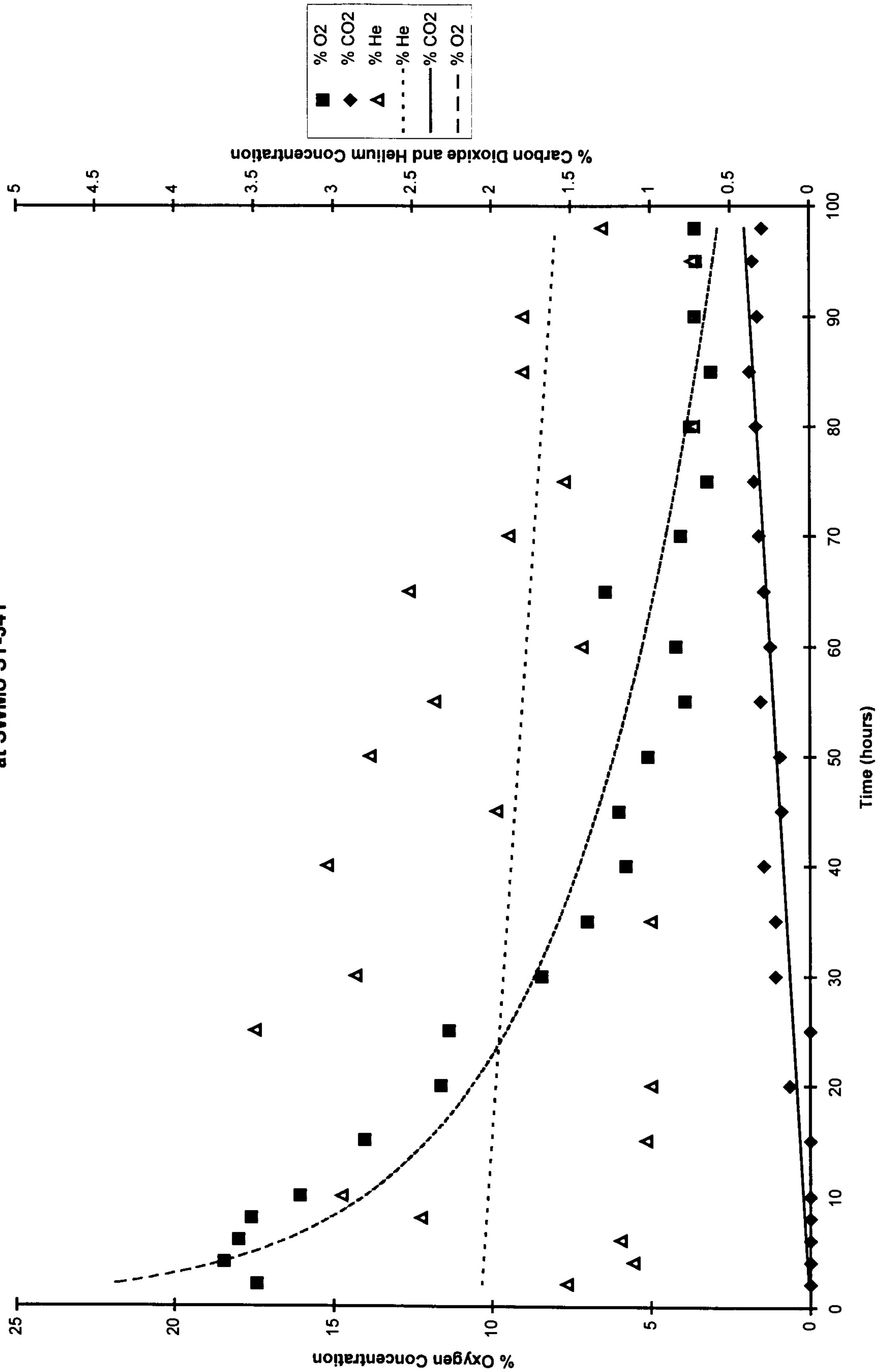


Figure 5-3. In-Situ Respiration Test, Analytical Results for Vapor Implant MP45 at SWMU ST-341

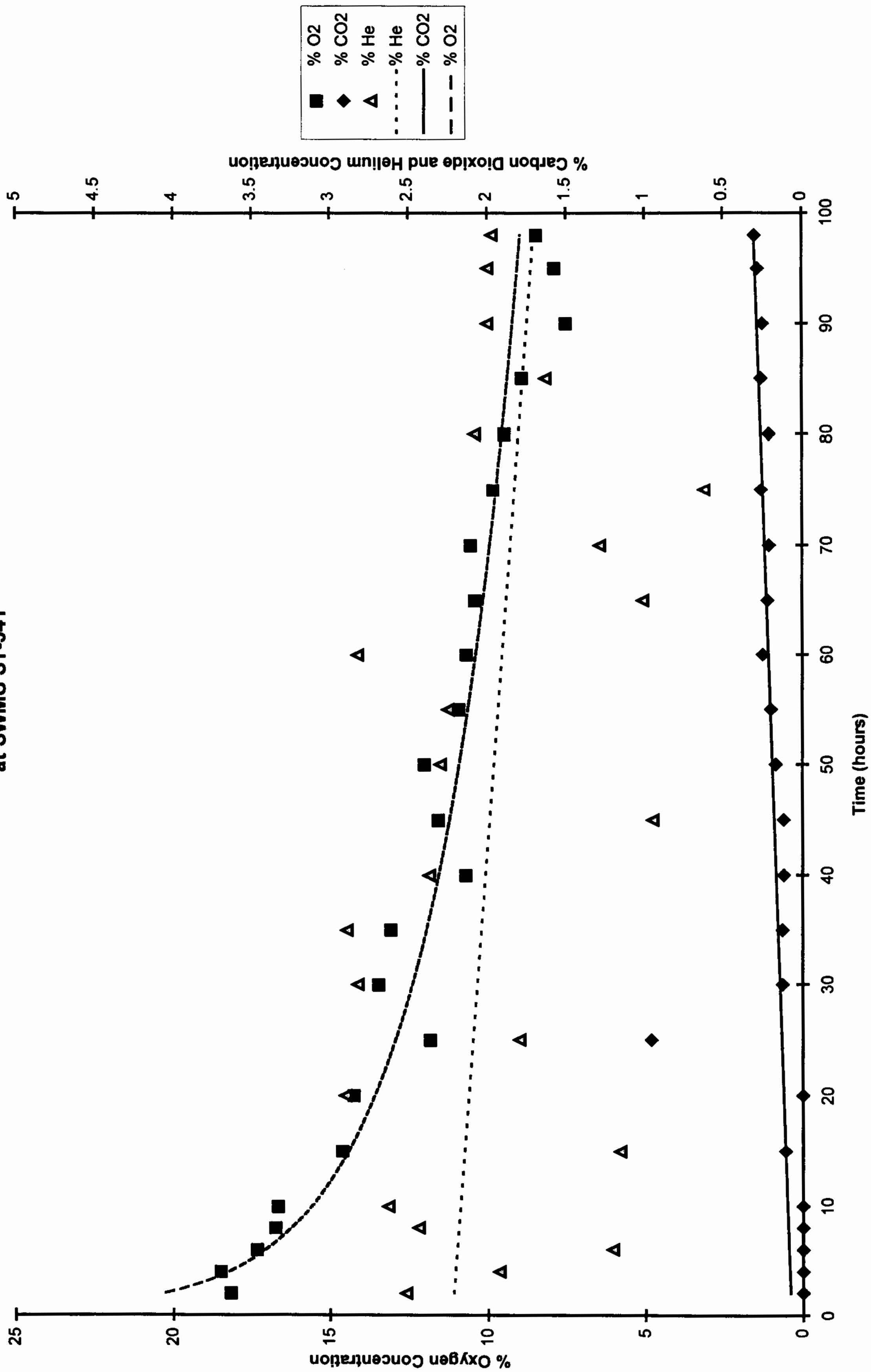
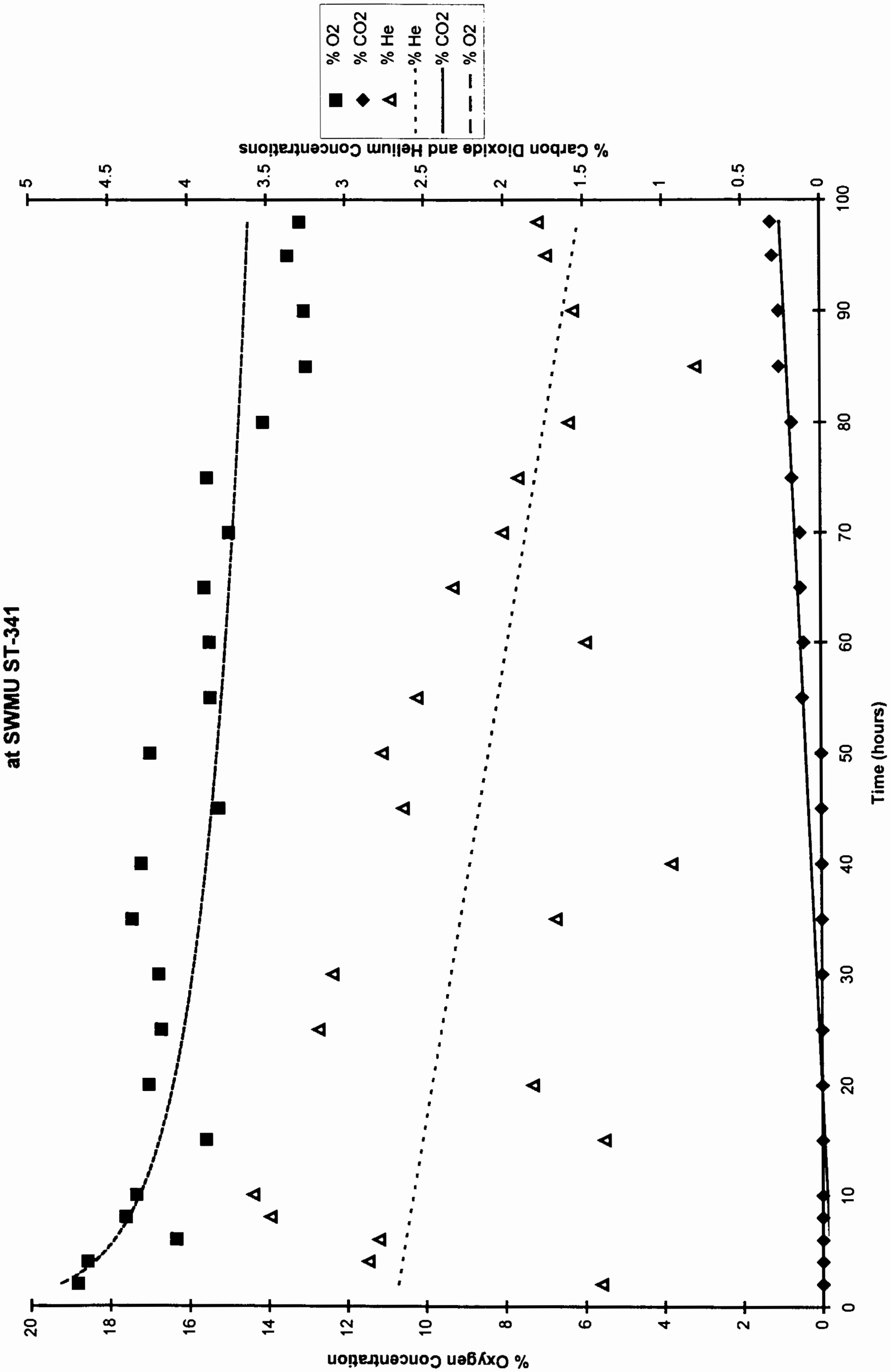


Figure 5-4. In-Situ Respiration Test, Analytical Results for Vapor Implant MP60 at SWMU ST-341



The calculations of biodegradation rates for each depth interval are included in Appendix G. Calculated hydrocarbon biodegradation rates are 4.15 mg/kg-day at 15 ft bgs, 3.95 mg/kg-day at 30 ft bgs, 1.24 mg/kg-day at 45 ft bgs, and 0.50 mg/kg-day at 60 ft bgs. Oxygen utilization rates derived from Figures 5-1 through 5-4 are 8.21 % per day at 15 ft bgs, 6.60 % per day at 30 ft bgs, 2.39 % per day at 45 ft bgs, and 1.14 % per day at 60 ft bgs. Oxygen utilization rates are greater than the 1 % per day threshold designated in the Bioventing Initiative guidelines. Therefore, this site is suitable for applying bioventing technology in terms of oxygen utilization by aerobic biodegradation.

Section 6

6. SOIL CHARACTERIZATION SAMPLING

The soil characterization sampling was designed to characterize what microbial populations are present at the site and to define the nutrient and hydrocarbon concentrations in soil. The soil analytical results provide information regarding intrinsic parameters (i.e., moisture content, particle size) that influence microbial activity. These data will identify nutrient conditions and other potential limiting conditions that need to be addressed in the bioventing pilot study design.

6.1 Methodology

The results of the soil gas survey were used for selection of soil sampling locations. Five boreholes locations were selected in a cross-sectional pattern across the site: one borehole (SC05) was located at the area of highest petroleum hydrocarbon concentrations, two in the contaminated area (SC03 and SC04), one at the edge of the plume (SC02), and one at a background location beyond the edge of the plume (SC01). Soil characterization boring locations are depicted in Figure 6-1.

The five boreholes were drilled with an HSA rig. Soil samples were collected using two in. diameter split-spoon samplers equipped with brass liners. Five soil samples were collected from each borehole at depths of 15, 30, 45, 60, and 75 ft bgs. Each soil sample was screened for volatile organics using a Mini-Rae PID. Each soil sample description and PID screening result was recorded on a borehole lithologic log prior to capping the brass liners with teflon lined plastic caps. After capping the brass liners, soil samples were labeled and packed on ice in shipping coolers. Soil samples were shipped overnight with chain-of-custody documentation to the fixed-base laboratory for the following analyses: microbial populations (aerobic, microaerophillic, and anaerobic), nitrogen as ammonia, total Kjeldahl nitrogen (TKN), sulfate, ortho-phosphate, pH, total organic carbon (TOC), soil moisture, bulk density, air-filled pore space, particle size, TPH, and BTEX. The borehole lithologic logs are included in Appendix C.

6.2 Results

Soil characterization laboratory analytical reports are included in Appendix E. Soil characterization hydrocarbon analytical results are summarized in Table 6-1. Figure 6-2 is an isoconcentration cross section map of TPH concentrations. Hydrocarbon analytical results indicate that BTEX and TPH concentrations are highest in borings SC04 and SC05. The lateral extent of hydrocarbon contamination sorbed to soil is less extensive than hydrocarbon contamination in the vapor phase. Soil borings SC02 and SC03 were drilled in areas representative of the fringe of the lateral extent of soil vapor contamination. However, no sorbed hydrocarbon contamination was detected in samples from these two borings. Hydrocarbon concentrations are highest between the 30- and 60-ft intervals in borings SC04 and SC05; concentrations begin to decline between the 60- and 75-ft intervals. Gasoline range TPH constituents are the predominant hydrocarbon residuals at the site. Total BTEX concentrations are low and benzene concentrations are very low relative to the more persistent BTEX constituents, such as xylenes. This indicates that volatilization and degradation of hydrocarbons is likely occurring at the site.

Soil samples were analyzed for aerobic, microaerophillic, and anaerobic microbial populations. The different subsurface oxygen conditions at the site are expected to support different microbial

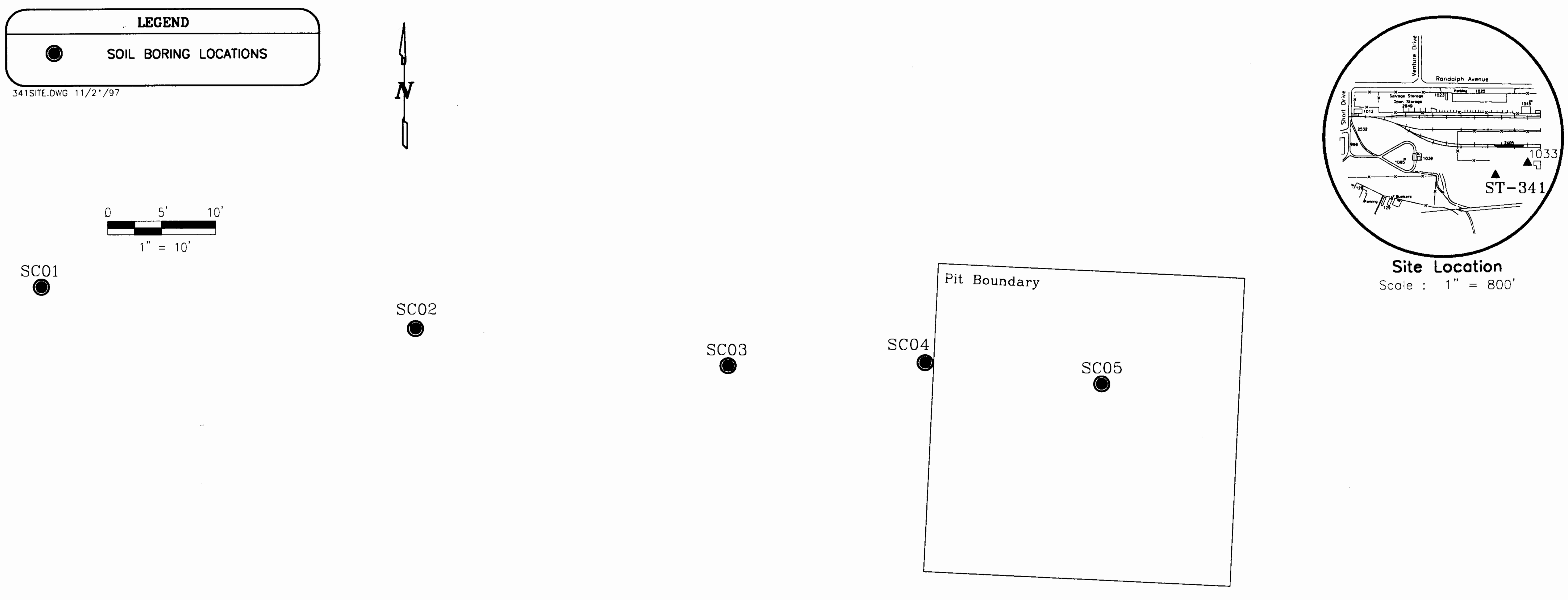


Figure 6-1.

SWMU ST-341, Soil Characterization Boring Locations

Table 6-1. Summary of Soil Characterization - Hydrocarbon Analytical Results at SWMU ST-341

Soil Sample Location / ID	Sample Depth (ft bgs)	Date Sampled	Benzene (mg/kg)	Toluene (mg/kg)	Ethyl Benzene (mg/kg)	Xylenes (total) (mg/kg)	Total BTEX (mg/kg)	TPH GRO (mg/kg)	TPH DRO (mg/kg)	PID Field Screen (ppm-v)
ST341-SC01-1518	15	10/6/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10.0	NA
ST341-SC01-2931	30	10/6/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10.0	NA
ST341-SC01-4446	45	10/6/97	<0.05 UJ	<0.1 UJ	<0.1 UJ	<0.2 UJ	BDL	<10 UJ	<10.0 UJ	NA
ST341-SC01-5961	60	10/6/97	<0.05 UJ	<0.1 UJ	<0.1 UJ	<0.2 UJ	BDL	<10 UJ	<10.0 UJ	NA
ST341-SC01-7578	75	10/6/97	<0.05 UJ	<0.1 UJ	<0.1 UJ	<0.2 UJ	BDL	<10 UJ	<10.0 UJ	NA
ST341-SC02-1416	15	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO2-3033	30	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
*ST341-99-3033	30	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO2-4548	45	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO2-5961	60	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO2-7476	75	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO3-1416	15	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
ST341-SCO3-2931	30	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	NA
ST341-SC03-4446	45	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	15
ST341-SC03-5961	60	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	35
ST341-SC03-7476	75	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	30
ST341-SC04-1418	15	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	<10	<10	0
*ST341-99-1418	15	10/7/97	<0.05	<0.1	<0.1	<0.2	BDL	370	140	0
ST341-SC04-2931	30	10/7/97	0.34	11	11	87	109.34	7100	1600	0
ST341-SCO4-4446	45	10/8/97	<0.5	88	22	180	290	6800	6300	160
ST341-SCO4-5961	60	10/8/97	<.05	0.16	0.1	0.2	0.46	110	<10	420
ST341-SCO4-7476	75	10/8/97	<.05	<0.1	<0.1	<0.2	BDL	35	<10	36
ST341-SC05-1416	15	10/8/97	<0.05	7.5	9.7	70	87.2	1700	1200	120
ST341-SC05-2931	30	10/8/97	<0.5	66	35	300	401	7300	4100	460
ST341-SC05-4446	45	10/8/97	<0.25	15	13	66	94	3300	1300	>2000
ST341-SCO5-5961	60	10/8/97	<0.05	3.2	9.3	31	43.5	13000	1100	778
ST341-SC05-7476	75	10/8/97	<0.05	0.1	<0.1	<0.2	0.1	81	<10	>2000

Footnotes:

Complete laboratory analytical results and method detection limits are presented in Appendix E

ppm-v parts per million volume (ml/L)

BDL Below detection limits

* Field replicate sample

UJ estimated values

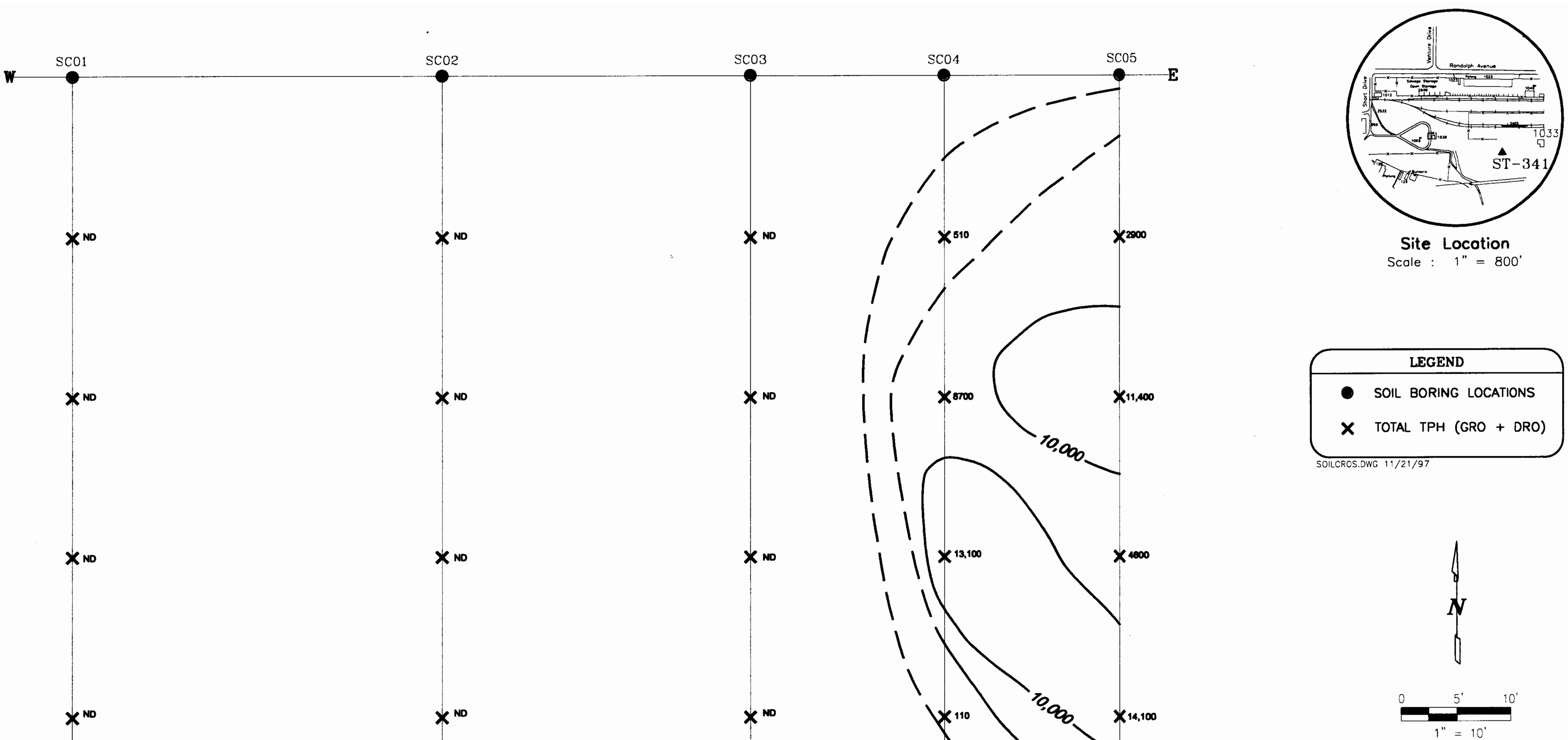


Figure 6-2.

Soil Characterization Analytical Results – Total TPH (GRO+DRO) Concentrations

subpopulations; aerobic populations for ambient oxygen or oxygenated conditions, microaerophillic populations for low oxygen conditions, and anaerobic populations for anoxic conditions.

Soil characterization microbial analytical results are summarized in Table 6-2. The results indicate that aerobic microbes are the dominant microbial subpopulation at the site. Figure 6-3 is an isoconcentration cross section map of aerobic microbial population distribution. Microbial analytical results indicate that aerobic microbial populations were present in all soil characterization samples at concentrations ranging from 3 to nearly 700,000 colony-forming units per gram of soil (cfu/gm). The majority of samples exhibited concentrations in the 100 to 2,000 cfu/gm range; the addition of oxygen to subsurface soils prior to soil characterization sampling (during the soil gas permeability test and the in-situ respiration test) may explain the higher aerobic microbial populations detected in some of the samples. Anaerobic microbial populations were present in most samples at concentrations ranging from 3 to nearly 55,000 cfu/gm. The higher occurrence of aerobic microbial populations relative to anaerobic populations is likely representative of the greater effectiveness of aerobic populations as hydrocarbon degraders. The detection of carbon dioxide during the soil gas survey is indicative of aerobic microbial degradation of hydrocarbons. Anaerobic microbe degradation by-products such as methane were not detected during the soil gas survey. This suggests that the anaerobic microbe populations are not active hydrocarbon degraders.

Soil physical properties analytical results are summarized in Table 6-3. Soil nutrient conditions analytical results are summarized in Table 6-4. Potential limiting conditions identified in the physical properties and nutrient conditions analytical results are low soil moisture, high pH (soil alkalinity) and a phosphorous deficiency. Soil moisture content of the samples ranges from 3.1 to 14 percent by weight (Table 6-3). Since microorganisms require moisture for metabolic processes and for solubilization of energy and nutrient supplies, the relatively low soil moisture contents may limit biodegradation at the site. In order to support aerobic microbial activity, soil moisture content should be in the range of 25 to 85 percent of the soil water holding capacity; with a range of 50 to 80 percent being optimal for biodegradation (Wisconsin DNR, 1994). The ratio of soil moisture content to soil water holding capacity is below this recommended range in 7 of the 27 samples. The ratio in the majority of the soil samples is below the optimal range of 50 to 80 percent, with all the 60 ft bgs samples falling outside this range. The low moisture content in the 60 ft bgs samples may explain the low oxygen utilization rates observed at this depth during the in-situ respiration test.

A soil pH range of 6.5 to 8.5 is considered optimal for biodegradation efficiency (Wisconsin DNR, 1994). Analytical results indicate a soil pH range of 7.5 to 8.8 at the site. Although the pH values detected at the site are not excessive, soil pH affects the availability of nutrients to microbial populations. The solubility of phosphorous, an important nutrient, is maximized at a pH value of 6.5 (Wisconsin DNR, 1994). Available phosphorous was detected in soil samples at a concentration ranging from <0.1 to 3.3 mg/kg. The Wisconsin DNR guidelines for optimum phosphorous concentrations are established as a ratio of carbon to phosphorous of less than 120:1. Carbon to phosphorus ratios detected in soil characterization samples ranged from 606:1 to 20,000:1 indicating a significant phosphorous deficiency. This deficiency may be compounded by the alkaline soil conditions at the site.

Soil characterization analytical results indicate that hydrocarbon concentrations, microbial populations, and physical properties at SWMU ST-341 evaporation pond are favorable for bioremediation. Nutrient conditions are limited by a phosphorous deficiency possibly compounded by soil alkalinity.

Table 6-2. Summary of Soil Characterization - Microbial Analytical Results at SWMU ST-341

Sample ID	Total Aerobic Populations (concentrations in cfu/gm)			Total Microaerophillic Populations (concentrations in cfu/gm)			Total Anaerobic Populations (concentrations in cfu/gm)		
	Mean	Low	High	Mean	Low	High	Mean	Low	High
ST341-SC01-1518	67,981	60,829	75,252	5,826	4,074	8,508	108	6	690
ST341-SC01-2931	1,864	1,500	2,263	3	less than 1	13	< 100	NA	NA
ST341-SC01-4446	692	490	955	62	19	155	5	1	36
ST341-SC01-5961	1,397	1,111	1,744	90	NA	NA	<90	NA	NA
ST341-SC01-7578	1,052	794	1,400	76	27	174	3	less than 1	12
ST341-SC02-1416	8,548	7,680	9,427	324	200	506	3	less than 1	12
ST341-SC02-3033	888	661	1,212	90	NA	NA	90	NA	NA
*ST341-99-3033	1,939	1,590	2,350	47	11	138	90	NA	NA
ST341-SC02-4548	154,352	144,028	165,336	2,871	2,459	3,384	1,338	1,049	1,671
ST341-SC02-5961	290	174	462	4	1	27	90	NA	NA
ST341-SC02-7476	694	501	982	132	60	257	145	66	281
ST341-SC03-1416	41,333	36,084	46,919	17,480	13,804	22,229	3,909	2,512	6,002
ST341-SC03-2931	1,001	759	1,330	45	11	129	< 100	NA	NA
ST341-SC03-4446	43	10	125	12	1	64	90	NA	NA
ST341-SC03-5961	141	68	263	125	56	246	90	NA	NA
ST341-SC03-7476	309	186	491	30	5	111	< 100	NA	NA
ST341-SC04-1418	699,816	626,029	775,323	485,645	424,298	551,455	430	105	1,262
*ST341-99-1418	131,444	121,230	141,407	48,258	42,302	54,310	687	209	1,719
ST341-SC04-2931	98,471	89,941	107,567	132,912	123,277	143,265	30,731	25,980	35,958
ST341-SC04-4446	130	59	256	113	48	228	< 100	NA	NA
ST341-SC04-5961	124	56	241	156	78	285	90	NA	NA
ST341-SC04-7476	276	162	446	45	11	129	< 100	NA	NA
ST341-SC05-1416	35,022	30,124	40,654	5,357	4,699	6,027	29	5	105
ST341-SC05-2931	71	22	179	28	4	104	3	less than 1	13
ST341-SC05-4446	3	less than 1	5	3	less than 1	12	< 100	NA	NA
ST341-SC05-5961	457,735	398,881	518,893	246,473	205,525	293,070	54,760	47,741	61,519
ST341-SC05-7476	131	60	257	48	12	139	3	less than 1	5

Footnotes:

Complete laboratory analytical results are in Appendix E

* Field replicate sample

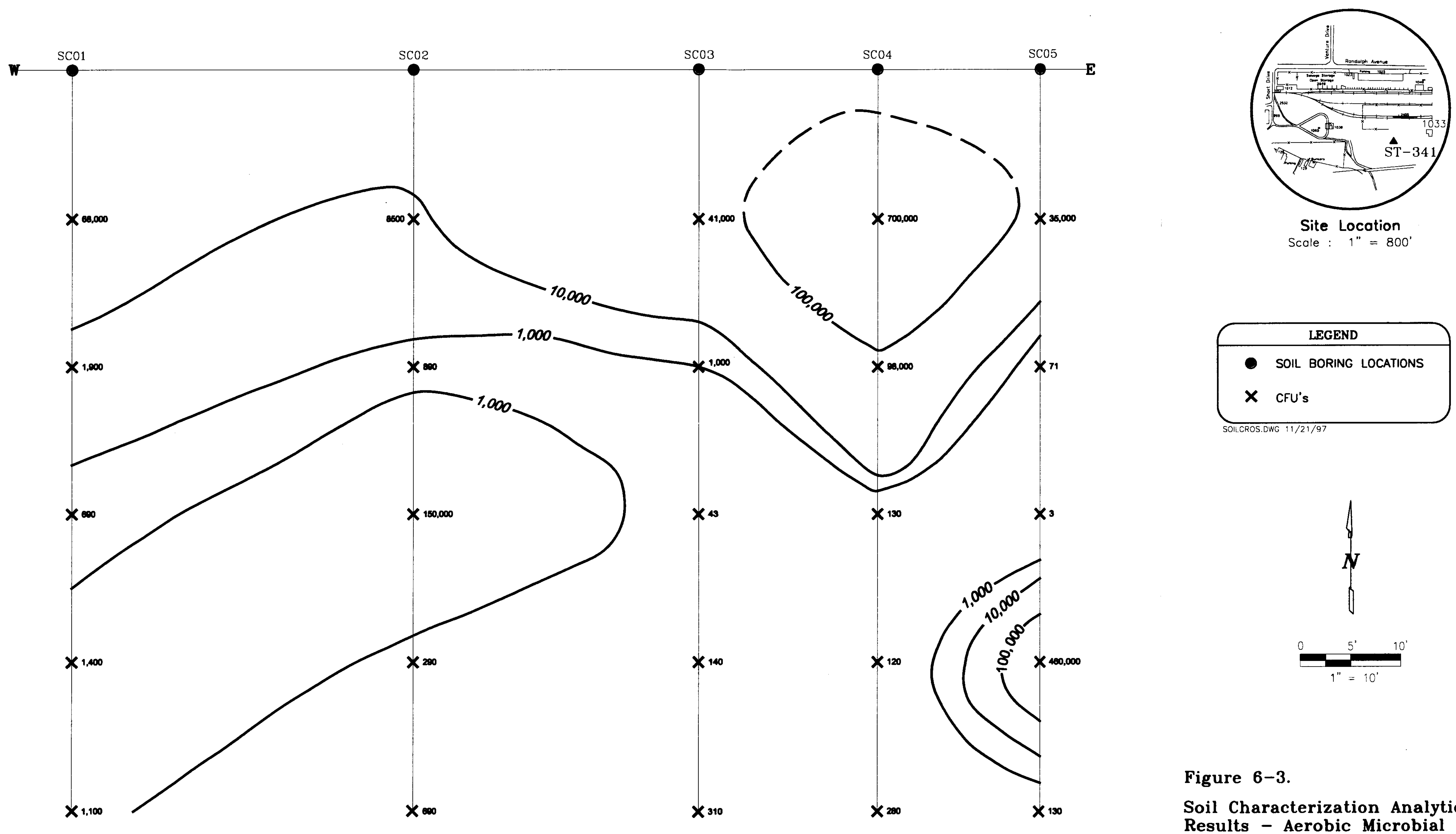


Figure 6-3.

Soil Characterization Analytical Results – Aerobic Microbial Populations (Mean Values)

Table 6-3. Summary of Soil Characterization - Physical Properties Analytical Results at SWMU ST-341

Sample ID	Gravel	Coarse	Medium	Fine	Silt	Clay	H_20 wt/total	SWHC H20 wt/total	Solids dry wt/total	AFPS vol/ tot vol	Bulk Density Dry	Bulk Density Field
	%	%	%	%	%	%	%	%	%	%	dry g/cc	wet g/cc
ST341-SC01-1518	0	8.6	9.9	64.3	7.9	9.4	4.2	19.5	95.8	49.1	1.7	1.8
ST341-SC01-2931	4	3.7	4.9	40.6	22.6	24.1	10.3	23.7	89.7	32.0	1.7	1.9
ST341-SC01-4446	6.3	15.4	12.9	40	15.9	9.5	8.1	18.6	91.9	28.0	1.8	2.0
ST341-SC01-5961	0.9	9.8	11.7	54.9	9	13.7	5.5	16.1	94.5	34.9	1.9	2.0
ST341-SC01-7578	0.4	2.9	7	56.2	14.4	19.1	5.8	22.2	94.2	42.1	1.7	1.9
ST341-SC02-1416	2.7	6.1	10.6	61.6	5.8	13.3	4.0	19.5	96.0	46.4	1.8	1.8
ST341-SC02-3033	0.5	3.6	5.2	59.6	17.6	13.5	4.3	19.9	95.7	42.4	1.7	1.8
*ST341-99-3033	0	3.5	4.6	50.4	15	26.4	5.8	23.1	94.2	38.3	1.7	1.8
ST341-SC02-4548	2.6	6.2	10.8	33.4	19.9	27.2	6.4	22.6	93.6	37.9	1.7	1.9
ST341-SC02-5961	6.7	33.1	27.9	20.6	5.1	6.6	3.1	14.9	96.9	39.8	2.0	2.0
ST341-SC02-7476	0	0.2	0.9	36.8	31.5	30.6	7.6	25.3	92.4	35.2	1.6	1.8
ST341-SC03-1416	0.3	9.1	27.3	51.6	5.1	6.6	4.3	17.7	95.7	47.1	1.8	1.9
ST341-SC03-2931	0	5.1	6.7	46.9	24.9	16.4	9.6	23.8	90.4	28.7	1.7	2.0
ST341-SC03-4446	0	2.2	6.7	34.2	27.7	29.2	4.4	21.7	95.6	46.4	1.7	1.8
ST341-SC03-5961	1.3	6.6	18.8	49.9	12.2	11.2	3.4	18.8	96.6	39.7	1.9	1.9
ST341-SC03-7476	0	0.4	0.8	33.1	49.4	16.3	7.9	21.7	92.1	39.7	1.7	1.9
ST341-SC04-1418	0	2.9	7.7	66	9.8	13.7	7.1	17.9	92.9	34.2	1.8	2.0
*ST341-99-1418	0	2	6.4	55.9	16	19.7	8.0	21.9	92.0	29.3	1.8	2.0
ST341-SC04-2931	2.7	6.9	7.5	23.8	28.7	30.3	9.1	22.2	90.9	29.7	1.8	2.1
ST341-SC04-4446	6.3	15.4	12.9	40	15.9	9.5	8.1	18.9	91.9	31.9	1.9	2.1
ST341-SC04-5961	0.9	9.8	11.7	54.9	9	13.7	5.5	15.7	94.5	42.8	1.9	2.0
ST341-SC04-7476	0	0.3	0.2	56.4	28.7	14.4	8.8	20.8	91.2	35.6	1.8	1.9
ST341-SC05-1416	0.8	4	9.3	63.7	12	10.3	8.8	16.4	91.2	24.9	1.9	2.1
ST341-SC05-2931	0.4	5.2	8	42.9	18.3	25.3	11.8	18.6	88.2	29.5	1.9	2.2
ST341-SC05-4446	4.5	8.9	7.6	38.3	18.3	22.5	14.0	22.1	86.0	22.8	1.7	2.0
ST341-SC05-5961	3.2	7.8	14.8	46.7	16.3	11.3	6.3	16.1	93.7	20.4	1.8	1.9
ST341-SC05-7476	0	0.4	1	47.8	30.8	20	7.7	20.3	92.3	41.9	1.7	1.9

Footnotes:

Complete laboratory analytical results are in Appendix E

* Field replicate sample

AFPS - Air Filled Pore Space

SWHC - 100% Soil Water Holding Capacity (Field Capacity)

Table 6-4. Summary of Soil Characterization - Nutrient Conditions Analytical Results at SWMU ST-341

Sample ID	TKN (ppm)	NH_4-N (ppm)	P (ppm)	pH	SO_4 (ppm)	TOC (%)
ST341-SC01-1518	989.2	<0.1	0.2	7.5	9	0.1
ST341-SC01-2931	2263.2	<0.1	3.3	8	8.6	0.2
ST341-SC01-4446	1255.3	<0.1	1.2	8.3	7.9	0.1
ST341-SC01-5961	485.3	<0.1	0.9	8.5	10	0.1
ST341-SC01-7578	1542.6	<0.1	0.8	8.5	8.2	0.1
ST341-SC02-1416	699.4	<0.1	1.4	8	63.3	0.1
ST341-SC02-3033	984.4	<0.1	0.3	7.8	54.12	0.05
*ST341-99-3033	871.8	<0.1	<0.1	8.1	154.18	0.1
ST341-SC02-4548	1212.1	<0.1	0.4	8.3	268.86	0.1
ST341-SC02-5961	1359.6	<0.1	0.9	8.7	77.7	0.1
ST341-SC02-7476	516.8	<0.1	0.6	8.5	76.85	0.1
ST341-SC03-1416	763.4	<0.1	0.3	8.3	145.56	0.1
ST341-SC03-2931	808.1	<0.1	0.2	8.3	116.22	0.1
ST341-SC03-4446	783.5	<0.1	1.1	8.8	132.88	0.1
ST341-SC03-5961	973.4	<0.1	0.4	8.7	71.48	0.1
ST341-SC03-7476	1084.4	<0.1	0.3	8.6	<1	0.05
ST341-SC04-1418	1599.7	<0.1	0.2	8.7	159.96	0.1
*ST341-99-1418	2146.1	<0.1	<0.1	8.7	117.51	0.1
ST341-SC04-2931	1290	<0.1	0.1	8.5	172.16	0.2
ST341-SC04-4446	586	<0.1	0.4	7.8	75.66	0.2
ST341-SC04-5961	393.7	<0.1	0.4	8.5	56.19	0.1
ST341-SC04-7476	990	<0.1	0.2	8.2	176.01	0.1
ST341-SC05-1416	2027.1	<0.1	0.8	8.2	157.83	0.1
ST341-SC05-2931	1329.4	<0.1	0.5	8.1	96.36	0.2
ST341-SC05-4446	1412.1	<0.1	0.7	8.1	89.82	0.4
ST341-SC05-5961	908.7	<0.1	0.8	8.4	466.81	0.1
ST341-SC05-7476	884	<0.1	0.3	8.4	96.53	0.1

Footnotes:

Complete laboratory analytical results are in Appendix E

* Field replicate sample

Section 7

7. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the Bioventing Feasibility Site Characterization, in-situ bioremediation is a feasible remedial alternative at SWMU ST-341. The site characterization has provided sufficient data for determining the technical approach and design of the pilot study phase of the CMD/I.

Soil gas survey analytical results indicate that TPH soil gas concentrations are highest near the center of the evaporation pond and generally increase with depth until approximately 60 ft bgs. Oxygen concentrations decrease and carbon dioxide concentrations increase toward the center of the petroleum hydrocarbon plume. The relationship of carbon dioxide and oxygen concentrations to TPH concentrations indicate that biodegradation is occurring at the site, resulting in oxygen depletion and carbon dioxide production at the center of the plume.

The soil gas permeability test resulted in a pressure radius of influence of approximately 95 ft at a 20 cfm flow rate to approximately 258 ft at a 120 cfm flow rate. Calculated values of soil permeability to vapor flow ranged from 4.25×10^2 to 1.85×10^3 darcy, well in excess of the 0.1 darcy threshold for sufficient air exchange to support bioventing. In terms of soil air permeability, SWMU ST-341 is well suited for the application of bioventing technology.

The in-situ respiration test resulted in measured oxygen utilization rates ranging from 1.14 % per day at 60 ft bgs to 8.21 % per day at 15 ft bgs. Calculated hydrocarbon biodegradation rates ranged from 0.50 mg/kg-day at 60 ft bgs to 4.15 mg/kg-day at 15 ft bgs. Oxygen utilization rates are greater than the 1 % per day threshold designated in the Bioventing Initiative guidelines (EPA, 1995a,b). Therefore, this site is suitable for applying bioventing technology in terms of oxygen utilization.

Soil characterization hydrocarbon analytical results indicate that petroleum hydrocarbon contamination extends vertically to a depth of approximately 75 ft bgs and that vapor phase petroleum hydrocarbons are more widespread than the petroleum hydrocarbons sorbed to soil. Soil microbial population and physical properties analyses indicate that aerobic microbial populations are present at the site and that the physical properties of the soil are conducive to bioventing. Soil moisture contents at the site are generally below the range considered optimal for biodegradation. In the deeper portion of the hydrocarbon plume, at 60 ft bgs, low soil moisture content may limit microbial activity Soil nutrient conditions analyses indicate that the site is deficient in phosphorous, an important nutrient for microbial populations. The phosphorous deficiency may be compounded by the alkalinity of site soils.

Overall, site characterization results indicate that bioventing is a feasible remedial alternative at SWMU ST-341. The pilot study design will address the three conditions that potentially limit biodegradation at the site. These three site conditions are: (1) low oxygen soil gas concentrations within the hydrocarbon plume, (2) low soil moisture content, and (3) deficient soil phosphorus concentrations. The pilot study will be conducted in three phases. The three proposed phases include: 1) passive (barometric) soil venting, 2) active soil venting with moisture addition, and 3) soil venting combined with phosphorous and moisture addition. It is anticipated that moisture injection during the second and third phases of the pilot study will result in a reduction of soil alkalinity through natural carbonic acid production. The reduction in soil alkalinity should increase the solubility of phosphorous for microbial consumption. Results from the three pilot study phases will be compared to identify optimum conditions for in-situ bioremediation at SWMU ST-341. If the pilot study proves to be successful at SWMU ST-341 evaporation pond area, it will be expanded to the condensate tank area near building 1033, as well as other similar sites on base.

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