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A NEGATIVE BIOVENTING FEASIBILITY TEST

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ABSTRACT

A bioventing feasibility test was conducted at a hydrocarbon fuel spill site at Oak Ridge National Laboratory. The soils at this site are generally of low air permeability and are representative of the clayey soils encountered at several Department of Energy sites and throughout the southeastern United States. The tests included an in situ air permeability test and in situ respiration tests at three wells where highest soil contamination was measured. The in situ respiration tests showed that there was the potential for significant biodegradation in the soil with adequate oxygenation. The in situ permeability tests indicated that the majority of flow was through fractures, rather than through the bulk soils. A helium tracer test verified that injected gas flowed directly to the surface through a small number of fractures, with no flow reaching the monitoring wells. These results indicate that oxygen transport to the bulk soils would be severely limited by diffusion, such that bioventing was deemed not feasible for this site. In light of these results, the importance of testing for fracture flow in soils of lower permeability is stressed - whether the technology is bioventing or conventional soil venting.

INTRODUCTION

Bioventing is a method of enhancing in situ microbial degradation of contaminants in the soil. The technique utilizes air movement caused by soil venting to oxygenate the soil. The term bioventing is based upon the observation that, in many cases, in situ microbial activity is limited by the availability of oxygen; thus the rate of microbial degradation may be enhanced by application of soil vapor extraction. Although bioventing is related to the process of soil venting, the primary objectives are different. Soil venting is designed and operated to maximize the volatilization of low molecular weight compounds, with some biodegradation occurring. Conversely, bioventing is designed and operated to maintain aerobic biodegradation of contaminants, while minimizing volatilization. The primary difference is that bioventing employs a lower gas flow rate in either an extraction or injection mode to increase the relative importance of biodegradation relative to volatilization for contaminant removal.

Initial documentation of the enhancement of biodegradation of fuel hydrocarbons in the unsaturated zone by soil venting was made in experiments conducted by the Texas Research Institute for the American Petroleum Institute. Evaluation of the material balance in bench tests revealed that as much as 38 percent of the hydrocarbon mass was biologically removed. (Thornton and Wootan, 1982) Researchers at Hill Air Force Base, Utah reported that 15 to 20 percent of the JP-4 jet fuel removed from impacted soils in the unsaturated zone was due to biodegradation, even though volatilization was the intended removal mechanism and no effort was made to optimize bioactivity (Hinchee et al., 1991). Miller (1990) conducted a controlled field study which supported the bioventing concept by determining that the ratio of biodegradation and volatilization rates could be optimized by adjustment of gas flow rate. Numerous field investigations have since been reported. Although most have been conducted in relatively permeable soils, Downey et al. (1992) have successfully implemented bioventing systems in soils having up to 80 percent clay content.

While still considered an innovative remediation technology, bioventing has been utilized a sufficient number of times to demonstrate its effectiveness. The Air Force is currently conducting a large number (over 200) of field tests, with the goal of determining design parameters and limitations of bioventing (Miller, 1993). As part of the Air Force program, a protocol for treatability tests was prepared (Hinchee et al., 1992) to guide the collection of pertinent and consistent site data. Based upon the in situ respiration test of Hinchee and Ong (1992) and the radial flow approximation for in situ permeability testing of Johnson et al. (1990), the test protocol is designed to measure the two most important site variables affecting the success of bioventing - the biodegradation rate and the air permeability of the soil.

This paper describes the investigation of the feasibility of bioventing for the remediation of a fuel spill site at Oak Ridge National Laboratory (ORNL). A field test based upon the protocol of Hinchee et al. is described, along with results which indicate that fractures in the low permeability soil make bioventing infeasible for efficient site remediation.

SITE DESCRIPTION

The building 7069 facility (see Figure 1) serves as the central gasoline/diesel fuel dispensing facility for ORNL and stores fuel in several underground storage tanks (USTs) and above-ground tanks. In June 1986, water was detected in unleaded gasoline pumped from UST 7069B. Subsequent soil and groundwater sampling conducted near the tank revealed the release of gasoline from the tank. The tank was removed in 1988 and a remedial action plan was prepared. However, a second release was discovered from nearby tank 7069D (diesel) before the remedial plan could be implemented. Also, a valve leak in a gasoline transfer line associated with tank 7069F was discovered in September 1990. An additional leak was detected at the 7069E diesel dispenser during the environmental assessment of 7069B and 7069F (Ogden, 1993).

Under current remedial plans for the building 7069 area no corrective action is planned for the site 7069B soils because concentrations are below the action levels of 500 ppm total petroleum hydrocarbons (TPH) and 250 ppm benzene, toluene, and xylenes (BTX) (Ogden, 1993a).

Geohydrology

The ORNL 7000 Area is located in the Bethel Valley sub-basin of the upper White Oak Creek watershed. Natural drainage in the area has been modified by site grading and construction of plant support facilities. At the building 7069 facility, the ground surface slopes gently (less than 2 percent) toward the north, west, and south (Ogden, 1993a).

Depth to groundwater at the 7069B site is generally less than 7 ft below ground surface (BGS). However, perched groundwater conditions exist locally within the unsaturated zone in alternating layers of compacted clay and gravel due to construction activities. The general groundwater flow direction at the site is toward the southwest. However, heterogeneities in soil structure and texture from both natural variations and construction alterations may cause deviations in the flow pattern. The calculated hydraulic gradients in the area are 0.073 ft/ft (7069B) and 0.064 ft/ft (7069F). Hydraulic conductivities calculated from slug tests for two monitoring wells in the area were 2.3×10^{-6} cm/s and 2.6×10^{-4} cm/s, respectively (Ogden, 1993a).

Overburden at the 7069B site is silty clay approximately 8 to 12 ft thick. The silty clay soil has been disturbed by construction and associated underground utilities. Crushed gravel and reworked native soil have been used as backfill in utility trenches and in the UST excavation. This disturbed zone extends from the surface to within several feet above the bedrock. The effective porosity for the overburden materials is estimated to be 45 percent. The soil permeability from a sample collected from two to four ft BGS was 1.0 x 10^{-6} cm/s (Ogden, 1993a). The ground surface at the 7069B site is covered with grass.

Extent of Contamination

Three piezometers (PZ01, PZ02, and PZ03) and four monitoring wells (MW01, MW02, MW03, and MW07), were installed near the 7069B site, as shown in Figure 2, during the environmental assessment (Ogden, 1993). The wells were installed in boreholes that were advanced to bedrock (10 ft BGS) using hollow stem augers. Water samples collected from the wells were analyzed for TPH and BTX. Soil samples at the site were collected from 18 boring locations within a systematic grid with 10-foot spacings. Soil samples were also analyzed for TPH and BTX.

No free product was encountered on the groundwater at the 7069B site and dissolved contaminants from monitoring wells were generally low. However, TPH and benzene concentrations were above action levels at MW01 and MW03. TPH concentrations in soil samples were all below the action level of 500 ppm. As shown in Figure 3, concentrations ranged from non-detectable (detection level of 1 ppm) to 460 ppm. Soil samples were collected at a depth of 6 to 8 ft BGS.

Installation of Vent Wells and Monitoring Points

Prior to the environmental assessment field activities, the scope of work was expanded to include the installation of test wells and monitoring points to evaluate the feasibility of bioventing at the 7069B site. Two vent test wells, designated VW01 and VW02, were installed at soil boring locations B1 and B6, as shown in Figure 4. Construction of the wells (see Figure 5) consisted of 4-in. internal diameter (ID) PVC pipe, screened from 2.5 to 7.5 ft and 5.5 to 10.5 ft, respectively. Two thermocouples were installed at the midpoint of the screened interval of each well.

Eight monitoring points were also installed at the 7069B site. As shown in Figure 4, the points were installed at soil boring locations B2, B5, B7, B11, B14, B16, and B24. Two monitoring points of different depths were installed at location B14. All monitoring points were of identical construction as the vent test wells with the following exceptions: construction was of 1-in. ID PVC pipe, the screened interval was 1 ft in length (beginning in the range of 3.4 to 5.0 ft BGS), and only one thermocouple was installed in each well.

DESCRIPTION OF FIELD TEST

The bioventing field evaluation tests conducted at the ORNL 7069B site consisted of two specific tasks:

- An in situ air permeability test to determine whether soils at the site were sufficiently permeable to enable air to move through the contamination zone

- An in situ respiration test to evaluate whether existing microorganisms were capable of degrading existing petroleum hydrocarbons in the soil if sufficient oxygen was present.

In Situ Air Permeability Test

Two air permeability tests were to be conducted by injecting air at a known flow rate and pressure into each of the two vent test wells. For the VW01 test, eight peripheral monitoring points were to be utilized to observe pressure and temperature changes during the air injection period. However, for the VW02 test only the four closest points (B11, B2, B7, and B24) were to be monitored. The transient or steady-state values of pressure observed at the monitoring points could be used to estimate the air permeability of the soil using radial flow assumptions.

Equipment

A schematic of the equipment employed for air injection in the in situ permeability test is shown in Figure 6. The recommended blower for sites with silty and clayey soils, such as the 7069B site, is a pneumatic blower with a 5-horsepower (hp) motor capable of delivering 50 standard cubic feet per minute (scfm) at 130 inches of water pressure [approximately 5 pounds per square inch (psi)] (Hinchee et al., 1992). The blower employed was a Roots Universal RAI-122 rotary lobe, base-mounted blower powered by a Baldor single-phase, 230-volt, 5-hp motor. This blower is capable of flow rates ranging from 21 to 56 scfm and pressures ranging up to 10 psi. Flow into the well was controlled by adjusting a waste valve on the downstream side of the blower. Flow rate, temperature, and pressure of the injected gas was monitored using gauges installed on the inlet line.

Figure 7 shows a typical monitoring point and associated sensors used in the in situ permeability test. Temperatures readings were made by connecting an electronic thermometer to the existing type "T" thermocouples. Marshalltown pressure gauges (0 to 10 inches of water range) and a dual-range manometer (0 to 2.6 and 0 to 26 inches of water ranges) were employed for measurement of pressure.

Procedure

Before conducting the air permeability test, background soil vapor samples were to be collected from the vent test wells and all monitoring points and analyzed for oxygen and carbon dioxide. Following connection of the blower and associated equipment to the vent well, a brief check was to be performed to ensure proper operation of the system. This was to check the blower pressure and air-flow gauges and to measure the initial pressure response at each monitoring point. A leak test was also to be performed on all piping during the system check.

After the system check, the system was to be allowed to equilibrate and the pressure sensors at each monitoring point were to be returned to zero. The blower unit was to be turned on and the starting time recorded to the nearest second. Pressure readings at each monitoring point were to be recorded at specified intervals during the injection period. The pressure data was to be gathered for a period of four to eight hours, until the outermost monitoring point with a pressure reading did not increase by more than 10% over a one-hour interval. The pressure reading at the well head, the temperature readings, and the flow rate at the vent well were also to be monitored and recorded during the injection period. Following shutdown of the blower system, soil vapor from the vent well and monitoring points was to be analyzed for oxygen and carbon dioxide.

In Situ Respiration Test

The in situ respiration test was to be conducted by simultaneously injecting an air/helium mixture into monitoring points B2, B5, and B24 for a period of 24 hours and measuring oxygen, carbon dioxide, and ^{13}C levels over time following the injection period. These points were chosen for the test since they represent the three highest concentrations of TPH at the site. The appearance of carbon dioxide and the disappearance of oxygen would provide evidence for in situ microbial activity; the ^{13}C analysis would provide a means of determining the carbon dioxide source (i.e., recent plants versus petroleum products); and the helium concentration would be used to determine the diffusive loss of gases to the surrounding soil.

Equipment

Figure 8 shows the setup used for the in situ respiration tests. A gasoline-powered air compressor (Marshalk Corp., model 9300) was used to inject air simultaneously to the three monitoring points. The target flow rate and pressure entering each point is 1.5 cfm at 10 psi. Monitoring and control of the flow rate into each point was made possible with three rotameters (Omega FL-1808 with stainless steel float). Temperature and pressure gauges were included at each wellhead. Helium (99.9% purity) was mixed into the air at a 1% by volume concentration using a gas proportioning mixer (Omega FL-5GP with three flow tubes: one FLT-02C with glass float for helium, two FLT-40ST with carboloy float for air). A quick-disconnect fitting was included to allow easy removal of the air source to allow the coupling to serve as the sample port for collection of soil vapor samples.

A closed-loop pump system was included in the design to recirculate the gas within the well to ensure homogeneity. (During initial soil gas analyses, it was noted that readings were initially elevated for light gases such as methane; as more sample was removed from the well, readings for lighter gases were reduced and levels of heavier gases such as carbon dioxide increased. This indicated that recirculation of the gases would indeed be valuable to reduce the effects of segregation due to molecular weight differences.) A peristaltic pump (Cole-Parmer, model 7549-36 with pump head 7019-25 and 6411-81 silicone tubing) drew gas from the sampling port, recirculating it back inside the well through Tygon tubing (Cole-Parmer 6409-15).

A field portable IR analyzer (Geotechnical Instruments UK Ltd., model GA-90) was used for measuring oxygen and carbon dioxide levels. A helium detector (Mark Products, Inc. model 9821) was used for helium determinations. Samples for ^{13}C analyses were collected in gas sample bulbs for analysis by mass spectroscopy.

Procedure

Before the injection period began, background levels of oxygen and carbon dioxide were to be measured from the monitoring points, and a brief system check was to be performed to ensure proper operation of the system and to check for leaks. Pressure and flow readings were to be recorded at each monitoring point during the injection period and the gas mixture analyzed periodically to ensure the proper air/helium mixture.

After the injection period, the soil gas was to be analyzed for oxygen, carbon dioxide, and helium at 2, 4, 6, and 8 hours, and then every 4 to 12 hours, depending on the rate at which oxygen was utilized. Analysis of samples for ^{13}C were to be made at the discretion of the project staff. The respiration test was to be terminated when the oxygen levels dropped to 5 %, the oxygen levels reached pre-injection background levels, or after five days of sampling.

RESULTS

Permeability Test

Background soil vapor measurements were taken from the monitoring points following assembly of the air permeability test components. The samples were analyzed in the field for oxygen and carbon dioxide using a portable infrared (IR) gas analyzer. The results were similar to measurements taken prior to the in situ respiration test - see Table 1. The blower was attached to vent test well VW01 for the initial test. It was observed during equipment setup that surface soil fractures were present near the concrete collars of the vent test well and the monitoring points.

The equipment system check was performed by turning on the blower and observing system parameters, and by conducting a leak test during a 30-minute operational period. During the check the injection system flow was approximately 25 scfm at 7 psi pressure. Several small leaks were identified during the check, and no pressure readings were observed at the monitoring points.

Following the initial system check, leaks were repaired in the system piping. A second system check was performed later the same day. The operational period for the second check was approximately 45 minutes. During this period, the injection system pressure was increased to 10 psi with a flow of approximately 50 scfm, in an attempt to induce pressure readings at the monitoring points. However, the increased pressure and temperature indicated stress on the system plumbing; thus, operating parameters were reduced to approximately 25 scfm at 5 psi for the remainder of the check. No pressure changes were observed at the monitoring points. However, leak tests verified that piping repairs were successful.

The system was run for a longer period to see if air flow would affect the monitoring points. However, during a subsequent 2-hour, 45-minute test with operating parameters of approximately 25 scfm at 5 psi, no pressure changes were observed.

Due to the failure to induce pressure changes at any of the monitoring points, modifications to the test procedure were initiated in an attempt to identify the fate of the injected air. It was suspected that the air was short-circuiting back up through the annulus of the vent test well or through nearby surface fractures. Thus a helium tracer test was conducted as follows. A helium cylinder was coupled via a high-pressure hose to the injection manifold of vent test well VW01. With the blower running 99.9% purity helium was injected into the system at a rate of approximately 12 cfm. During this time, total flow of the injection system was approximately 40 cfm. Helium injection continued for approximately 20 minutes until the cylinder was empty; however, the blower continued to run, distributing the approximately 240 standard cubic feet of injected helium.

Helium measurements were taken with a portable helium detector (Mark Products, Inc, model 9821) beginning approximately 1 minute after the initial injection period and continuing until no further readings were observed. This resulted in a total of 60 measurements during a 90-minute period. The initial helium measurement at the concrete collar of VW01 indicated leakage from the well annulus. However, subsequent measurements at surface fractures within a 6-ft radius of the well revealed helium readings of equal or greater concentration. Additional measurements at the study site indicated that extensive fracture flow was occurring. In fact, helium was detected in surface fractures at distances up to 35 ft from the injection point. Measurements were also taken from the monitoring point sample ports; however, no helium was detected. Figure 9 is a map of the surface fractures that had detectable levels of helium during the test. The fractures ranged from ⅛ to ⅝ inches (3 to 16 mm) in width and 3 to 36 inches (8 to 91 cm) in length.

Based on the results of the helium tracer test at VW01, the air permeability test planned for the second vent test well was not conducted. It was concluded that the extensive network of soil fractures precluded effective aeration of the contaminated subsurface soils at the 7069B site.

Respiration Test

Based on the results of soil gas measurements, shown in Table 1, monitoring point B16 was chosen as an injection point in place of monitoring point B24. This modification was made so that the respiration test could be conducted at those points with a combination of low oxygen and high hydrocarbon levels. The other two monitoring points were B2 and B5.

Following a system check, the air injection portion of the in situ respiration test began. During the 21-hour injection period, the system was monitored for temperature, pressure, flow, and helium concentration. Flow to each monitoring point was maintained at approximately 1.5 scfm as measured by a venturi digital calibrator (F&J Specialty Products, Inc., model D-802). The helium concentration was maintained at approximately 1%. The injected air created pr[illegible]essure increases at monitoring points B2 and B16. An initial pressure rise was seen at monitoring p[illegible] B5 (0.7 psig); however, the reading dropped to zero after approximately 15 hours. Helium measurements were also taken at surface soil fractures during the injection period. The results of these measurements are presented in Figure 10, showing that extensive fracture flow was occurring during gas injection.

Beginning at 2 hours after system shutdown, measurements for oxygen, carbon dioxide, and helium were collected from each monitoring point at specified intervals. Prior to sampling, soil vapors within each monitoring point were recirculated using the closed-loop pump system. This procedure was also conducted prior to ^{13}C sample collection. The test was concluded after 75 hours of monitoring.

Soil vapor measurements at monitoring points B2, B5, and B16 are given in Tables 2, 3, and 4, respectively. As seen from the data, the air injection process was successful in increasing soil gas oxygen levels to near ambient levels. A decrease in oxygen concentration) was seen at each monitoring point, particularly at B5, which had the lowest background oxygen level and the highest TPH concentration. An increase in carbon dioxide level was seen only at monitoring point B2. Helium levels showed a steady drop at all three points during the monitoring period. This is not surprising, since the injection points were shown to be connected to the surface through fractures. It is interesting to note that the initial helium levels measured at the monitoring points (3 to 5% were significantly higher than the concentration in the injected air (1%). The possible reasons for this are: 1) the gases within the monitoring points were stratified and the recirculating procedure was not completely effective in remixing the vapors, or 2) helium readings were artificially high due to the presence of methane (Mark Products, Inc., 1991). Measurements taken with the IR analyzer indicated that methane was present; however, a purge cycle (a built-in function of the helium detector) was completed after each sample event and should have eliminated this problem.

Because of the magnitude of the decrease in helium levels, it is not possible to obtain reliable measurements of biodegradation rate at the three monitoring points. Indeed, the complete loss of helium and lack of carbon dioxide production at B5 and B16 makes it questionable as to what portion of the oxygen consumption at these points was due to biodegradation. However, fractional oxygen loss is likely much lower than helium loss both due to a lower diffusion coefficient (Hinchee and Ong, 1992) and to a buoyancy-driven convectional flow of helium up the fractures to which heavier oxygen and carbon dioxide would not be subject. With these facts in mind, the more consistent soil gas values from B2 may be used to derive a best-case value for biodegradation rate. Over 75 hours, oxygen loss was 6.1 percent, while carbon dioxide gain was 2.1 percent, giving a carbon dioxide to oxygen ratio of 0.344, reasonably consistent with published values of 0.36 (Miller, 1990) and 0.474 (Hinchee and Ong 1992). The oxygen consumption rate may then be estimated as 0.081 %/hr using the raw oxygen data or 0.059 %/hr using the carbon dioxide data with the carbon dioxide to oxygen ratio of Hinchee and Ong. These values are on the lower limit of oxygen consumption rates considered suitable for bioventing (Hinchee et al., 1992).

Duplicate samples for ^{13}C analyses were collected from each monitoring point (6 samples total) approximately 10 hours into the respiration test. Another set of samples was collected from monitoring point B2 at the completion of the test. Results of ^{13}C analyses are shown in Table 5. The results are shown in terms of the ratio of ^{13}C to ^{12}C by the δ notation. The ^{13}C values would be expected to lie between a normal atmospheric level of $\delta^{13}C = -7.8\%$ and levels representative of carbon dioxide derived from organic materials or hydrocarbons ($\delta^{13}C = -25$ to -35%).

As seen in Table 5, the $\delta^{13}C$ values suffered from precision errors which limit their reliability. These measurements exhibited varying symptoms of contamination which may be due to hydrocarbons in the soil gas that were not effectively removed during cryogenic cleanup prior to measurement or potentially other factors that were introduced during or following sample collection. However, values for the B2 monitoring point appear somewhat consistent. The $\delta^{13}C$ measurement (-5.5%) early in the respiration test was on the order of atmospheric carbon dioxide, while the final measurements (-15.5 and -21.5) were much closer to the range expected for carbon dioxide derived from hydrocarbons. This finding, matched with the generation of carbon dioxide at this monitoring point, provides convincing evidence of significant hydrocarbon biodegradation.

CONCLUSIONS

The treatability tests indicated that the 7069B site is not suitable for bioventing mainly due to the magnitude of gas flow in fractures in the soil. Reliable estimates of the biodegradation rate under oxygenated conditions were not achievable because of uncertainties due to the fracture flow. Somewhat consistent carbon dioxide and oxygen level data were collected at one of the three monitoring points. This data indicated that the biodegradation rate was on the order of 0.06 %/hr - a value on the low end of the acceptable range for bioventing. The finding of biodegradation at this monitoring point was supported by carbon isotope measurements.

The findings of this test have several implications regarding bioventing and conventional soil venting. The detrimental impact of diffusional limitations, including fracture flow, has been discussed in several papers (e.g., Wilson, 1990). However, the detection and quantification of these limitations in field conditions remains a practical problem. In this field test the extensive fracture flow was detected during the air permeability test by the fact that no significant pressure rise was measured at any monitoring point despite a relatively high injection pressure. This fracture flow may not have been apparent had there been small pressure measurements at the monitoring points. In such a case the air permeability would have been greatly overestimated and an inefficient system would be implemented. Thus, it is recommended that tracer injection be included in air permeability tests, particularly in lower permeability soils. Tracer injection would also be valuable in non-fractured media for determination of preferential flow paths.

DISCLAIMER

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Table 1. Background soil vapor measurements taken from monitoring points prior to *In Situ* respiration test.

Monitoring Point	% CO_2	% O_2	Total Hydrocarbons (ppm)
B2	7.9	10.5	95
B5	2.7	0.9	130
B7	3.7	17.0	3
B11	5.2	15.6	102
B14S	8.4	[illegible]	115
B14D	0.0	19.6	9
B16	7.9	8.7	145
B24	0.0	12.8	125

Table 2. Soil vapor measurements from monitoring point B2 following air injection period

Monitoring Point B2			
Background Concentrations: Oxygen - 10.5%, Carbon dioxide - 7.9%			
Elapsed time (hr)	O_2 (%)	CO_2 (%)	Helium (%)
2	20.0	0.0	4.10
4	20.1	0.0	2.80
6	20.1	0.0	1.50
8	19.8	0.0	0.74
12	19.3	0.0	0.43
18	18.3	0.3	0.16
29	16.8	0.5	0.11
38	15.8	1.0	0.06
50	15.2	1.3	0.00
59	15.3	1.5	0.00
75	13.9	2.1	0.00

Table 3. Soil vapor measurements from monitoring point B5 following air injection period

Monitoring Point B5			
Background Concentrations: Oxyg^n - 0.9%, Carbon dioxide - 2.7%			
Elapsed time (hr)	**O_2 (%)**	**CO_2 (%)**	**Helium (%)**
2	18.5	0.0	3.10
4	17.4	0.0	2.40
6	15.8	0.0	1.80
8	13.9	0.0	1.50
12	12.5	0.0	0.56
18	8.1	0.0	0.56
29	4.8	0.0	0.26
38	3.6	0.0	0.19
50	2.3	0.0	0.13
59	2.0	0.0	0.01
75	2.0	0.1	0.00

Table 4. Soil vapor measurements from monitoring point B16 following air injection period

Monitoring Point B16			
Background Concentrations: Oxygen - 8.7%, Carbon dioxide - 7.9%			
Elapsed time (hr)	O_2 (%)	CO_2 (%)	Helium (%)
2	20.0	0.0	5.20
4	20.2	0.0	2.80
6	20.4	0.0	1.50
8	20.0	0.0	1.30
12	19.6	0.0	0.51
18	18.8	0.0	0.48
29	18.1	0.0	0.43
38	17.3	0.0	0.35
50	16.2	0.0	0.32
59	16.0	0.0	0.17
75	14.8	0.0	0.08

Table 5. Results of ^{13}C measurements of soil gas samples

Sample point	Hours into test	$\delta^{13}C_{PDB}$ (%)
B2	10	sample leaked
B2	10	-5.5
B5	10	-33
[illegible]	10	~ -80
[illegible]6	10	-3.4
B16	10	-14.5
B2	75	-15.5
B2	75	-21.5

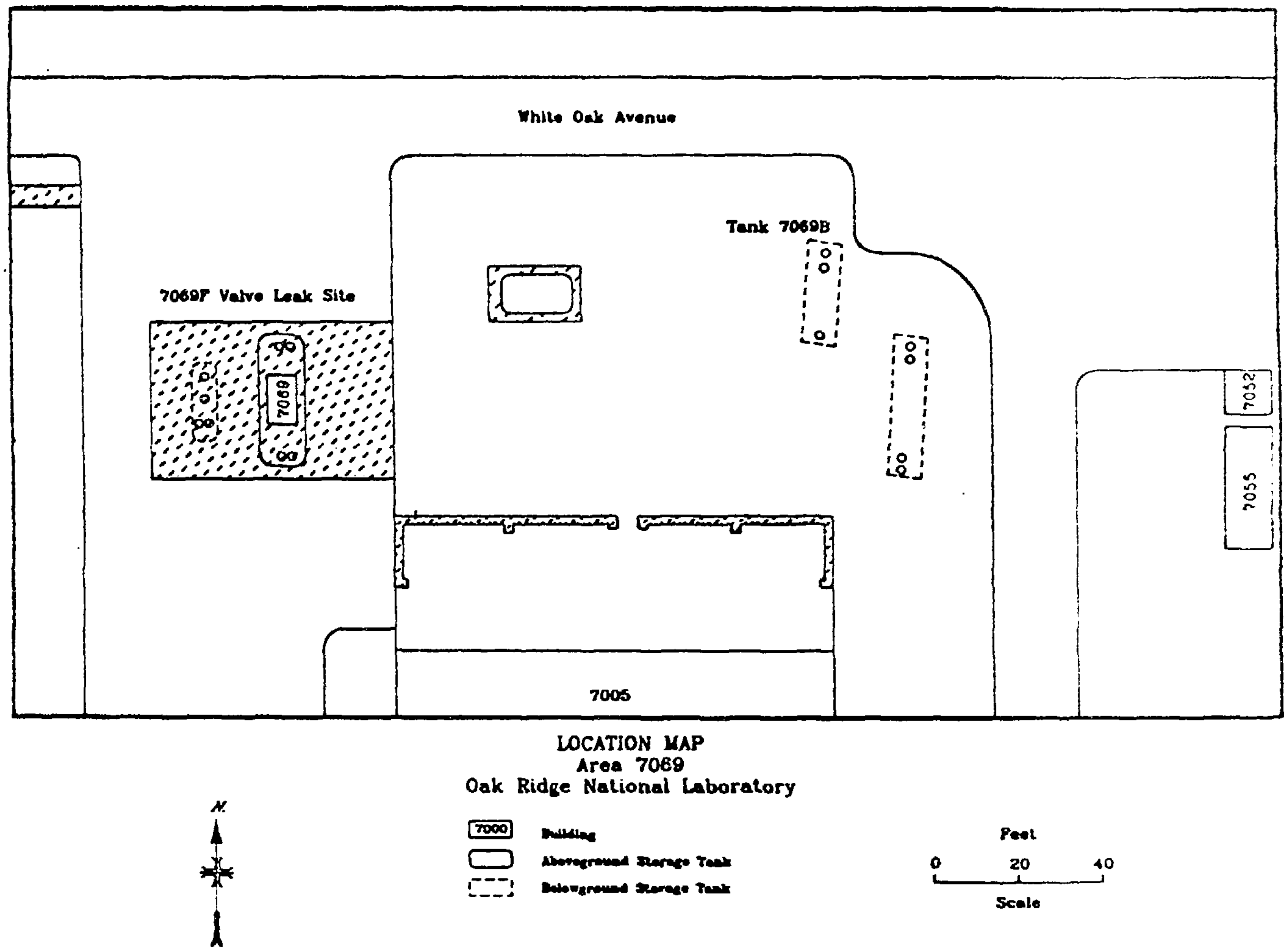

Figure 1. Building 7069 area of Oak Ridge National Laboratory

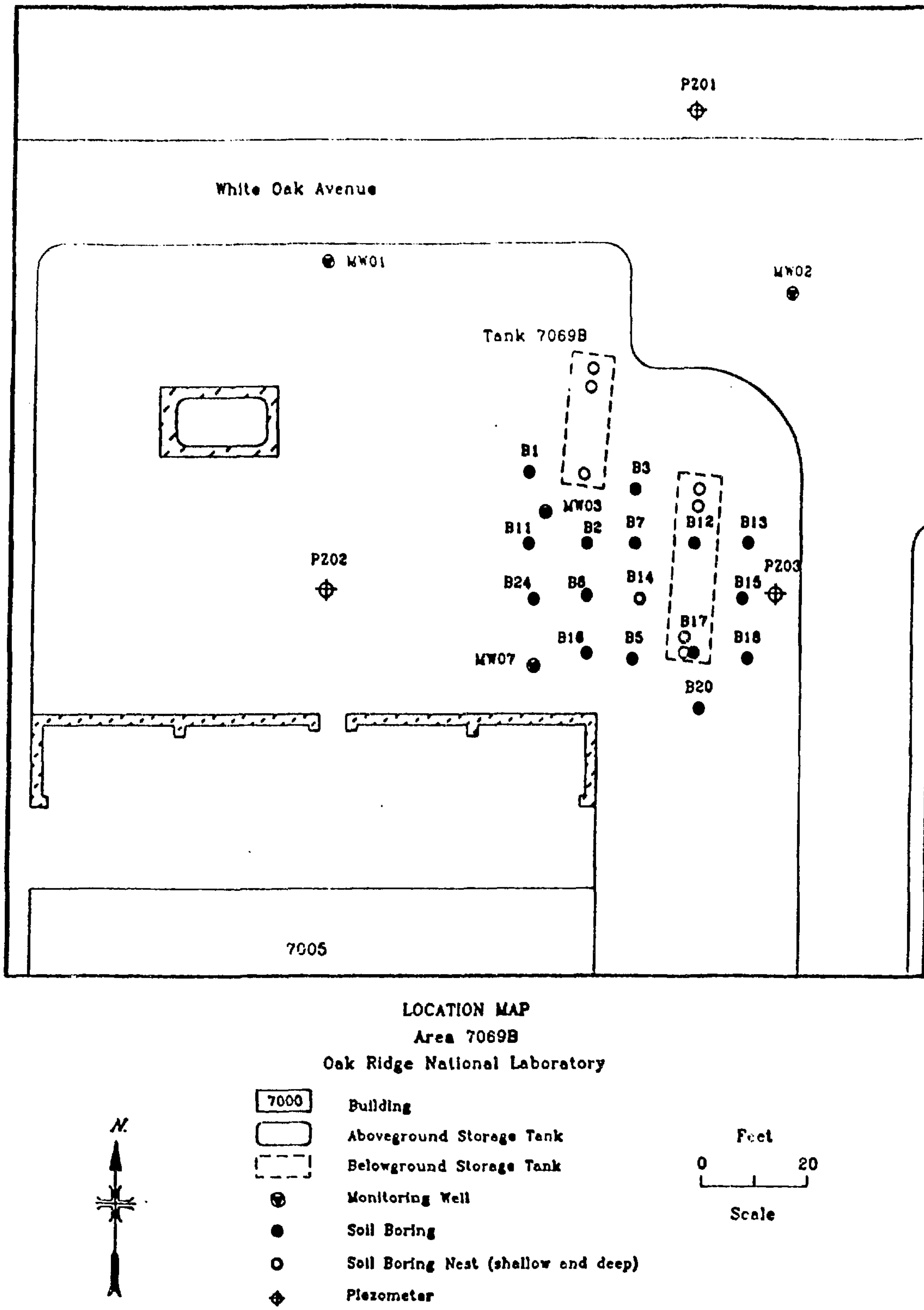

Figure 2. Locations of piezometers, monitoring wells, and borings in Building 7069 area

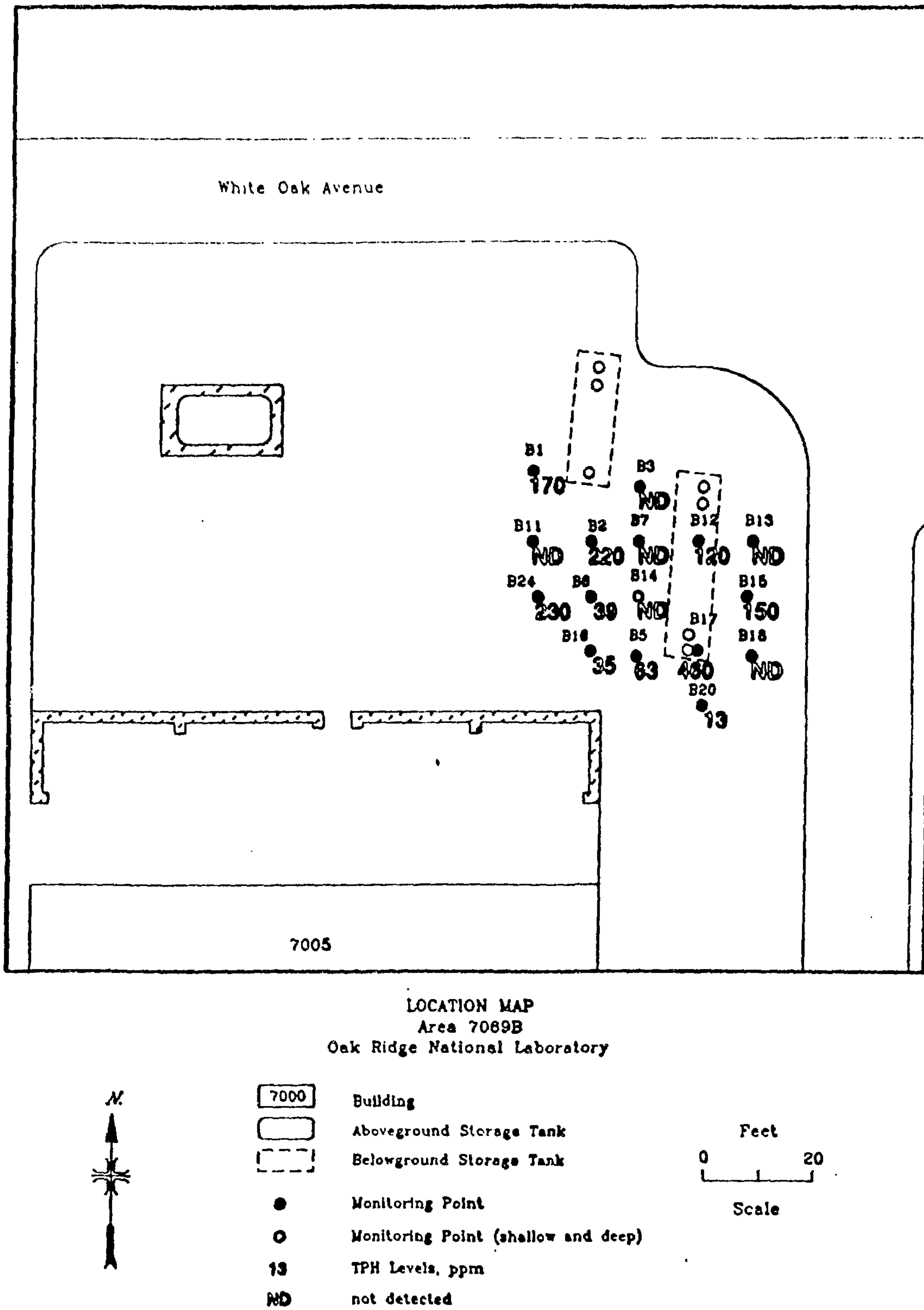

Figure 3. Total petroleum hydrocarbon concentration in soil samples from 7069 area

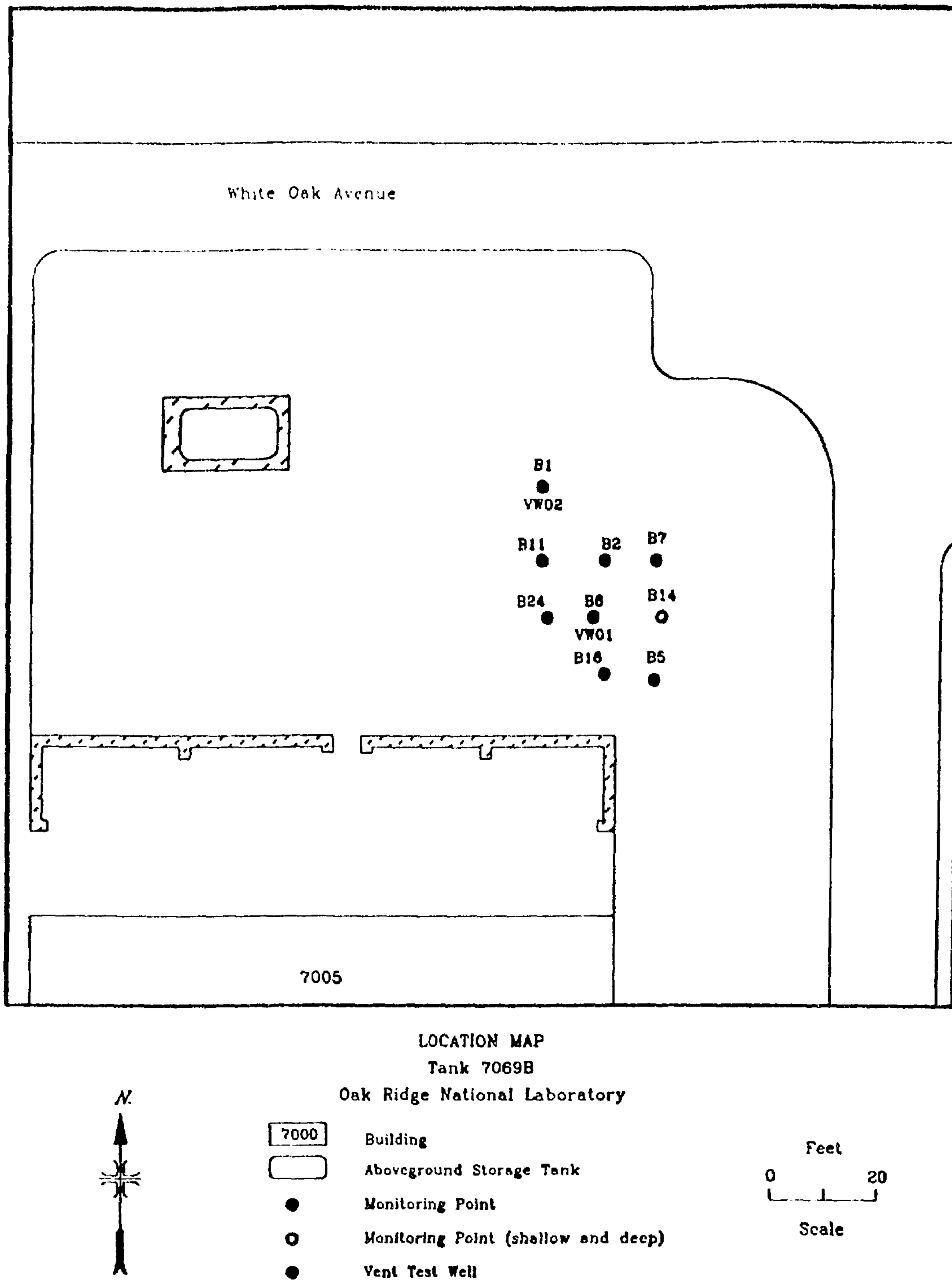

Figure 4. Locations of vent test wells and monitoring points

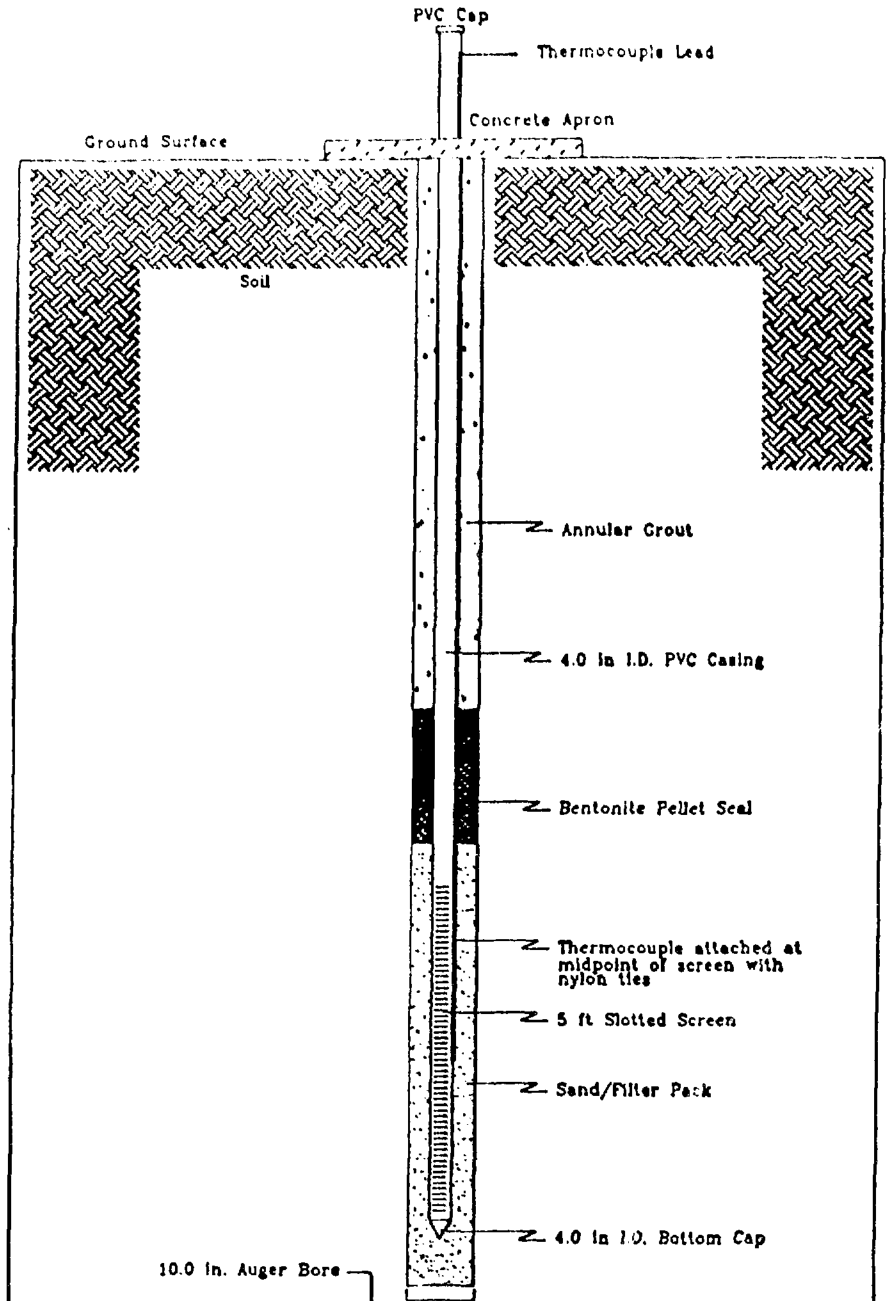

Figure 5. Construction of vent test wells

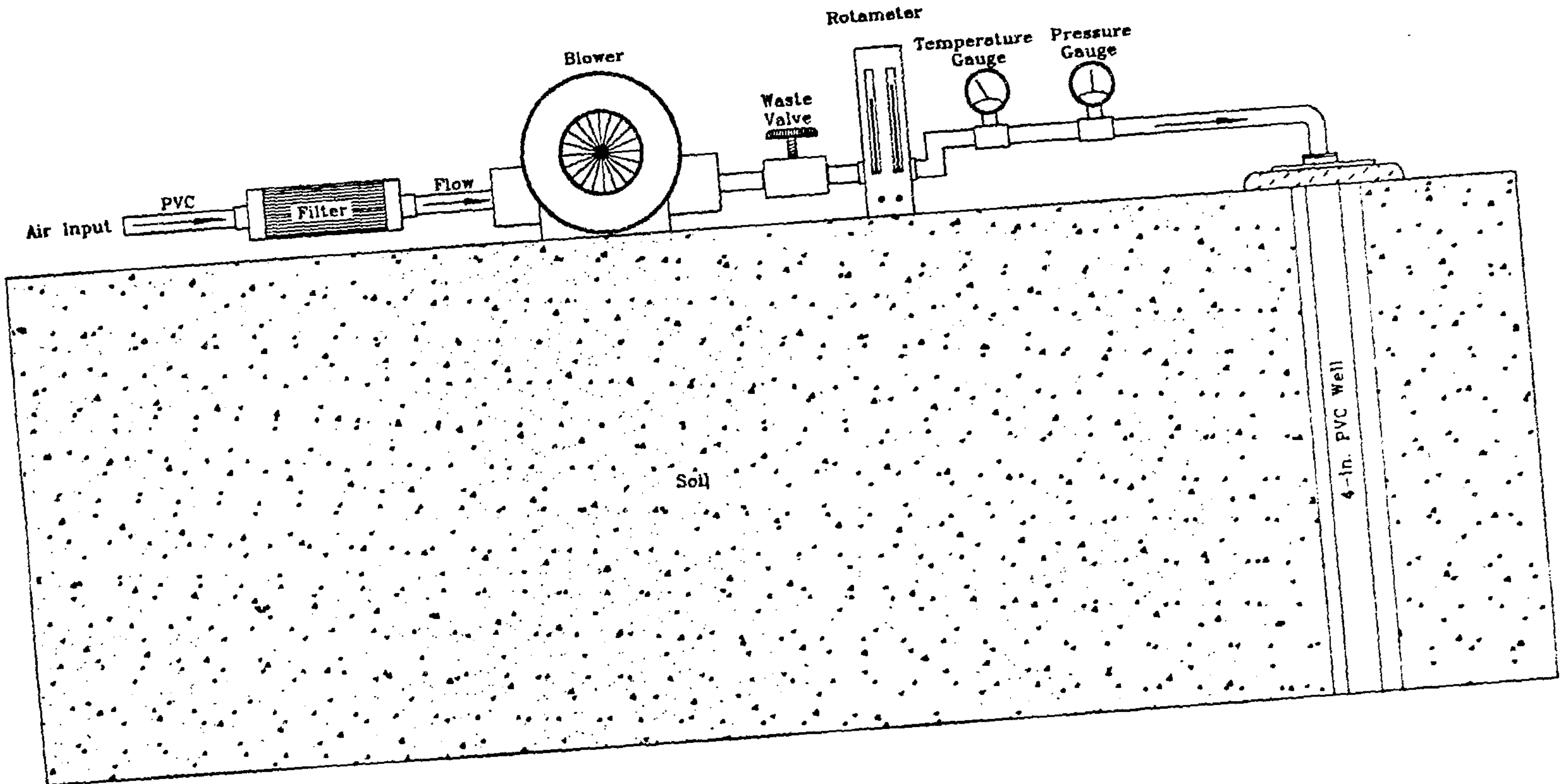

Figure 6. Air injection equipment employed for in situ permeability test

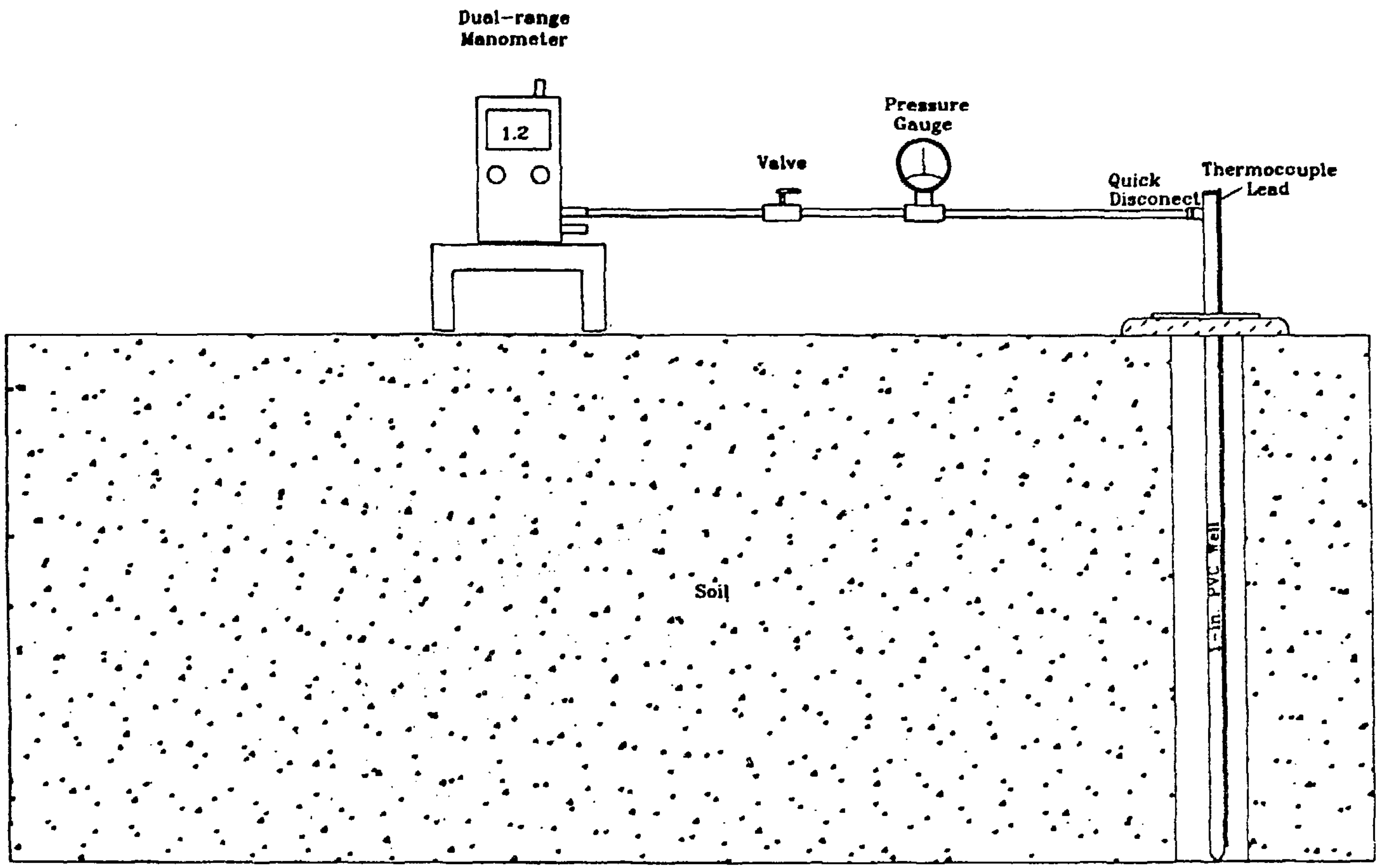

Figure 7. Monitoring point and measuring equipment employed for in situ permeability test

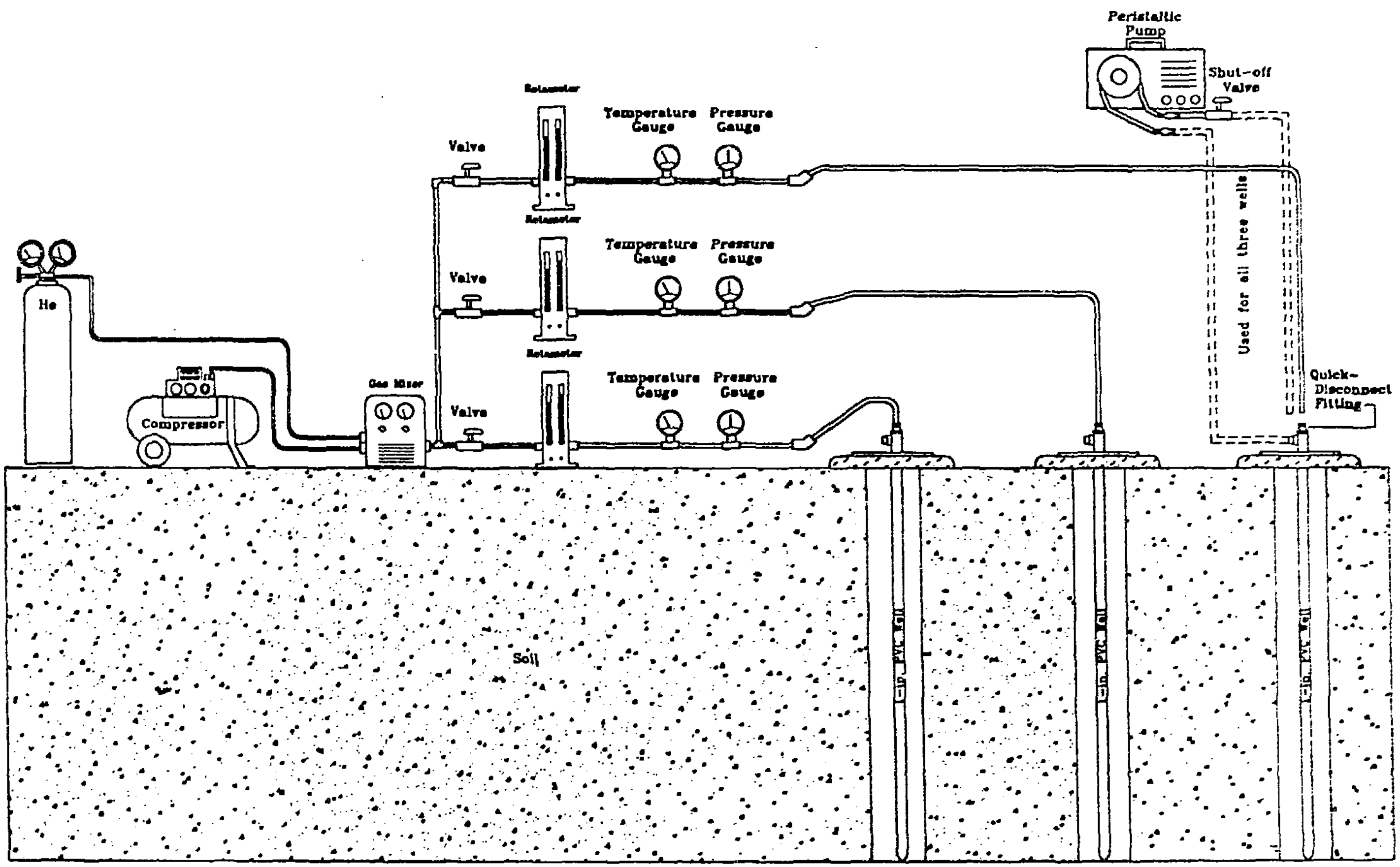

Figure 8. Equipment setup for in situ respiration test

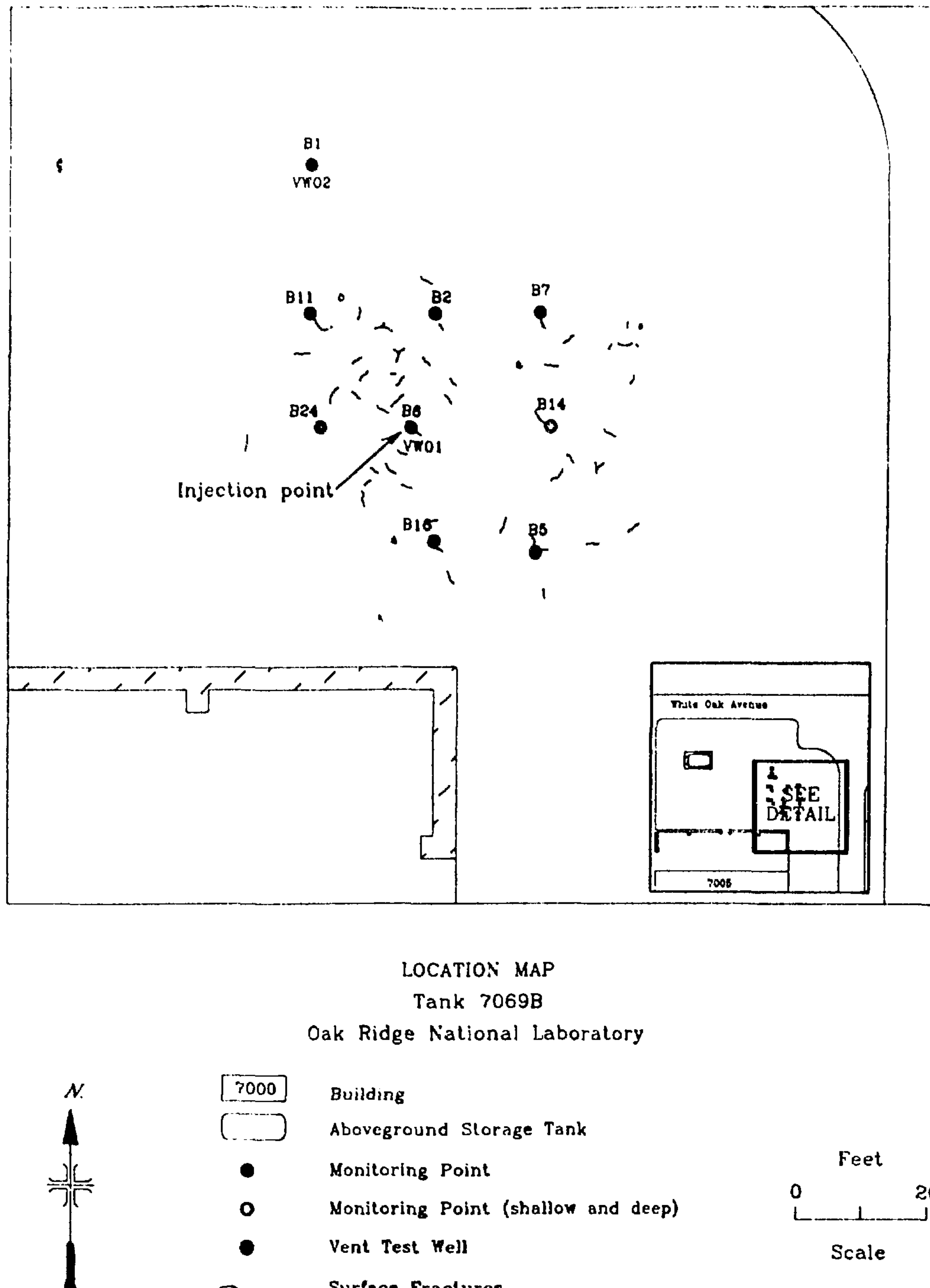

Figure 9. Map of surface fractures detected during air permeability tracer injection test

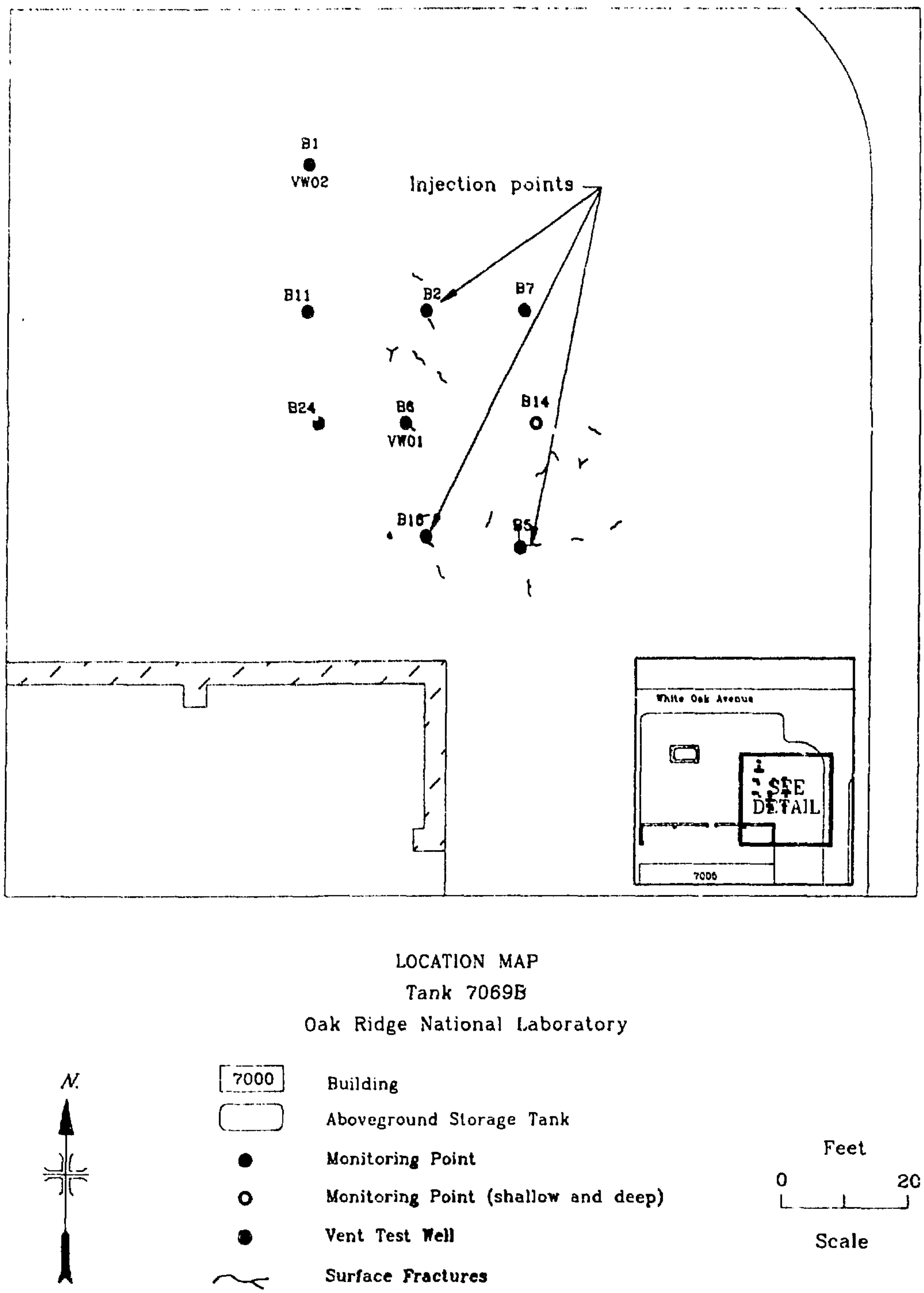

Figure 10. Fracture flow identified during in situ respiration test