PRAXIS
ENVIRONMENTAL TECHNOLOGIES, INC.

Final *PneuLog*® EVALUATION REPORT

Bulk Fuels Facility Spill
Solid Waste Management Units ST-106 and SS-111

Kirtland Air Force Base, Albuquerque, New Mexico

Version 1.0, June, 2012

Prepared for:

Shaw Environmental & Infrastructure Group
Albuquerque, New Mexico

Prepared by:

PRAXIS Environmental Technologies, Inc.
1440 Rollins Road
Burlingame, California 94010

TABLE OF CONTENTS

Page

SECTION 1 – **INTRODUCTION**..... 4

SECTION 2 – **PNEULOG® PROFILES**..... 8

SECTION 3 – **DATA INTERPRETATION FOR SVE DESIGN AND OPERATION** 16
Site Background

SECTION 4 – **DATA INTERPRETATION FOR BIOLOGICAL DEGRADATION**..... 34

REFERENCES

ATTACHMENT A – **PneuLog Profile Data and Vapor Sampling Results**

ATTACHMENT B – **Vapor Flow Model**

ATTACHMENT C – **Evaporation of Residual Fuel to Estimate Duration of Treatment**

ATTACHMENT D – **PneuLog Standard Operating Procedure**

LIST OF FIGURES

Figure	Title	Page
1	Location of PneuLog Test Borings	5
2	Total VOC Vapor Plume Footprints by Elevation	6
3	Benzene Vapor Plume Footprints by Elevation	7
4	Schematic of Pneumatic Well Logging Equipment	9
5	Composite PneuLog Profiles from Boring KAFB-106-148	11
6	Composite PneuLog Profiles from Boring KAFB-106-149	13
7	Composite PneuLog Profiles from Boring KAFB-106-150	15

LIST OF TABLES

Table	Title	Page
1	Summary of Field Activities	4
2	Summary of Hydrocarbon Extraction and Degradation Rates During Testing	35

PneuLog® Evaluation Report
Bulk Fuels Facility Spill

1. INTRODUCTION

PneuLog® testing was performed in three boreholes with a total of nine well screen intervals to support the expansion of the soil vapor extraction (SVE) system operating at the Bulk Fuels Facility Spill on Kirtland AFB, New Mexico. Each borehole contains a nest of three well screens that span nearly the full extent of the vadose zone from 25 feet below ground surface (ft bgs) to just above the water table found about 500 ft bgs. The boreholes are designated as KAFB-106148, KAFB-106149, and KAFB-106150. The borehole locations are indicated on the site map provided in Figure 1. The tests were performed at the end of April 2012. An SVE system consisting of internal combustion engines (ICE) has operated at the site since 2003. The SVE system details and results from historical operations are reported in "Quarterly Pre-Remedy Monitoring and Site Investigation Report for October – December 2011, Bulk Fuels Facility Spill, Solid Waste Management Units ST-106 and SS-111, April 2012," authored by Shaw Environmental and Infrastructure, Inc. (Shaw). For reference, Figures 2 and 3 provide interpreted vapor plumes of total volatile organic compounds (VOCs), primarily petroleum hydrocarbons and benzene, respectively, at various depths. These figures were copied from the cited quarterly report.

One of the trailer-mounted ICE units was used for vapor extraction and treatment during the PneuLog testing. The unit required about one to two hours of operation to attain a relatively steady extraction rate although extraction rates were increasing during the logging of several wells and complicated, but did not compromise, the data analyses. After a minimum of one hour of vapor extraction on each well, PneuLog was implemented to profile the flow and concentration along the screen. Following the initial log, vapor samples were collected in Tedlar bags at depths of interest and were later analyzed with a calibrated gas chromatograph operated by Praxis. The results yielded profiles of the total volatile petroleum hydrocarbon (TVPH) vapor concentrations from each well screen interval as well as a permeability profile. A summary of field activities is provided in Table 1.

Table 1. Summary of PneuLog Testing

Start Date	Well KAFB-106-	Screen Interval (feet bgs)	Vacuum (inH2O)	Extraction Rate (scfm)	Wellhead TVPH Conc* (ppm)
18- Apr -12	148-S	24-194	10.0	81	9,200
18- Apr -12	148-M	199-349	16.4	87	9,700
19- Apr -12	148-D	354-484	32.5	139	4,300
16- Apr -12	149-S	24-194	14	126	940
17- Apr -12	149-M	199-349	28.5	142	3,500
17- Apr -12	149-D	354-484	30.5	131	14,400
20- Apr -12	150-S	25-200	11.5	112	210
20- Apr -12	150-M	206-350	26.5	137	4,200
20- Apr -12	150-D	355-484	22.0	95	16,900

* Total Volatile Petroleum Hydrocarbon (TVPH) Concentrations with hexane as the standard

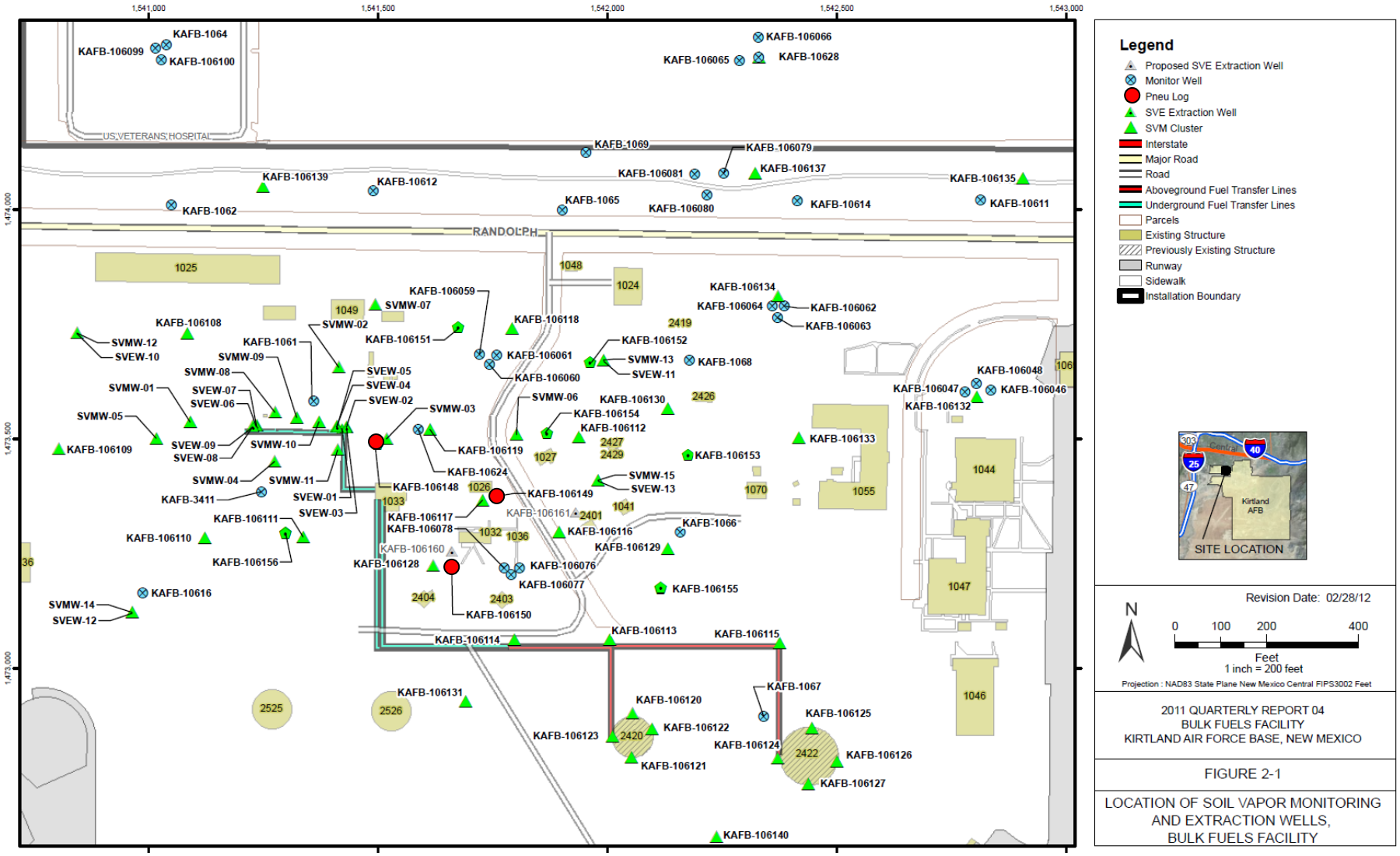


Figure 1. Location of PneuLog Test Borings

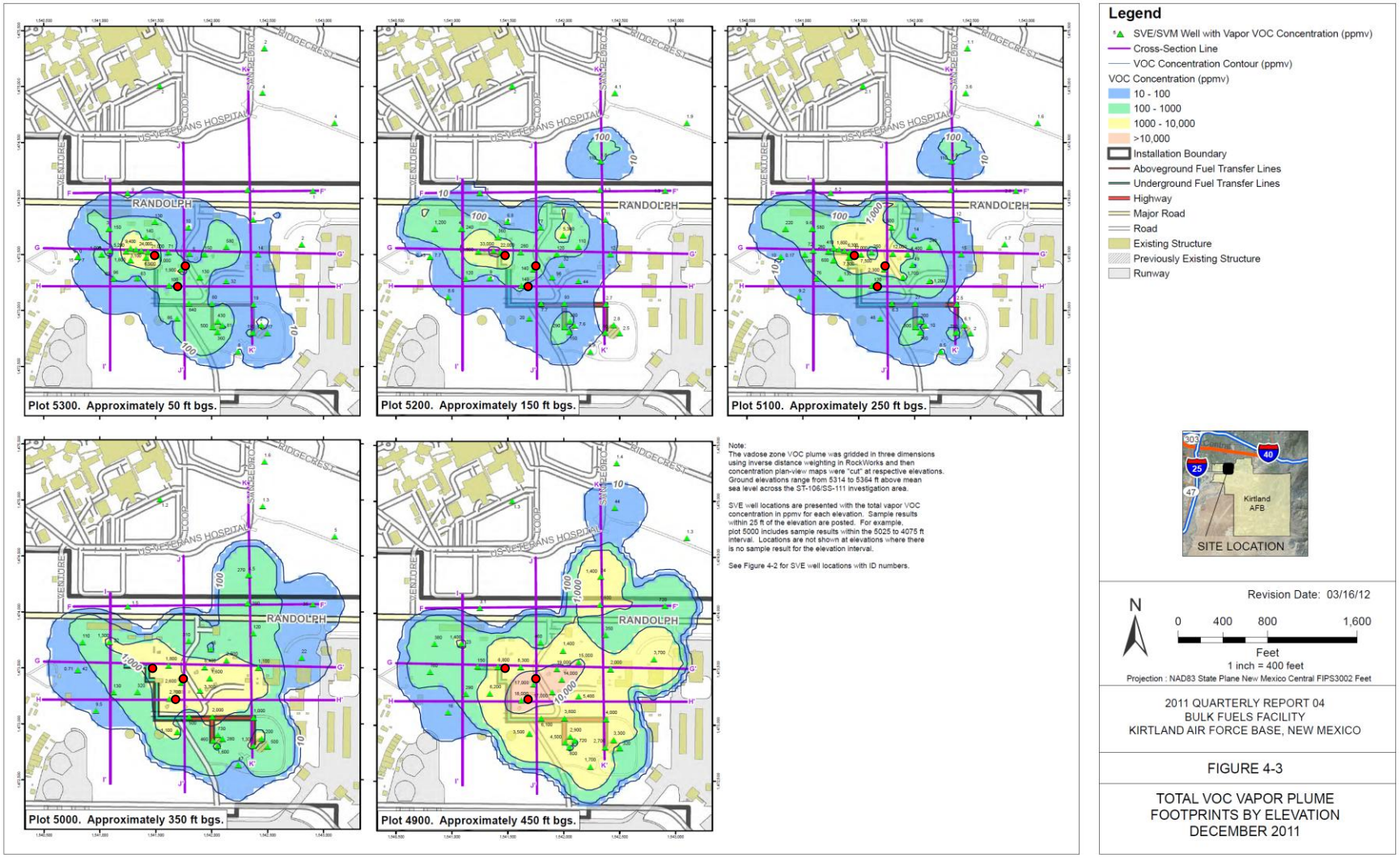


Figure 2. Total VOC Vapor Plume Footprints by Elevation

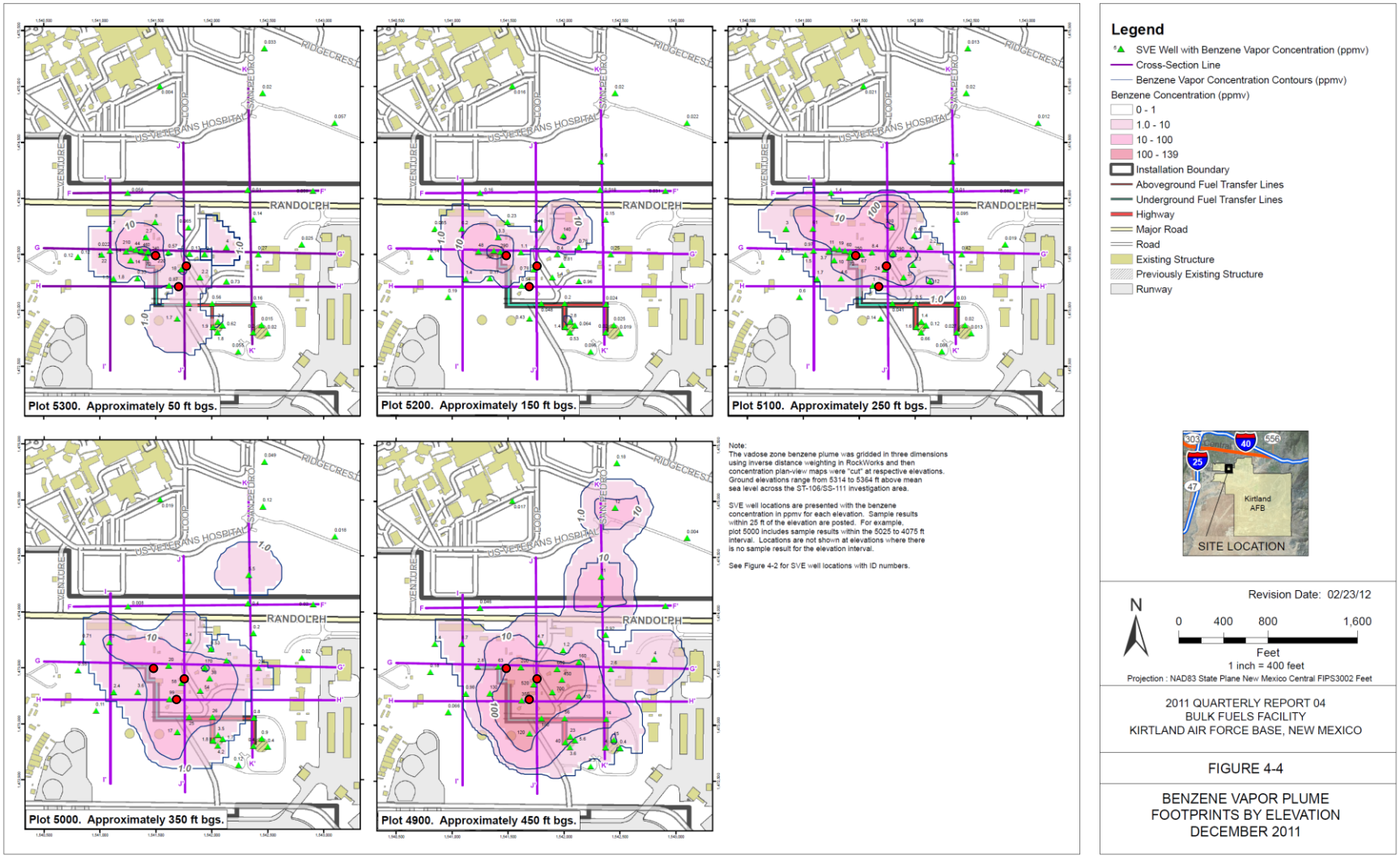


Figure 3. Benzene Vapor Plume Footprints by Elevation

As indicated in Figures 2 and 3, the location of boring KAFB-106-148 is in the midst of the highest vapor concentrations in the shallow and middle vadose zone while borings KAFB-106-149 and –150 are located in the highest vapor concentrations in the deep vadose zone. These observations are supported by the vapor concentrations measured in the three wells installed in each boring and reported in Table 1. The total volatile petroleum hydrocarbon (TVPH) vapor concentration measured at the deep wellheads in KAFB-106-149 and –150 were 14,400 ppm and 16,900 ppm, respectively. The TVPH vapor concentrations measured in the shallow and middle wells installed in boring KAFB-106-148 were 9,200 ppm and 9,700 ppm, respectively. Much lower wellhead TVPH vapor concentrations were measured at the shallow wellheads of borings KAFB-106-149 and –150 (940 ppm and 210 ppm, respectively).

2. PNEULOG PROFILES

For both vadose zone characterization and remedial optimization, Praxis has developed, field-tested and commercialized a pneumatic well logging process. Known as PneuLog®, the well logging is performed by simultaneously measuring the cumulative air flow and contaminant concentrations along the depth of an extraction well screen during active SVE. To make these measurements, a flow sensor is moved through the well during vacuum extraction and gas samples are collected from the same depth and analyzed continuously. The standard operating procedure for PneuLog and the method of data interpretation are provided in Attachment D.

The equipment for the logging is illustrated in Figure 4. The Pneulog® instrumentation is attached to a cable, which passes through alignment pulleys and a vacuum-tight fitting at the wellhead. The instrumentation is raised or lowered by a motorized reel around which the cable is wound. The logging proceeds at roughly 5 feet per minute in the SVE well. Sensors in the pulley assembly indicate the depth of the instrument. Electrical leads connect the flow sensor to a data acquisition (DAQ) system located on the motorized reel. A vapor sampling tube connects the sample port on the downhole instrument to a surface vacuum pump. This sampling pump draws a continuous stream of air through the sampling tube to the surface where it is analyzed. A photoionization detector (PID) is used to provide a continuous reading of total VOC concentration. Tedlar bag samples are collected for gas chromatographic (GC) analysis to determine compound-specific concentrations at discrete depths and for PID calibration. Duplicate samples are analyzed in the field for carbon dioxide and oxygen content using a calibrated GasTech Model GTCO2.

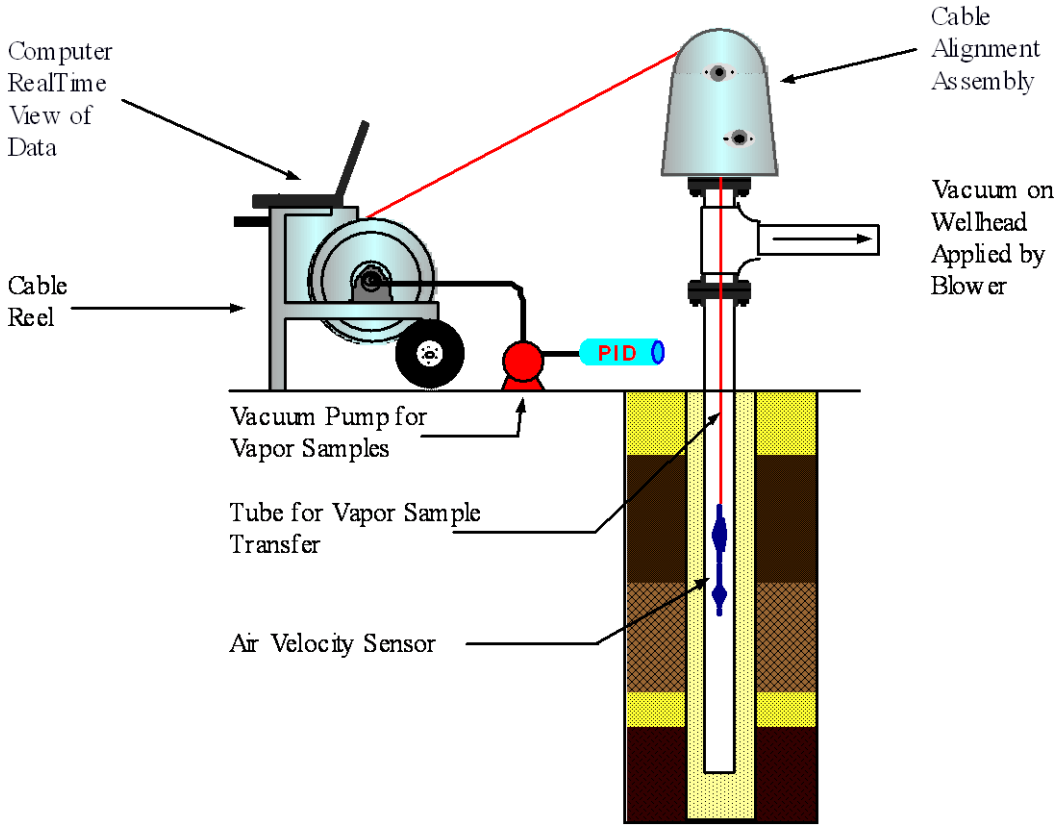


Figure 4. Schematic of Pneumatic Well Logging Equipment

The composite permeability and TVPH concentration profiles for boreholes KAFB-106148, -149 and -150, respectively are illustrated in Figures 5, 6 and 7, respectively. The measured profile data and speciated results from the GC and field instrument analyses on vapor samples collected from the wells are provided in Appendix B. Vapor samples were collected in Tedlar bags to determine compound-specific vapor concentration profiles and to calibrate the continuous total concentration profile measured by the PID. The vapor samples collected in Tedlar bags were shipped and analyzed by Praxis at its laboratory within 72 hours of collection using a calibrated gas chromatograph (Agilent 6890). The analyses followed a modified EPA Method 18 and were not state-certified. The quality of the data is commensurate with field screening since no analyses were performed with a mass spectrometer to confirm the compound identifications. The analytical results from the GC, reported in parts per million by volume (ppmV), include vapor concentrations for:

- Total volatile petroleum hydrocarbons (TVPH) as hexane
- Benzene
- Toluene
- Ethylbenzene
- m,p-Xylenes
- o-Xylene
- 1,2,4-Trimethylbenzene (1,2,4-TMB)
- Methane
- Hexane

The analytical results from the field instrument (GasTech Model GTCO2), reported as volumetric percentages, include:

- Carbon Dioxide (CO2)
- Oxygen (O2)
- Lower Explosion Limit (LEL) as methane

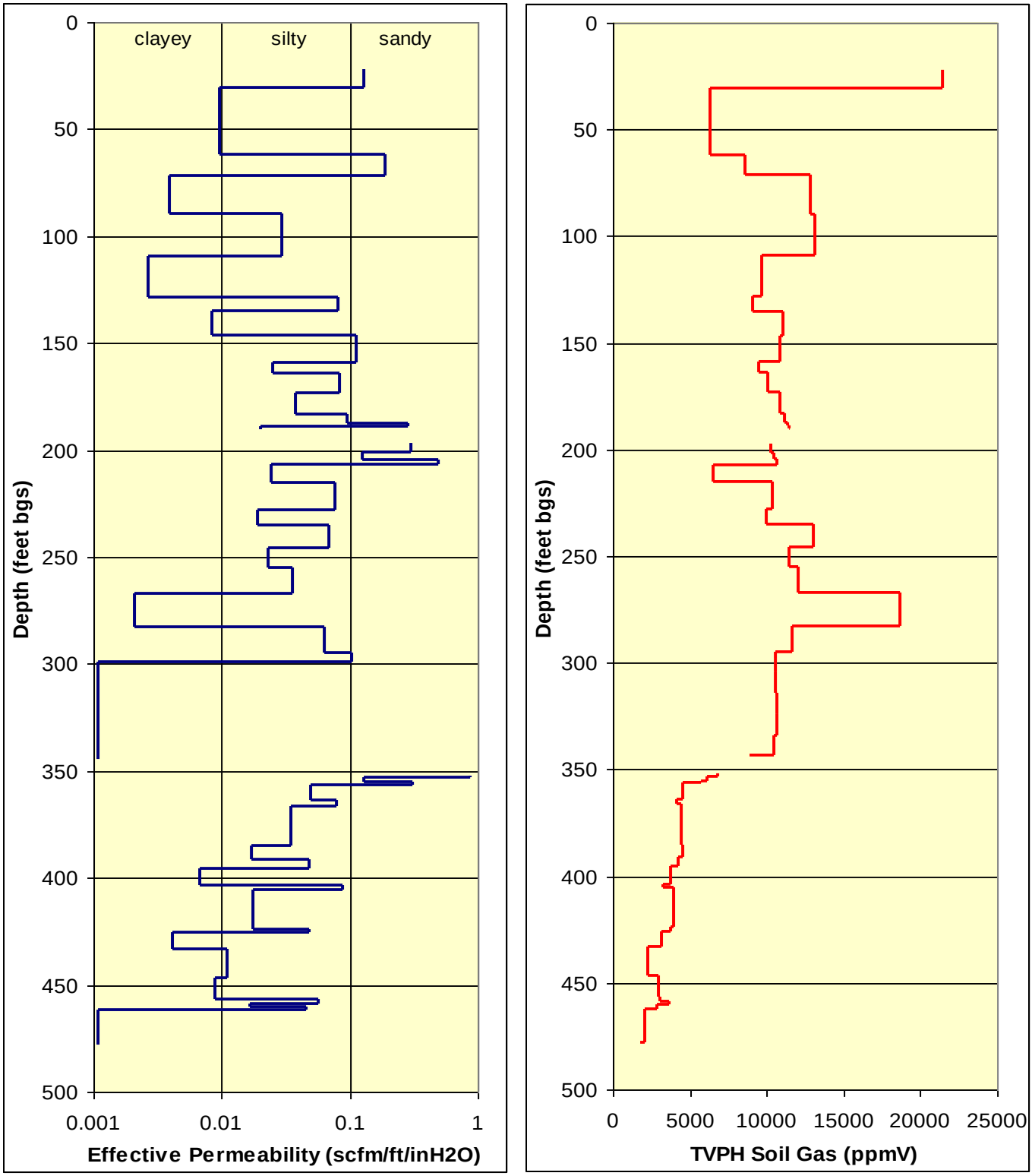
As indicated in Figures 5, 6 and 7, vapor samples were collected at the wellheads, near the bottom of the screen interval, and near the bottom of each major flow zone encountered along each of the well screens.

PneuLog testing was performed in the three wells of boring KAFB-106-148 on April 18-19, 2012. The measured flow and cumulative concentration profiles for each well are provided in Attachment A along with the results from the GC analyses and field instruments. The summary profiles provided in Figure 5 are the interpreted effective permeability and the calculated soil pore vapor concentration of TVPH. The effective permeability profile was generated from the changes in flow observed over depth intervals divided by the thickness of the interval and then divided again by the applied wellhead vacuum. The effective permeability can be used to predict extraction rates for other applied vacuums through linear extrapolation. Note the effective permeability is plotted on a log scale and, based on previous field efforts, the soils can be roughly characterized as dominated by sands, silts or clays as indicated on Figure 5.

In the shallow vadose zone around 148, a thin permeable interval is identified in Figure 5 at the top of the screen (~25 feet bgs) and another from about 62 to 72 feet bgs. The permeable interval at top of the screen suggests a shallow source of contaminant vapors that may exceed 20,000 ppm of TVPH. The low permeability interval from 31 to 62 feet bgs appears to harbor little contamination. The effective permeability of the soils from 72 to 128 feet bgs were moderate to low with some vapor production from 90 to 110 feet bgs. This interval displayed soil vapor concentrations of about 13,000 ppm. From 128 feet bgs to the bottom of the screen at 190 feet bgs, the soil permeability was slightly higher and exhibited more heterogeneity than the overlying intervals. The soil TVPH vapor concentration was around 10,000 ppm across this interval although slightly higher values were encountered from 135 to 159 feet bgs.

The trend of increased heterogeneity continued at the top of the middle screen of 148 where moderately permeable soils were observed from 199 to 267 feet bgs. A thin permeable interval was identified at the top of this screen; however, this spike may be the result of the sand pack extending two feet above the top of the screen exposing more of the soil interval to extraction. The soil TVPH vapor concentration persisted around 10,000 ppm across this interval although a decrease to about 6,000 ppm was observed from 207 to 215 feet bgs. From 267 to 283 feet bgs, a relatively low permeability interval was encountered that appears to harbor significant contamination, as evidenced by its elevated soil vapor concentration of almost 20,000 ppm. A moderately permeable interval was identified from 283 to 299 feet bgs where the TVPH concentration decreased to about 11,000 ppm. The thick soil interval from 299 to 344 feet bgs produced no appreciable vapor flow from the soil indicating this interval has a relatively low permeability. The soil TVPH vapor concentration persisted at about 10,000 ppm across this interval although a drop in concentration was observed at the bottom of the screen at 343 feet bgs.

Figure 5. Composite PneuLog Profiles from Boring KAFB-106-148

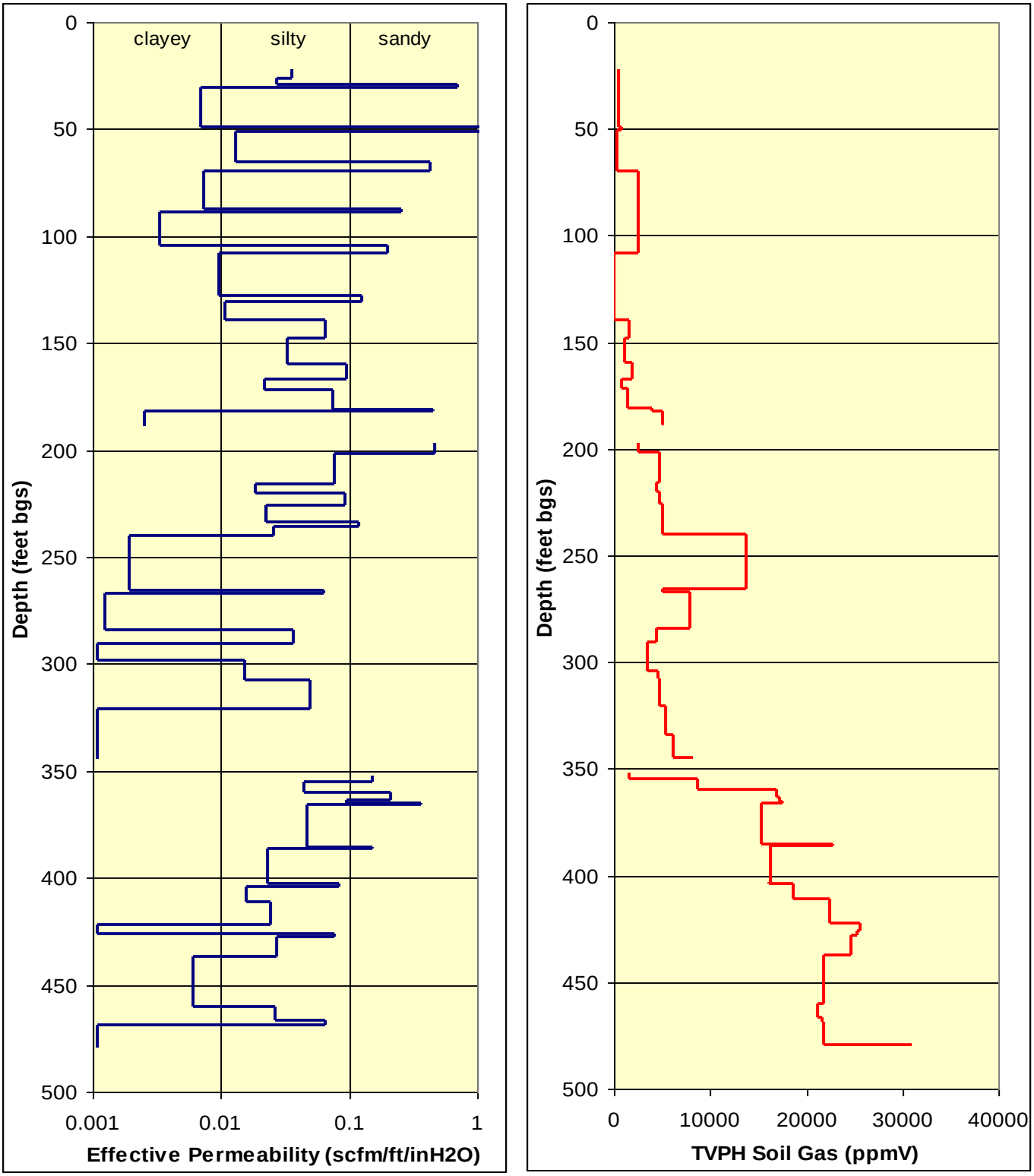


The top of the deep screen interval in borehole 148 revealed a thin permeable interval with a soil TVPH vapor concentration of almost 7,000 ppm that correlates well with the bottom of the middle screen interval. Below this permeable interval, the soils from 356 to 462 feet bgs have a moderate permeability with the permeability trending toward a decrease with increasing depth. No appreciable flow was extracted from the bottom of the screen from 462 to 478 feet bgs. The soil TVPH vapor concentration also trended downward with depth from about 4,500 ppm at 362 feet bgs down to about 1,800 ppm at 478 feet bgs. These trends suggest the lesser permeable soils below 362 feet bgs have inhibited the downward migration of NAPL and the deeper contamination is likely associated with vapor migration that may be remediated relatively quickly with SVE.

The summary profiles for borehole KAFB-106-149 are provided in Figure 6. In the shallow vadose zone around 149, the soils exhibited a series of six thin, permeable intervals dispersed in relatively low permeability soils from about 25 to 140 feet bgs. The predominantly low permeability of these soils inhibited the entry of significant contamination as evidenced by soil TVPH vapor concentrations less than 500 ppm except for the interval from 70 to 108 feet bgs where the vapor concentration was locally elevated at about 2,500 ppm. This interval of higher vapor concentration is likely the result of horizontal vapor migration along one or more of the thin permeable intervals that is connected to a soil volume harboring residual NAPL. The lack of significant contamination above and below the interval indicates the migration is not vertical. The low permeability interval from 108 to 140 feet bgs yielded no significant contaminant mass during the testing. Below 140 feet bgs down to the bottom of the screen at 188 feet bgs, the soil permeability trended upward with decreasing depth as did the soil TVPH vapor concentration. The soil TVPH vapor concentration increased from approximately zero at 108 feet bgs up to 5,000 ppm at 188 feet bgs. These trends suggest a volume of residual NAPL resides deeper in the vadose zone along this borehole and upward vapor diffusion is limited by the low permeability soils encountered above 140 feet bgs.

Moderately permeable soils were also encountered along the top of the middle well at borehole 149 from 199 to 240 feet bgs continuing the trend from the bottom of the shallow well. The soil TVPH vapor concentration at the top of the middle well also correlated well with the bottom of the shallow well as the TVPH vapor concentration in soils adjacent to the borehole from 200 to about 240 feet bgs was also about 5,000 ppm. A low permeability soil interval was encountered from 240 to 284 feet bgs and the soils yielded high TVPH vapor concentrations of 14,000 and 8,000 ppm. This interval appears to correlate with the low permeability interval identified in borehole 148 from 267 to 283 feet bgs that yielded a soil TVPH vapor concentration of nearly 20,000 ppm. Laterally spreading of fuel NAPL is likely along this interval in the vicinity of these boreholes. In borehole 149, the soil permeability is moderate from 284 to 320 feet bgs, except for one low permeability stratum at 290 feet bgs. The soil TVPH vapor concentration dropped to about 4,500 ppm below 284 feet bgs and slightly increased along this interval with increasing depth. The soils below 320 feet bgs and down to the bottom of the screen at 345 feet bgs did not produce appreciable vapor flow and had a low permeability. However, the TVPH vapor concentration increased with increasing depth along this interval and was about 8,000 ppm at 345 feet bgs suggesting a source of contaminant vapors resided in the deeper vadose zone along the borehole.

Figure 6. Composite PneuLog Profiles from Boring KAFB-106-149

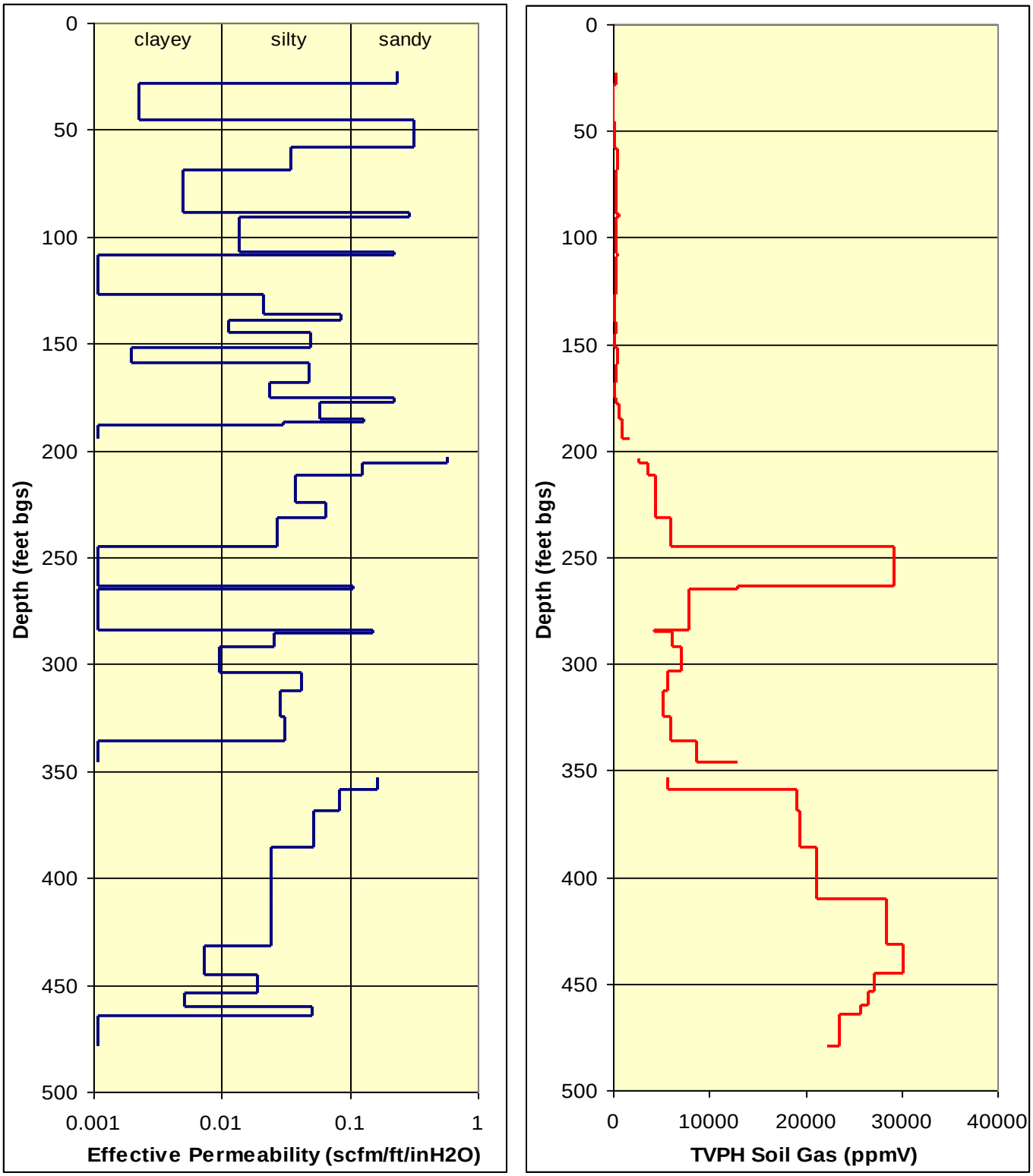


The top of the deep well in borehole 149 revealed thin permeable intervals with low TVPH vapor concentrations; however, the increasing vapor concentration trend observed in the bottom of the middle well continued. Below 360 feet bgs and down to 437 feet bgs, moderately permeable soils trended to lower values as the depth increased. The TVPH concentration in this interval jumped to about 17,000 ppm at 360 feet bgs and trended higher with increasing depth to about 25,000 ppm at 437 feet bgs. Low permeability soils were encountered from 437 feet bgs down to the bottom of the screen at 480 feet bgs except a moderately permeable stratum from 460 to 469 feet bgs. The soil TVPH concentration was relatively constant over this interval at about 22,000 ppm but then jumped to over 30,000 ppm at the bottom of the screen (480 feet bgs). This spike in TVPH concentration suggests NAPL resides atop the water table below borehole 149.

The summary profiles for borehole KAFB-106-150 are provided in Figure 7. In the shallow vadose zone around 150, the soils exhibited a series of six thin, permeable intervals dispersed in relatively low permeability soils from about 25 to 160 feet bgs; although, the interval from 45 to 58 feet bgs was somewhat thick. Very little contamination was found in the shallow vadose zone around borehole 150 and the detected vapors were likely the result of diffusive transport from distant NAPL sources. Below 160 feet bgs and down to the bottom of the shallow well at 195 feet bgs, the moderately permeable soils were encountered; however, the soil TVPH vapor concentration increased from less than 500 ppm to about 1,800 ppm at the well bottom. This trend points to a NAPL source below the shallow well and indicates upward vapor diffusion is limited by the low permeability soils above 160 feet bgs.

At the top of the middle well in borehole 150, a thin permeable interval was encountered with a relatively low soil TVPH vapor concentration (~2,600 ppm) that correlated well with the bottom of the shallow well. Below this interval, the soils from 212 to 245 feet bgs were moderately permeable and the TVPH increased with depth from about 3,700 ppm to almost 6,000 ppm. Low permeability soils were encountered from 245 down to 284 feet bgs (except for one very thin permeable stratum). This low permeability interval produced little flow; however, the TVPH concentration was estimated to be around 30,000 ppm suggesting a residual NAPL may reside near the top of this low permeability interval and could require a long duration of SVE to remediate. This interval also correlates well with similar low permeability intervals with significant contamination identified in boreholes 148 and 149. Lateral spreading of fuel NAPL along the top of this low permeability interval throughout the vicinity of these boreholes is likely. The permeability of the soils from 284 to 336 feet bgs is moderate and the soil TVPH vapor concentration was somewhat constant around 7,000 ppm; also supporting the conclusion that the overlying interval harbors NAPL. However, at the bottom of the well, the TVPH vapor concentration sharply increased to about 13,000 ppm pointing to a deeper source of contamination along this borehole.

Figure 7. Composite PneuLog Profiles from Boring KAFB-106-150



The top of the deep well in borehole 150 revealed permeable intervals and trended with a decreasing permeability with increasing depth down to 386 feet bgs. A low TVPH vapor concentration was calculated for soil adjacent to the top of the screen; however, the increasing vapor concentration trend observed in the bottom of the middle well continued. Below 359 feet bgs and down to 410 feet bgs, the TVPH concentration jumped to over 20,000 ppm. At 410 feet bgs the TVPH concentration increased sharply to almost 30,000 ppm. The concentration remained relatively steady down to 445 feet bgs as the permeability tended to decrease. Moderately permeable intervals were encountered below 445 feet bgs and the TVPH concentration decreased. Low permeability soils were encountered from 464 feet bgs down to the bottom of the screen at 480 feet bgs and the soil TVPH concentration decreased to about 22,000 ppm at the bottom of the screen. This decrease in TVPH concentration suggests NAPL may not reside atop the water table below borehole 150 but may reside in the moderately permeable interval from 410 to 445 feet bgs.

3. DATA INTERPRETATION FOR SVE DESIGN AND OPERATION

Site Background

The following site summary is an edited excerpt from, "Quarterly Pre-Remedy Monitoring and Site Investigation Report for October – December 2011, Bulk Fuels Facility Spill, Solid Waste Management Units ST-106 and SS-111" authored by Shaw Environmental & Infrastructure, Inc. and dated April 2012.

The site utilizes four SVE and treatment systems each consisting of trailer-mounted units that include specialized on-board computer controllers, sensors, and a pair of 460-cubic-inch displacement Ford Model LSG-875 internal combustion engines (ICEs). Within each SVE system, the programmable logic controller (PLC) uses the engines as the vacuum pump to extract vapor from the vadose zone, and the internal combustion process along with the catalytic converters on each engine provide treatment of the hydrocarbon vapors. Operation of each unit is controlled by the PLC through adjustments to the influent soil vapor, ambient air, and a supplemental fuel source valve. The PLC adjusts the feed from the vapor well, ambient air, and supplemental fuel source valve to maintain the proper air/fuel ratio to support combustion in the engine. Propane is used as the fuel source during engine starting and warm-up, after which the system consumes recovered petroleum hydrocarbon vapors as the primary fuel source, using propane as needed to help stabilize engine performance. One drawback to the use of the ICE systems is the variability in extraction rate resulting from the continuous maintenance of the proper air/fuel ratio. The ST-106 SVE unit (RSI Unit 249) was installed in April 2003 (fully operational in July 2003), the Kirtland AFB 1065 unit (RSI Unit 335) was installed in August 2008, and the KAFB-1066 (RSI Unit 345) and KAFB-1068 (RSI Unit 344) units were installed in March 2009. The ST-106 unit (RSI Unit 249) is connected through manifold piping to nine SVE wells, SVEW-01 through SVEW-09 (locations shown on Figure 1).

The 2007 through 2011 soil vapor time-series concentration graphs show fluctuations in concentrations of selected vapor compounds; however, the one conclusion that can be reached from these time-series data is that, overall, the ongoing SVE efforts have not had a discernable

effect on vadose zone vapor concentrations. Even in extraction wells SVEW-01-260 and SVEW-05-460, which have been operating the longest, there have been only marginal changes in concentrations since 2007. Benzene in SVEW-01-260 declined from 350 to 120 ppm over four years of SVE remediation, and benzene concentrations in SVEW-05-460 declined from 394 to 120 ppm. Substantial contaminant mass has been removed from the vadose zone (approximately 400,000 gallons of NAPL-equivalent mass vapor); yet, the overall effect of the current SVE efforts is difficult to determine from the vapor concentration data as significant decays in concentration have not been observed. From this observation, it is concluded that current SVE efforts are undersized in relation to the size of the contaminant source.

Also apparent in the vapor data trend is that the TPH results from 2007 through 2010 are not consistent with the other vapor concentrations or the 2011 TPH aliphatic C5-C8 concentrations. It would be expected that TPH concentrations would be greater than or equal to the concentrations of the individual compounds. However, it is apparent that the TPH concentrations are less than a number of the individual compounds, particularly benzene and toluene. There is no verified explanation for this discrepancy. However, a likely explanation is the use of a flame ionization detector (FID) in the gas chromatographic analysis to quantify the concentrations. The response factor for aromatic compounds such as benzene and toluene is very high whereas the response factor for aliphatic compounds is low. The aliphatic compounds makeup roughly 80% of jet fuel. The quantification of TPH from an FID detector is based on the total response of all compounds and therefore a relatively low content of volatile aromatic compounds (compared to the jet fuel standard used to calibrate the detector) will yield a lower TPH concentration than the actual concentration. This result is common for analyses of weathered jet fuel vapors where the calibration is performed with a fresh jet fuel sample or an unrepresentative surrogate mix. As discussed later, the jet fuel at this site appears is weathered as a result of time and active soil vapor extraction.

The historical depth to water has also greatly impacted the disposition of NAPL in the subsurface. Based on historical analysis of water level data, in the 1940s through most of the 1970s, the groundwater table was at a depth of approximately 100 ft higher than the current 2011 water table. Beginning in 2009, the water table started rising in response to water conservation practices and municipal use of surface water resources. Water table changes have had a profound impact on the distribution of and future prognosis for vadose zone contamination. The results of the historical fall and recent rise in the water table elevation are summarized below:

- As surface or near-surface releases of NAPL occurred at the facility, the NAPL essentially migrated vertically downward with some minor horizontal movement related to the heterogeneities in the lithologic intervals. Once the NAPL encountered the historical capillary fringe above the water table at a nominal depth of 400 ft bgs, the NAPL spread out horizontally away from the release areas. The NAPL then accumulated on the water table and started migrating in a northeasterly direction following the downgradient groundwater flow direction.
- As the water table declined as a result of regional groundwater extraction, the NAPL from the initial and subsequent releases followed the falling water table downward. Over time, this had the effect of creating a residual NAPL smear zone from nominal depths of 400 to 500 ft bgs. • As the water table started rising in 2009, the NAPL that would flow

into wells (i.e., NAPL not already at residual saturation) became trapped below the water table.

- Because vapor can migrate in the vadose zone, the vapor concentrations define the overall volume of the vadose zone affected by residual NAPL contamination. To a lesser extent, the vapor concentrations define the areas of highest vadose zone contamination.
- Based on the 3D distribution of soil and vapor concentrations, the majority of the vadose zone contaminant mass is located a within 100 ft bgs above the present-day water table at depths of 400 to 500 ft bgs.
- The following compounds are compounds of concern (COCs) for the site: 1,2,4-TMB; 1,3,5-TMB; 2-butanone; acetone; benzene; C5-C8 aliphatic hydrocarbons; C9-C10 aromatic hydrocarbons; C9-C12 aliphatic hydrocarbons; cyclohexane; ethylbenzene; heptane; isopropanol; m,p,o-xylenes; methylene chloride; n-hexane; propene; propylene; and toluene.
- Volumetric analysis indicates the current extent of soil contamination, as defined by soil concentrations of total petroleum hydrocarbons (TPH) greater than 10 milligrams per kilogram (mg/kg), is approximately 29 million cubic yards with 12.4 million cubic yards (43%) at or below approximately 350 ft bgs.

Pages 19 through 33 of this report contained information that was unrelated to the Kirtland AFB Bulk Fuels project. These pages were removed from the report.

4.0 DATA INTERPRETATION FOR BIOLOGICAL DEGRADATION

Microbiological degradation rates can be estimated from measures of the vapor extraction rate and the oxygen and carbon dioxide contents of the extracted vapors. During aerobic degradation of the hydrocarbons, oxygen is utilized and carbon dioxide is produced. These can be stoichiometrically related the hydrocarbon destruction. The total oxygen utilization rate is calculated from field measures of total vapor extraction rate and the oxygen content in those vapors at the top of the extraction well. Similarly, the carbon dioxide production is calculated from field measures of total vapor extraction rate and the carbon dioxide content in those vapors at the top of the extraction well. For the PneuLog testing, these parameters were measured to allow the calculations; however, the sustainability of the oxygen utilization and carbon dioxide production over time requires a much longer period of extraction to assess. Data are likely available from previous operations at the site to make this determination with the equations provided in this section.

To estimate hydrocarbon biodegradation rates from the oxygen utilization rates, a stoichiometric relationship for the oxidation of the contaminant is used. For hydrocarbons, hexane is most often used as the representative hydrocarbon. The stoichiometric relationship used to determine petroleum degradation rates, based on hexane, is (Hinchee et al., 1992; Leeson & Hinchee, 1996):

$$C_6H_{14} + 9.5\ O_2 \rightarrow 6\ CO_2 + 7\ H_2O$$

Hence, one mole of hexane is degraded for each 9.5 moles of oxygen utilized. The oxygen utilization is determined by assuming air enters the vadose zone with an oxygen content of 20.95% by volume and subtracting the measured oxygen content at the vapor extraction manifold. Mathematically, this rate relationship is:

Oxygen Utilization Rate = Vapor Flow Rate * Vapor Density * (Atmospheric Air Oxygen Content – Vapor Extraction Oxygen Content)

$$m_{O2}\ [\text{lb O2 / min}] = Q\ [\text{ft}^3 / \text{min}] * \rho\ [\text{lb air / ft}^3] * \Delta O_2\%/100 * 32/28.97\ [\text{lb } O_2 / \text{lb air}]$$

The hydrocarbon degradation rate is, based on the stoichiometry for hexane:

$$m_{HC}\ [\text{lb HC / min}] = m_{O2}\ [\text{lb } O_2 / \text{min}] * (1 * 86.19) / (9.5 * 32)\ [\text{lb HC / lb } O_2]$$

$$m_{HC}\ [\text{lb HC / day}] = Q\ [\text{ft}^3 / \text{min}] * \rho\ [\text{lb air / ft}^3] * \Delta O_2\% * 4.5$$

Under standard conditions, at sea level, the density of air is 0.075 lb/ft3. For example, extraction of a vapor with an oxygen content of 17% at a rate of 60 scfm yields a hydrocarbon degradation rate of roughly 81 pounds per day. This result can be cross-checked if a simultaneous reading of the carbon dioxide content is available with the following similar relationship for carbon dioxide production:

$$m_{O2}\ [\text{lb } CO_2/\text{min}] = Q\ [\text{ft}^3/\text{min}] * \rho\ [\text{lb air / ft}^3] * \Delta CO_2\%/100 * 44/28.97\ [\text{lb } CO_2 / \text{lb air}]$$

m_{HC} [lb HC / min] = m_{CO2} [lb CO_2 / min] * (1 * 86.19) / (6 * 44) [lb HC / lb CO_2]
m_{HC} [lb HC / day] = Q [ft^3 / min] * ρ [lb air / ft^3] * ΔCO_2% * 7.14

These equations may overpredict the hydrocarbon degradation as soil organisms utilize oxygen and produce carbon dioxide in other respiration processes; however, they provide a good order-of-magnitude estimate. Using the values measured above the top of screen in each well for oxygen, carbon dioxide and TVPH, the degradation and mass extraction rates of total hydrocarbons were calculated for each well and the results are presented in Table 2. Again, these rates are measured after short periods of extraction and the sustainability of the rates has not been assessed.

Table 2. Summary of Hydrocarbon Extraction and Degradation Rates during Testing

Well KAFB-106-	Screen Interval	Extraction Rate	TVPH Conc	Oxygen Conc	Carbon Dioxide Conc	TPH Degradation Rate, O_2 basis	TPH Degradation Rate, CO_2 basis	TPH Extraction Rate, as hexane
	(feet bgs)	(scfm)	(ppm)	(%)	(%)	(lb/day)	(lb/day)	(lb/day)
148-S	24-194	81	9,200	1.5	>20	532	>867	238
148-M	199-349	87	9,700	3.6	18.2	510	846	270
148-D	354-484	139	4,300	10.8	5.8	477	429	193
149-S	24-194	126	940	14.5	3.6	275	241	38
149-M	199-349	142	3,500	14.4	4.2	314	317	160
149-D	354-484	131	14,400	17.4	1.4	157	96	604
150-S	25-200	112	213	15.8	3.8	195	226	8
150-M	206-350	137	4,200	14.5	3.9	299	284	182
150-D	355-484	95	16,900	13.5	3.5	239	176	516

The correlation between the calculated biological degradation rates based oxygen utilization and based on carbon dioxide production is very good. The carbon dioxide rate is only slightly higher overall. The highest calculated degradation rate was observed in well KAFB-106-148 shallow although this well did not have the highest hydrocarbon vapor concentrations. High degradation rates were also observed in the other two shallow wells (~25 to 200 feet bgs); however, the hydrocarbon extraction rates were proportionally very low compared to the degradation rates. The shallow wells of 149 and 150 yielded the lowest hydrocarbon extraction rates. Hence, these two locations provide good choices for active or passive bioventing to enhance remediation during SVE.

The three wells screened in the middle vadose zone (~200 to 350 feet bgs) all yielded commensurate hydrocarbon mass extraction rates however, the calculated mass degradation rates were all roughly double the extraction rates indicating biological degradation can provide a significant proportion of the vadose zone cleanup if these rates are sustainable. The degradation rate in the middle well of 148 was proportionally higher than the other two middle screens as the fuel in the vicinity of 148 is more weathered and contains a lower fraction of volatile hydrocarbons, as reported earlier. The degradation rate is less dependent on the volatility of the fuel than the extraction rate. The degradation should correlate more closely with solubility than volatility. The more weathered fuel around 148 may be the result of more significant vapor extraction in this area of the site although this phenomenon has not been investigated for this

report. In addition, the soils along this boring appear to be more permeable than the other locations.

Wells KAFB-106-149 deep and –150 deep produced the lowest biological degradation rates but yielded the highest hydrocarbon extraction rates with high TVPH concentrations (14,400 and 16,900 ppm, respectively). The soils along these screens have relatively low permeabilities as most intervals fall into the category of silts. However, the oxygen and water content are plentiful in the deep vadose zone therefore it is suspected that a secondary parameter, such as a nutrient or catalyst, is limiting the microbiological degradation rate. A review of geochemistry data from this deep interval, if any exists, may reveal a methodology for enhancing the degradation rate.

The measured methane concentrations in all the wells were very low indicating anaerobic degradation of hydrocarbons is currently insignificant compared to the high aerobic degradation rates reported in Table 2. The PneuLog profiles for the site suggested a small fraction of the subsurface fuel was residing in very low permeability soils. These soils are possibly under anerobic conditions. Hence, anaerobic degradation may be significant for the cleanup of this sequestered fuel over the longer term remediation of the site but is currently overwhelmed by the aerobic degradation of fuel in more permeable soils.

REFERENCES

EPA 2001, EPA. (2001). Development of recommendations and methods to support assessment of soil venting performance and closure. EPA/600/R-01/070. National Risk Management Research Laboratory, Office of Research and Development, U. S. EPA, Cincinnati, OH.

Hinchee, R.E., S.K. Ong, R.N. Miller, D.C. Downey, and R. Frandt. 1992. *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing,* Rev. 2. U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

Leeson, A. and R.E. Hinchee. 1996. *Principles and Practices of Bioventing, VolumeII: Bioventing Design*. U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

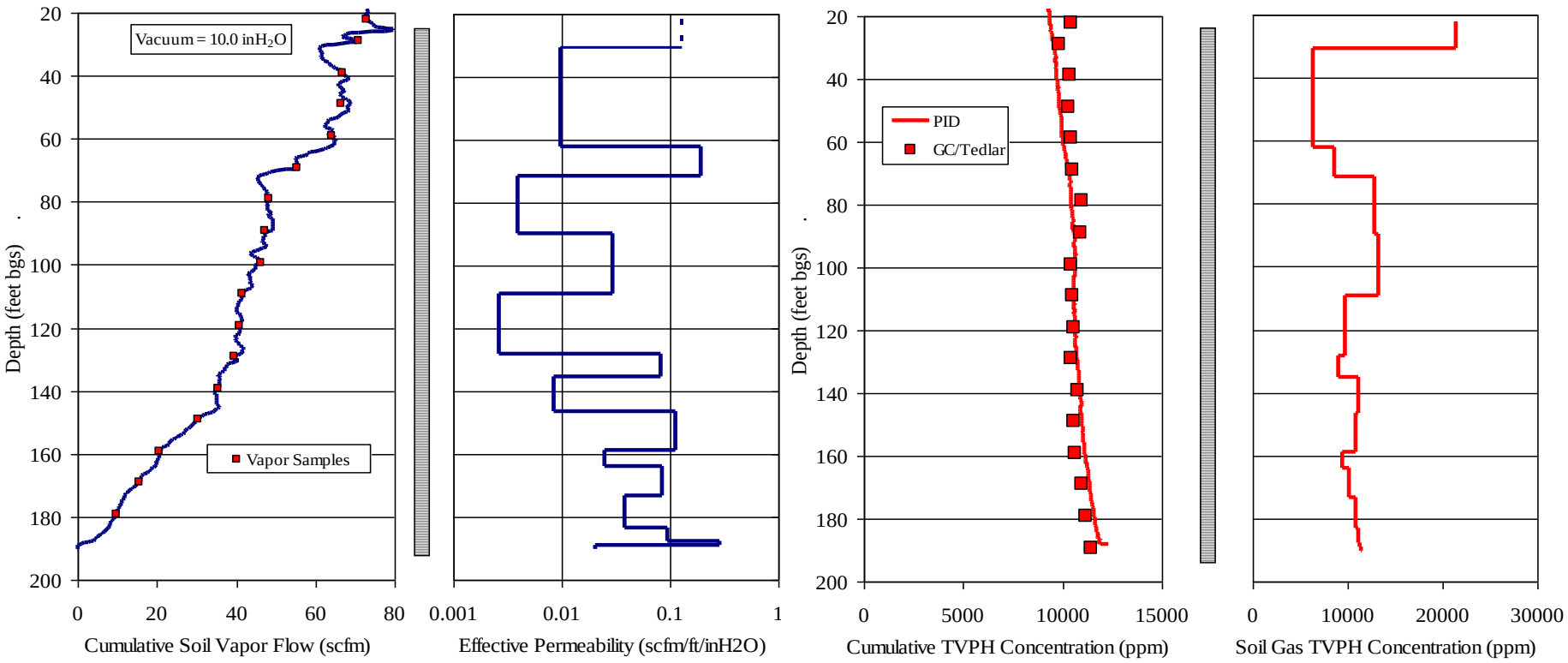
APPENDIX A

PneuLog Profile Data and Vapor Sampling Results

WELL	KAFB-106-148-S
SCREEN	24 – 194 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	18-APR-12

	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	10	80.7
FINAL	10	81.3

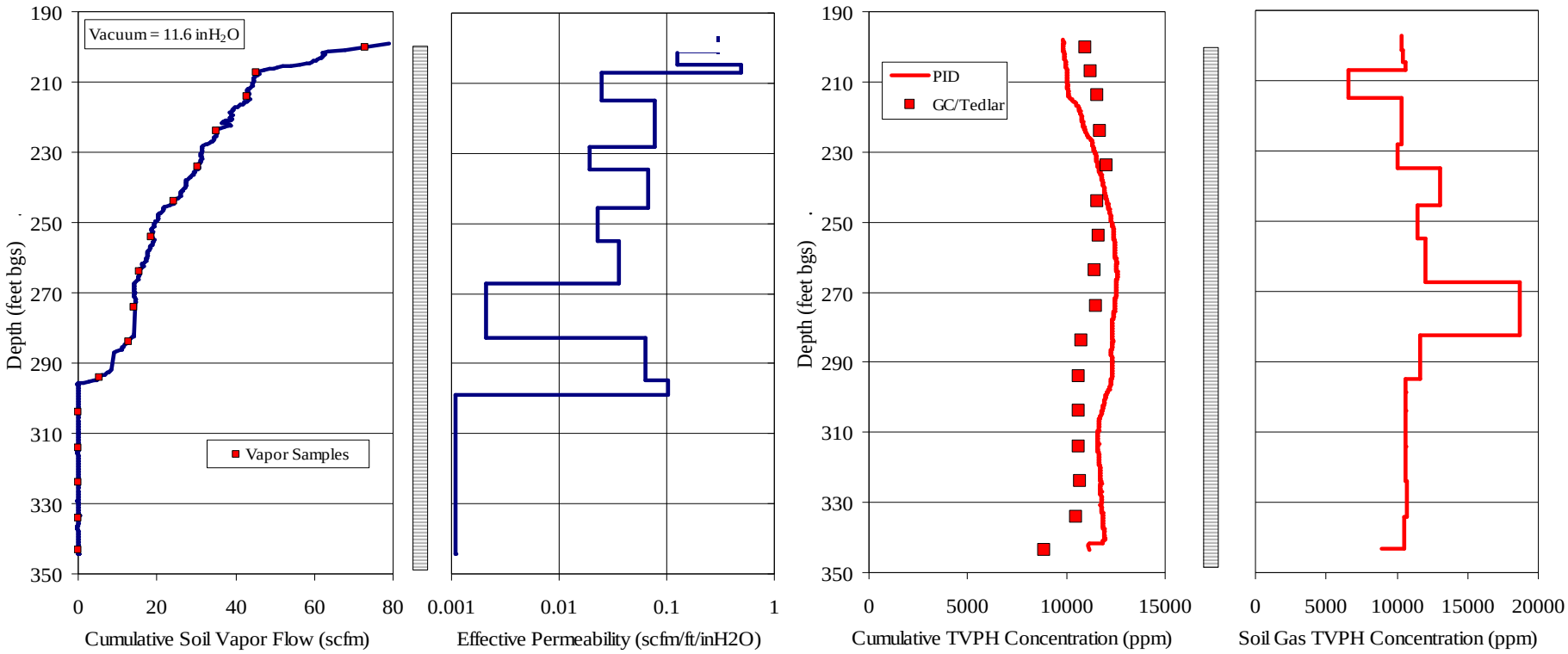
PROFILES:



WELL	KAFB-106-148-M
SCREEN	199 – 349 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	18-APR-12

	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	11.6	78.9
FINAL	16.4	87.4

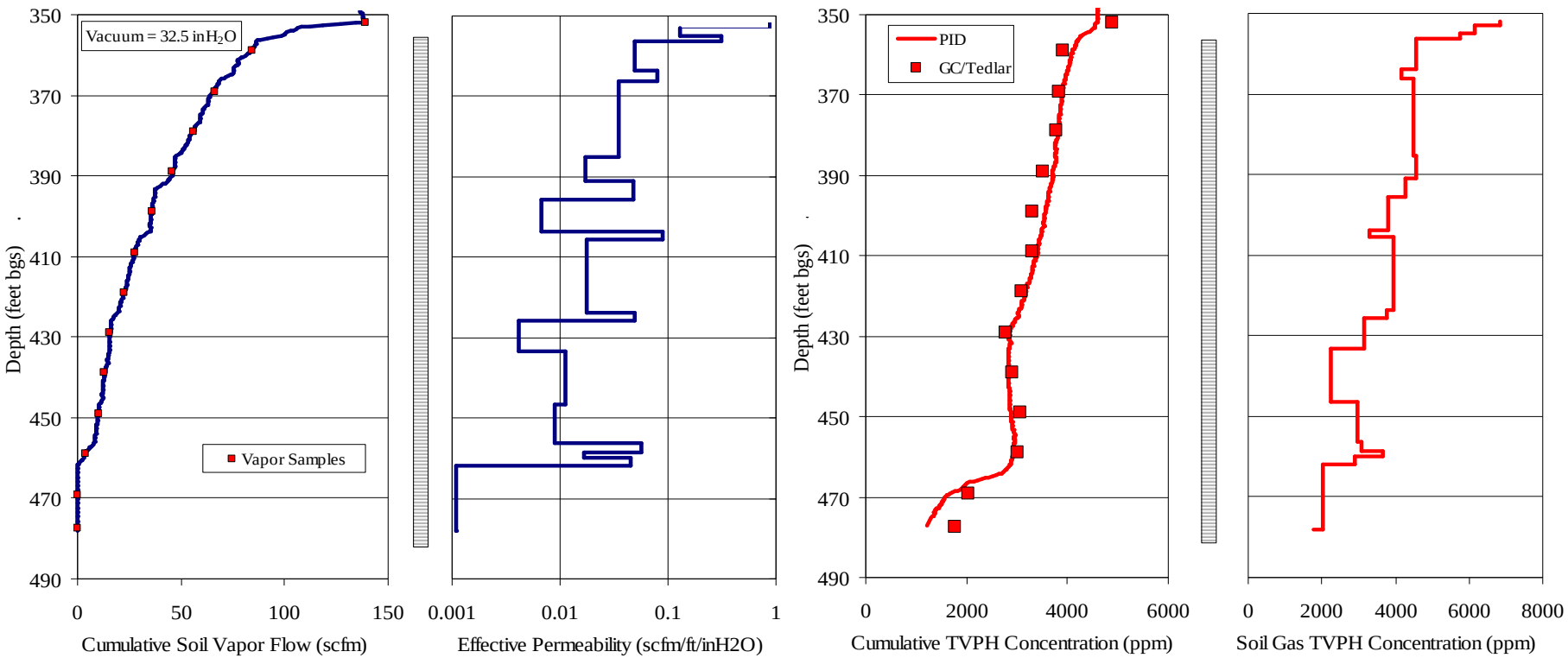
PROFILES:



WELL	KAFB-106-148-D
SCREEN	354 – 484 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	19-APR-12

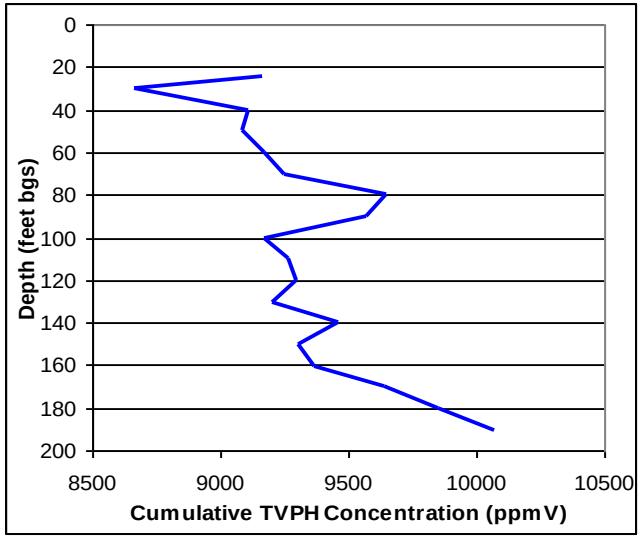
	APPLIED VACUUM (INH_2O)	EXTRACTION RATE (SCFM)
INITIAL	24.3	104.1
FINAL	32.5	139.1

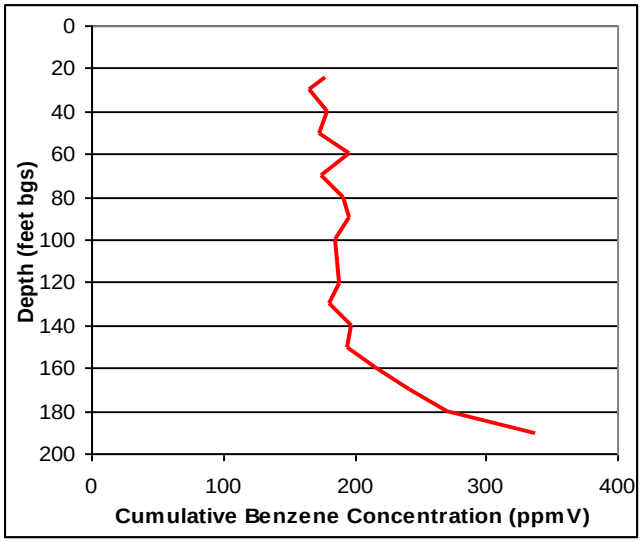
PROFILES:

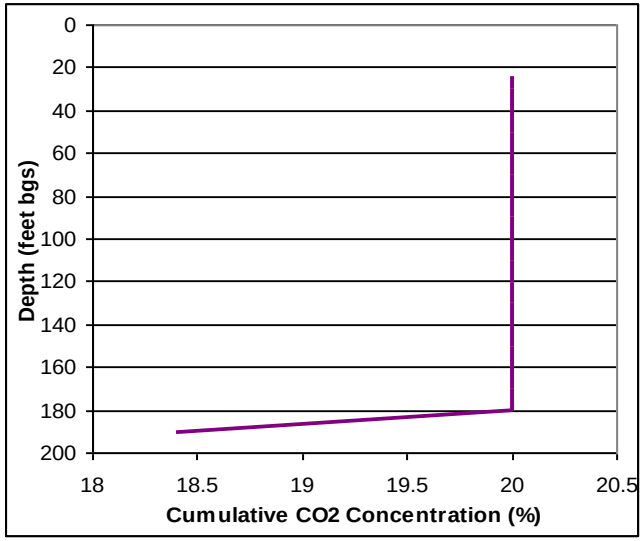


Vapor Analytical Results for 106-148-S

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/18/2012	10:34	153	148-S	190.3	13	474	338	364	23	43	15	11	10067	>100	18.4	3.6
4/18/2012	10:38	154	148-S	180.2	14	442	271	290	19	32	9	10	9852	39	>20	1.6
4/18/2012	10:40	155	148-S	170.1	14	422	242	264	18	31	11	10	9644	39	>20	1.5
4/18/2012	10:43	156	148-S	160.2	14	403	217	238	17	30	9	10	9371	35	>20	1.3
4/18/2012	10:46	157	148-S	150.1	14	393	195	220	17	30	10	10	9305	31	>20	1.0
4/18/2012	10:49	158	148-S	140.2	14	396	198	220	17	30	11	10	9462	29	>20	0.8
4/18/2012	10:52	159	148-S	130.1	14	384	182	210	17	29	10	10	9203	30	>20	0.9
4/18/2012	10:56	160	148-S	120.2	14	383	189	212	17	30	11	10	9294	30	>20	0.9
4/18/2012	10:59	161	148-S	110.1	15	382	187	213	17	30	10	10	9262	35	>20	1.3
4/18/2012	11:02	162	148-S	100.2	15	380	185	209	17	30	10	10	9169	34	>20	1.2
4/18/2012	11:06	163	148-S	90.1	15	405	197	218	18	31	11	10	9569	30	>20	0.9
4/18/2012	11:09	164	148-S	79.9	15	409	192	218	18	31	11	10	9646	34	>20	1.2
4/18/2012	11:12	165	148-S	70.1	14	394	175	209	17	30	10	10	9253	33	>20	1.1
4/18/2012	11:16	166	148-S	59.9	15	384	197	200	17	30	10	10	9172	32	>20	1.0
4/18/2012	11:19	167	148-S	50.1	15	380	174	198	17	29	10	10	9088	37	>20	1.3
4/18/2012	11:23	168	148-S	39.9	15	379	179	199	17	29	10	10	9110	35	>20	1.3
4/18/2012	11:27	169	148-S	30.1	14	363	165	188	16	27	9.5	9.1	8664	42	>20	1.7
4/18/2012	11:32	170	148-S	13.1	15	381	179	201	17	29	10	10	9163	39	>20	1.5
4/18/2012	8:35	152	148-S	Blank	0.9	0.3	0.9	2	0.2	0.5	0.1	0.3	25	na	na	na

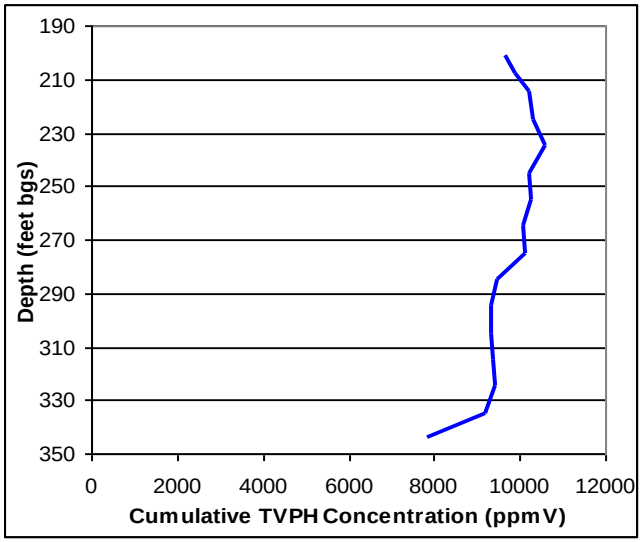


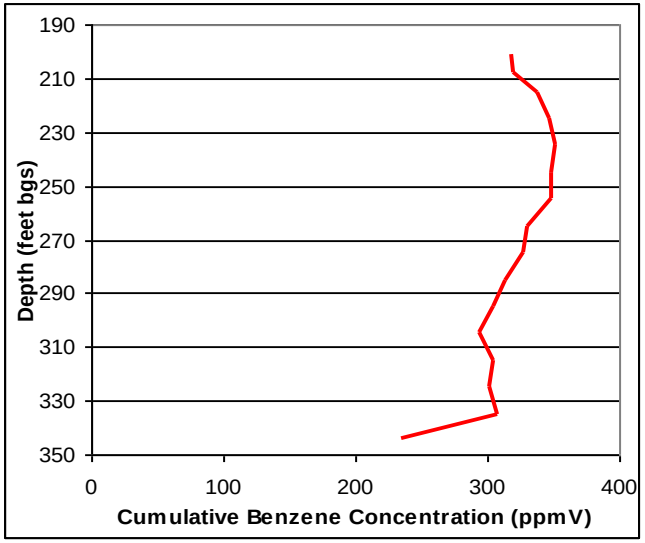


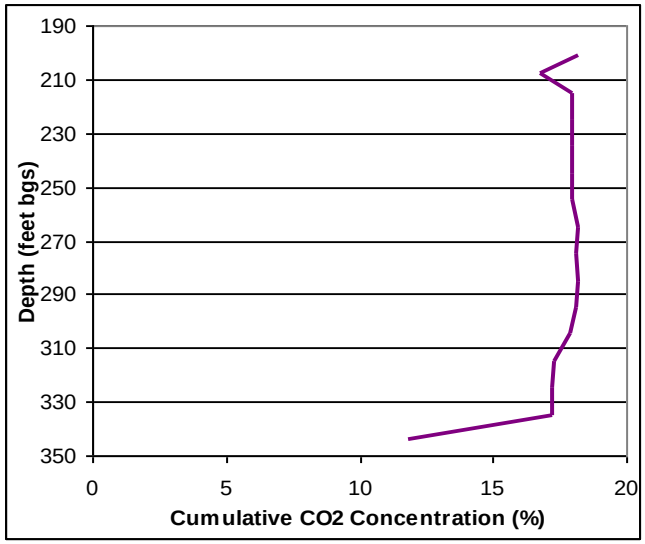


Vapor Analytical Results for 106-148-M

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/18/2012	14:31	171	148-M	344.4	9.7	346	234	292	20	39	13	11	7836	>100	11.8	6.9
4/18/2012	14:34	172	148-M	335.0	13	443	308	341	22	41	14	10	9221	81	17.2	3.5
4/18/2012	14:38	173	148-M	324.9	13	450	302	347	23	43	14	13	9441	100	17.2	3.8
4/18/2012	14:41	174	148-M	315.0	13	451	305	341	22	41	14	8.8	9365	>100	17.3	3.9
4/18/2012	14:45	175	148-M	304.9	13	450	294	342	22	41	14	9.3	9355	88	17.9	3.5
4/18/2012	14:48	176	148-M	295.0	13	450	304	342	22	41	14	7.9	9354	94	18.1	3.6
4/18/2012	14:51	177	148-M	284.9	13	463	314	351	22	39	13	7.7	9499	91	18.2	3.6
4/18/2012	14:54	178	148-M	275.0	13	487	328	383	25	46	16	10	10135	72	18.1	3.1
4/18/2012	14:57	179	148-M	264.9	13	492	331	379	25	45	15	9.2	10085	80	18.2	3.3
4/18/2012	15:00	180	148-M	255.0	13	509	349	388	25	45	15	8.8	10256	82	18.0	3.4
4/18/2012	15:04	190	148-M	245.15	13	513	349	383	24	44	15	9.1	10219	90	18.0	3.6
4/18/2012	15:08	182	148-M	235.0	14	525	352	410	27	50	17	11	10604	>100	18.0	4.0
4/18/2012	15:12	183	148-M	224.9	13	508	348	400	27	50	17	11	10309	>100	18.0	3.8
4/18/2012	15:15	184	148-M	215.0	14	504	337	391	26	47	16	10	10206	>100	18.0	3.7
4/18/2012	15:18	185	148-M	208.2	13	486	320	379	25	47	16	10	9920	>100	16.8	4.8
4/18/2012	15:23	186	148-M	201.1	14	469	318	369	25	46	16	10	9661	>100	18.2	3.6
4/18/2012	15:43	181	Equip	Blank	0.9	0.5	1.0	2.6	0.4	0.8	0.3	0.8	53	na	na	na

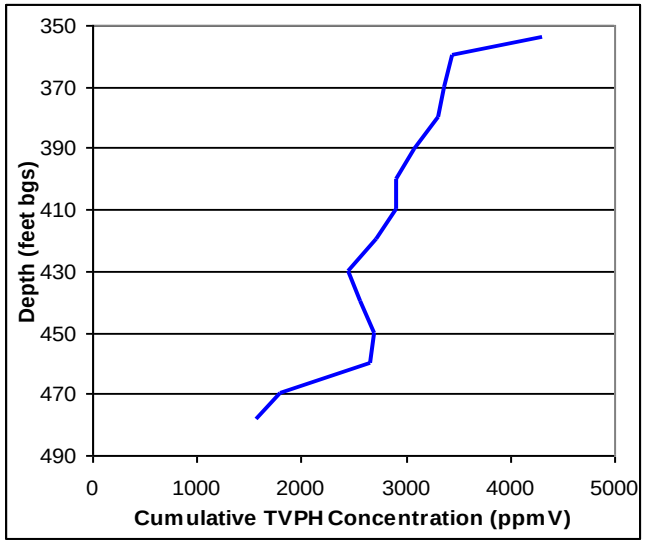


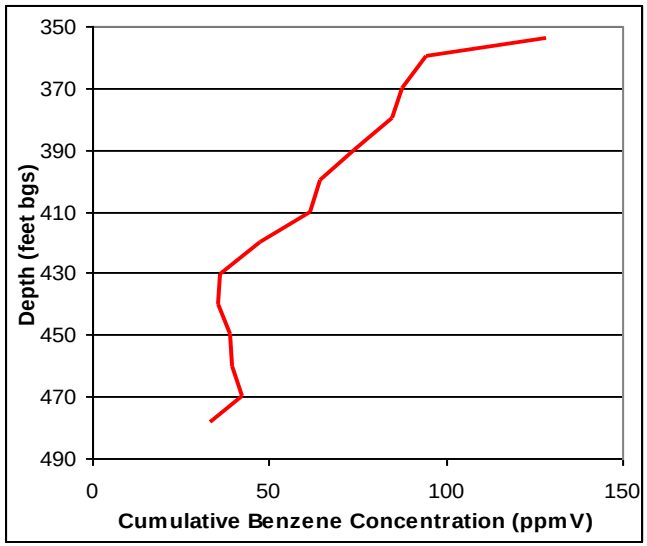


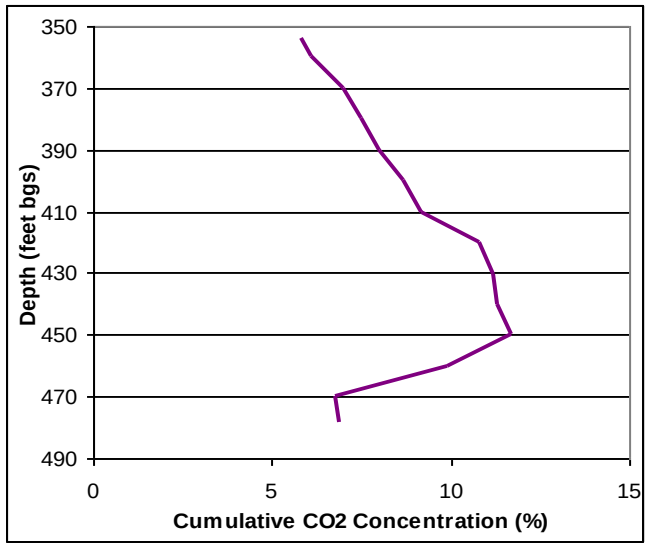


Vapor Analytical Results for 106-148-D

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/19/2012	10:36	191	148-D	478.4	3.6	47	34	48	2.9	7.3	2.4	2.0	1564	20	6.9	7.9
4/19/2012	10:41	192	148-D	470.1	3.6	63	42	59	3.4	8.5	2.8	2.4	1798	24	6.8	8.0
4/19/2012	10:46	193	148-D	459.9	4.6	52	39	65	3.7	10	3.1	3.2	2661	37	9.9	5.5
4/19/2012	10:51	194	148-D	450.1	4.6	48	39	64	3.6	10	2.8	3.1	2694	41	11.7	4.3
4/19/2012	10:56	195	148-D	439.9	4.6	44	36	59	3.4	9.5	2.9	3.1	2560	39	11.3	4.8
4/19/2012	11:01	196	148-D	430.1	4.6	45	36	58	3.3	9.0	4.3	2.8	2448	39	11.2	4.9
4/19/2012	11:07	197	148-D	419.9	4.5	57	48	71	4.0	11	8.6	3.3	2725	42	10.8	5.5
4/19/2012	11:12	198	148-D	410.1	4.4	69	61	85	4.5	12	4.4	3.5	2906	43	9.2	7.1
4/19/2012	11:18	199	148-D	399.9	4.3	76	65	91	4.5	11	4.9	2.9	2908	46	8.7	7.4
4/19/2012	11:22	200	148-D	390.1	4.3	85	74	104	5.0	13	5.8	3.0	3093	48	8.0	8.4
4/19/2012	11:27	201	148-D	379.9	4.7	94	85	120	5.7	14	5.1	3.2	3321	51	7.5	8.9
4/19/2012	11:32	202	148-D	370.1	4.6	98	88	126	5.8	15	4.8	3.2	3373	51	7.0	9.4
4/19/2012	11:36	203	148-D	359.9	4.6	107	94	136	6.1	15	6.2	3.0	3441	51	6.1	10.6
4/19/2012	11:42	204	148-D	354.0	4.9	154	129	188	9.2	22	12	4.1	4314	66	5.8	10.8
4/19/2012	13:00	205	Equip	Blank	0.9	0.2	0.3	0.9	0.1	0.3	0.1	0.2	18	na	na	na



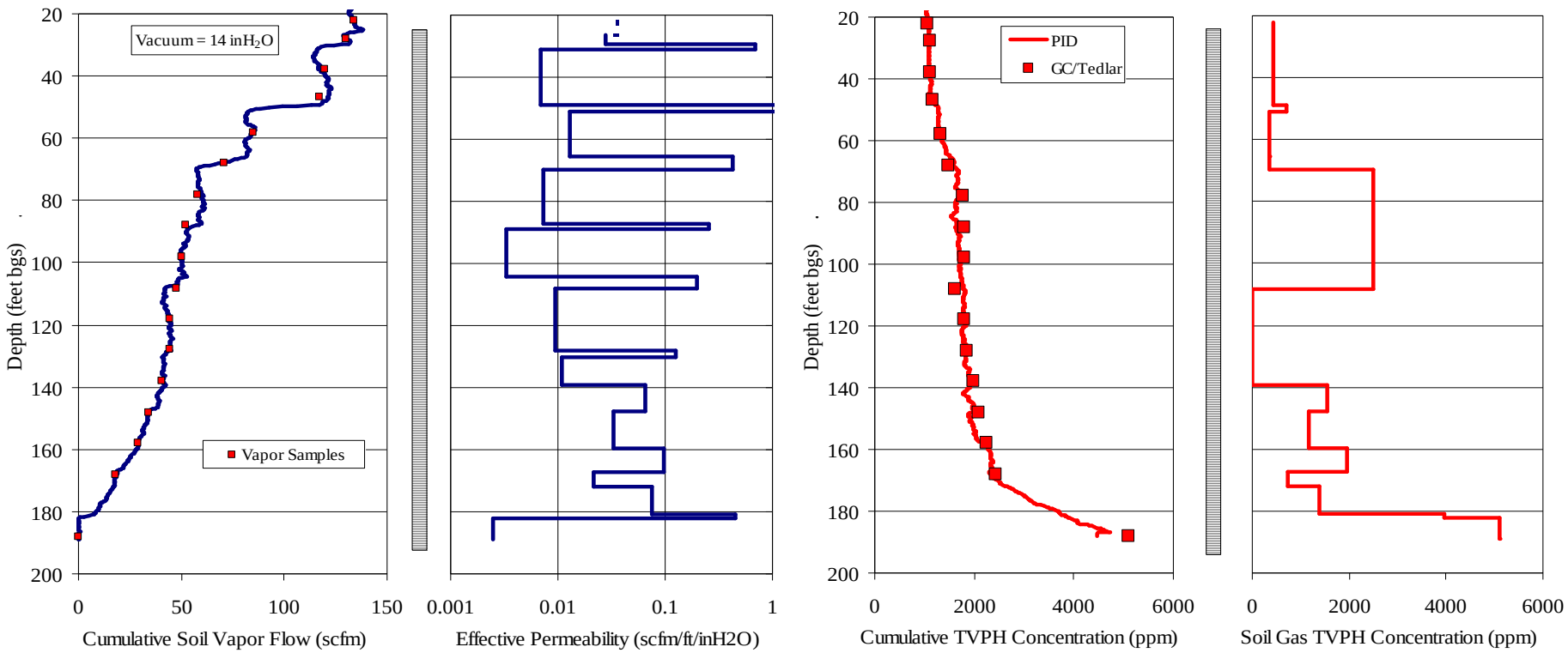




WELL	KAFB-106-149-S
SCREEN	24 – 194 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	16-APR-12

	APPLIED VACUUM (INH_2O)	EXTRACTION RATE (SCFM)
INITIAL	-	117
FINAL	14	126

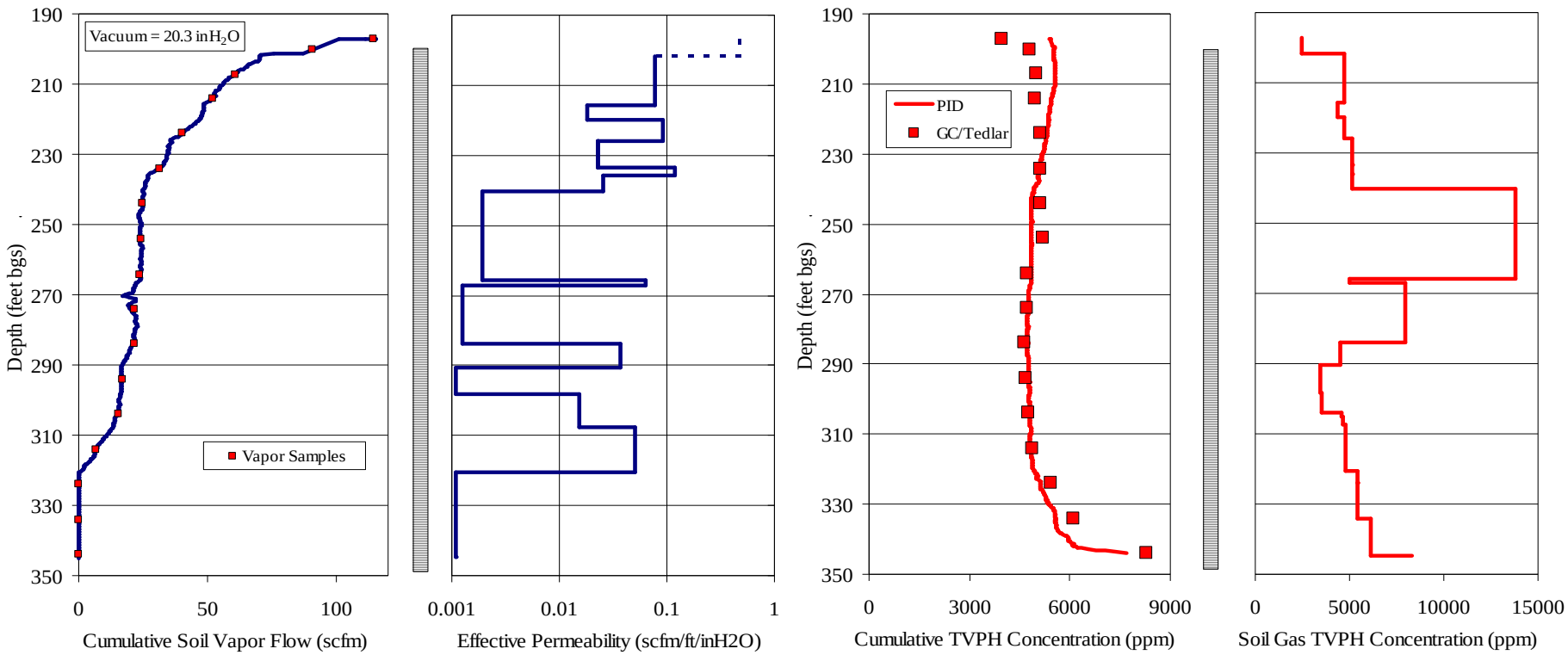
PROFILES:



WELL	KAFB-106-149-M
SCREEN	199 – 349 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	17-APR-12

	APPLIED VACUUM (INH_2O)	EXTRACTION RATE (SCFM)
INITIAL	20.3	104.7
FINAL	28.5	142.2

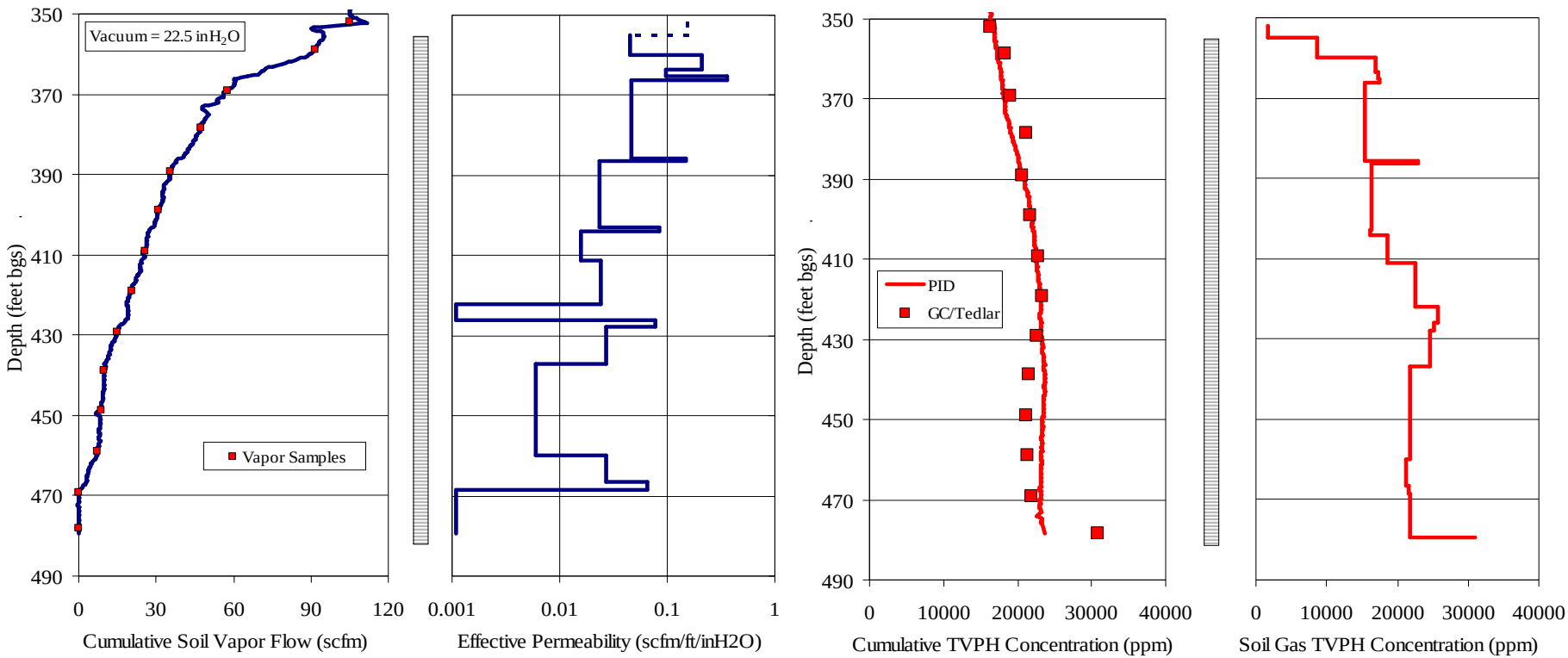
PROFILES:



WELL	KAFB-106-149-D
SCREEN	354 – 484 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	17-APR-12

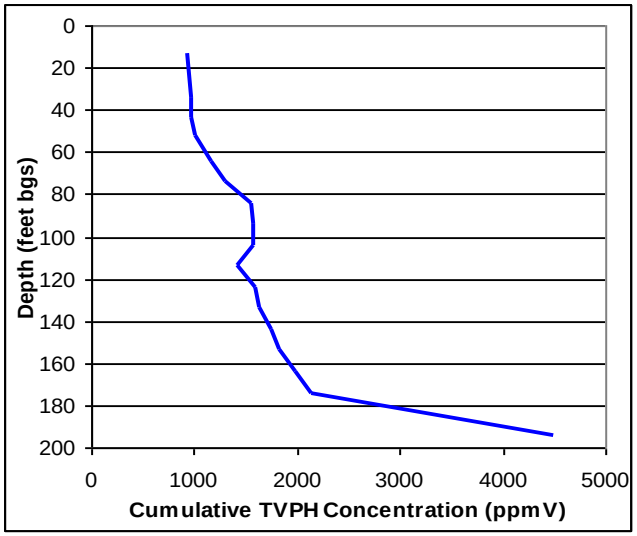
	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	22.5	106.7
FINAL	30.5	131.0

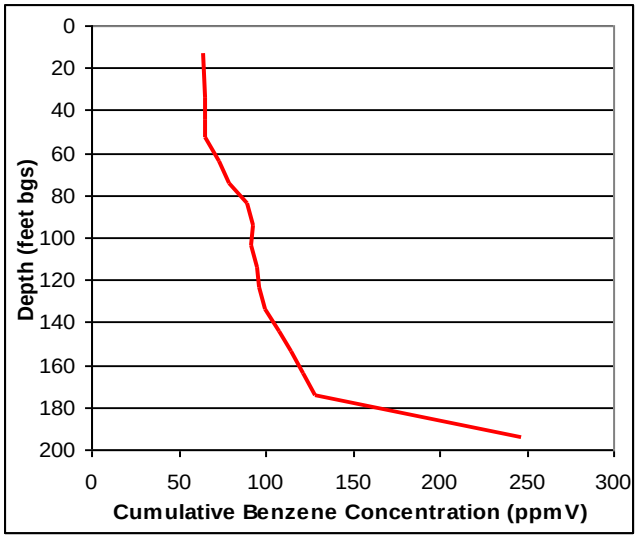
PROFILES:

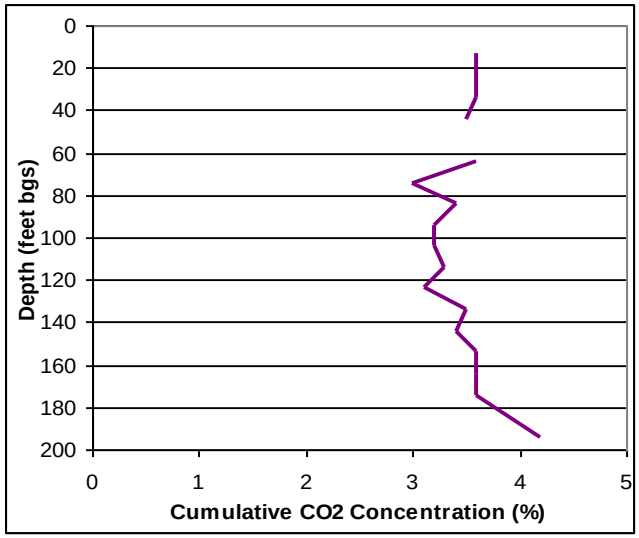


Vapor Analytical Results for 106-149-S

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/16/2012	13:55	101	149-S	194.1	4.5	285	247	210	11	20	8.6	3.0	4502	55	4.2	13.7
4/16/2012	14:05	102	149-S	184.0	Bad Bag	-	-	-	-	-	-	-	-	42	3.8	14.0
4/16/2012	14:12	103	149-S	174.1	3.9	129	129	95	4.6	8.4	4.2	1.5	2134	31	3.6	14.2
4/16/2012	14:15	104	149-S	164.0	3.9	117	122	88	4.3	7.6	4.0	1.2	1977	26	3.6	14.1
4/16/2012	14:19	105	149-S	154.0	4.0	108	115	82	3.8	6.8	4.2	1.3	1832	23	3.6	14.2
4/16/2012	14:23	106	149-S	144.0	3.7	103	108	76	3.6	6.3	3.9	0.9	1747	21	3.4	14.5
4/16/2012	14:28	107	149-S	133.9	3.8	98	100	70	3.3	5.8	3.2	0.9	1641	20	3.5	14.3
4/16/2012	14:32	108	149-S	124.0	3.7	94	96	68	3.2	5.6	3.1	0.8	1592	19	3.1	14.5
4/16/2012	14:39	109	149-S	114.1	3.8	93	95	69	3.3	5.8	3.2	0.8	1422	18	3.3	14.5
4/16/2012	14:44	110	149-S	104.0	3.9	91	93	68	3.3	5.8	3.2	0.9	1581	17	3.2	14.5
4/16/2012	14:48	111	149-S	94.1	4.0	88	93	68	3.2	5.9	3.2	0.9	1579	16	3.2	14.5
4/16/2012	14:52	112	149-S	84.0	3.9	87	90	68	3.2	5.9	3.2	0.9	1565	16	3.4	14.4
4/16/2012	14:58	113	149-S	74.1	3.7	64	80	56	2.6	4.8	2.7	0.7	1310	12	3.0	15.1
4/16/2012	15:04	114	149-S	64.0	3.7	58	74	51	2.4	4.3	2.8	0.8	1164	12	3.6	14.4
4/16/2012	15:59	115	149-S	52.6	3.7	57	66	43	2.0	3.8	2.1	0.7	1019	-	-	-
4/16/2012	15:12	116	149-S	44.0	3.7	53	66	42	1.9	3.5	2.1	0.6	967	8	3.5	14.6
4/16/2012	15:17	117	149-S	33.9	3.7	53	66	42	1.9	3.4	2.1	0.5	967	8	3.6	14.5
4/16/2012	15:22	118	149-S	13.2	3.7	51	65	40	1.8	3.3	2.0	0.5	939	8	3.6	14.5
4/16/2012	15:22	119	FD	13.2	3.5	51	63	40	1.8	3.3	2.0	0.5	824	na	na	na
4/17/2012	19:42	120	Blank	na	1.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	2.5	na	na	na

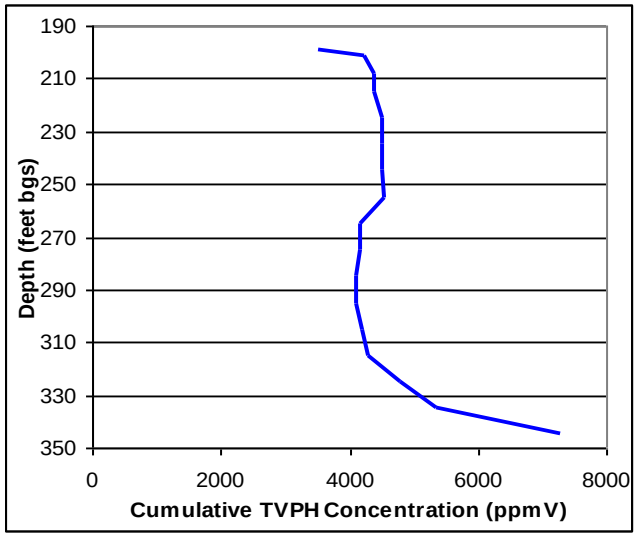


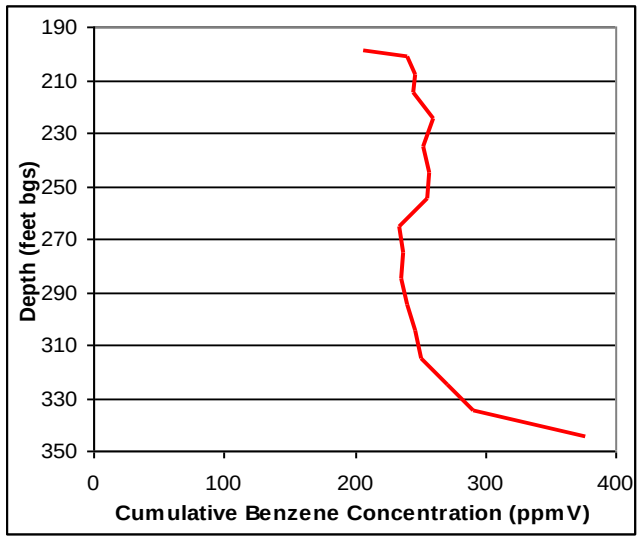


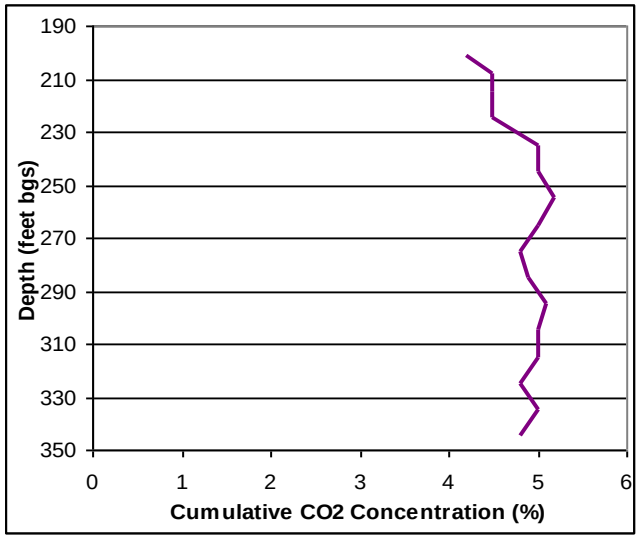


Vapor Analytical Results for 106-149-M

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/17/2012	10:12	121	149-M	345.0	0.0	570	377	298	14	28	10	2.9	7294	>100	4.8	13.3
4/17/2012	10:18	122	149-M	335.1	4.3	388	292	240	12	24	9.1	2.7	5369	98	5.0	13.4
4/17/2012	10:22	123	149-M	325.0	4.2	332	271	223	11	22	8.8	2.7	4783	77	4.8	13.5
4/17/2012	10:26	124	149-M	315.1	4.2	284	252	207	10	20	8.3	2.4	4308	70	5.0	13.4
4/17/2012	10:31	125	149-M	305.0	4.1	272	247	205	10	20	8.3	2.4	4206	67	5.0	13.5
4/17/2012	10:35	126	149-M	295.1	4.1	266	241	201	10	20	8.2	2.4	4120	66	5.1	13.5
4/17/2012	10:38	127	149-M	285.0	4.0	264	236	197	10	20	8.1	2.4	4096	66	4.9	13.5
4/17/2012	10:42	128	149-M	275.1	4.2	268	238	202	10	20	8.4	2.5	4172	66	4.8	13.5
4/17/2012	10:45	129	149-M	265.2	4.2	271	235	198	10	20	8.1	2.5	4171	70	5.0	13.4
4/17/2012	10:49	130	149-M	255.1	4.3	300	257	214	11	21	8.6	2.6	4559	75	5.2	13.3
4/17/2012	10:52	131	149-M	245.0	4.0	297	257	213	11	21	8.6	2.4	4509	75	5.0	13.5
4/17/2012	10:57	132	149-M	235.1	4.1	296	252	214	11	21	8.6	2.6	4511	75	5.0	13.5
4/17/2012	11:01	133	149-M	225.0	4.0	292	261	217	12	22	8.8	2.7	4513	72	4.5	14.3
4/17/2012	11:05	134	149-M	215.1	4.0	283	246	209	11	21	8.4	2.4	4374	73	4.5	14.1
4/17/2012	11:12	135	149-M	208.2	4.3	282	247	209	11	21	8.3	2.5	4383	75	4.5	14.0
4/17/2012	11:17	136	149-M	201.2	4.1	269	240	202	11	20	8.1	2.4	4220	71	4.2	14.4
4/17/2012	11:20	137	149-M	199.0	4.1	219	207	173	9.0	17	7.1	1.9	3507	na	na	na

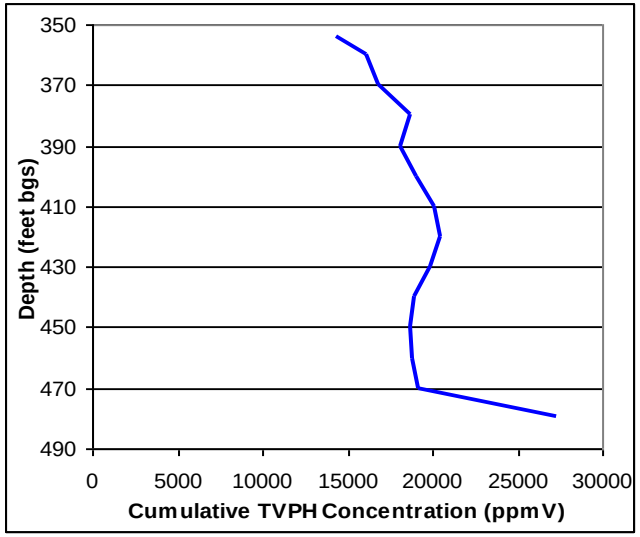


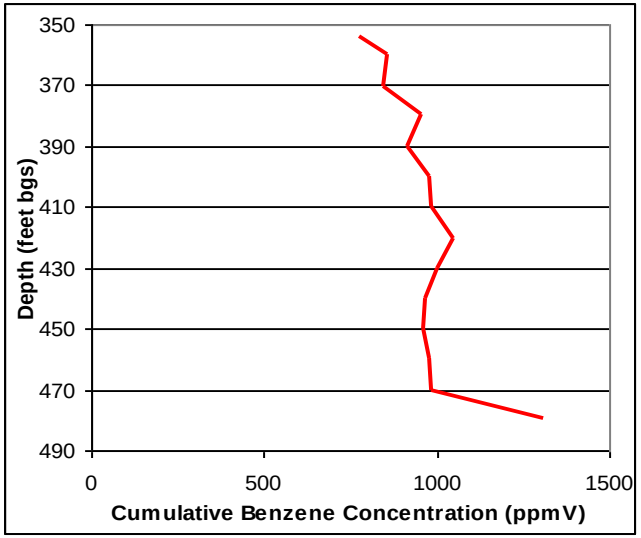


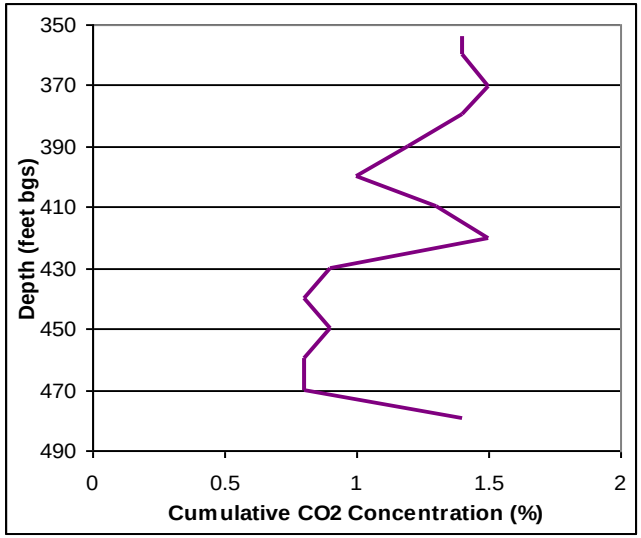


Vapor Analytical Results for 106-149-D

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/17/2012	14:51	138	149-D	479.3	0.0	2724	1310	903	49	89	29	5.2	27236	>100	1.4	15.7
4/17/2012	14:57	139	149-D	470.2	0.0	1640	985	736	35	71	23	5.7	19202	>100	0.8	17.7
4/17/2012	15:00	140	149-D	460.0	0.0	1574	981	732	33	68	22	5.7	18811	>100	0.8	17.3
4/17/2012	15:04	141	149-D	449.9	0.0	1568	962	722	32	66	21	4.7	18660	>100	0.9	17.4
4/17/2012	15:09	142	149-D	439.8	0.0	1629	965	719	32	66	21	5.1	18899	>100	0.8	17.5
4/17/2012	15:14	143	149-D	430.2	0.0	1783	1004	732	33	67	21	5.2	19839	>100	0.9	17.6
4/17/2012	15:19	144	149-D	420.0	0.0	1883	1047	753	34	70	22	5.5	20505	>100	1.5	16.5
4/17/2012	15:24	145	149-D	410.1	0.0	1843	987	738	33	68	22	5.6	20073	>100	1.3	16.9
4/17/2012	15:28	146	149-D	400.0	0.0	1745	979	703	32	66	21	5.6	19113	>100	1.0	17.5
4/17/2012	15:32	147	149-D	390.1	0.0	1647	913	660	30	61	20	5.4	18115	>100	1.2	17.5
4/17/2012	15:37	148	149-D	379.5	0.0	1657	958	701	31	65	21	6.0	18654	>100	1.4	17.4
4/17/2012	15:41	149	149-D	370.1	0.0	1449	843	656	29	61	20	5.8	16789	>100	1.5	17.2
4/17/2012	15:45	150	149-D	359.8	0.0	1347	860	663	29	62	20	5.9	16169	>100	1.4	17.7
4/17/2012	15:50	151	149-D	345.1	0.0	1173	777	601	26	55	18	5.3	14356	>100	1.4	17.4



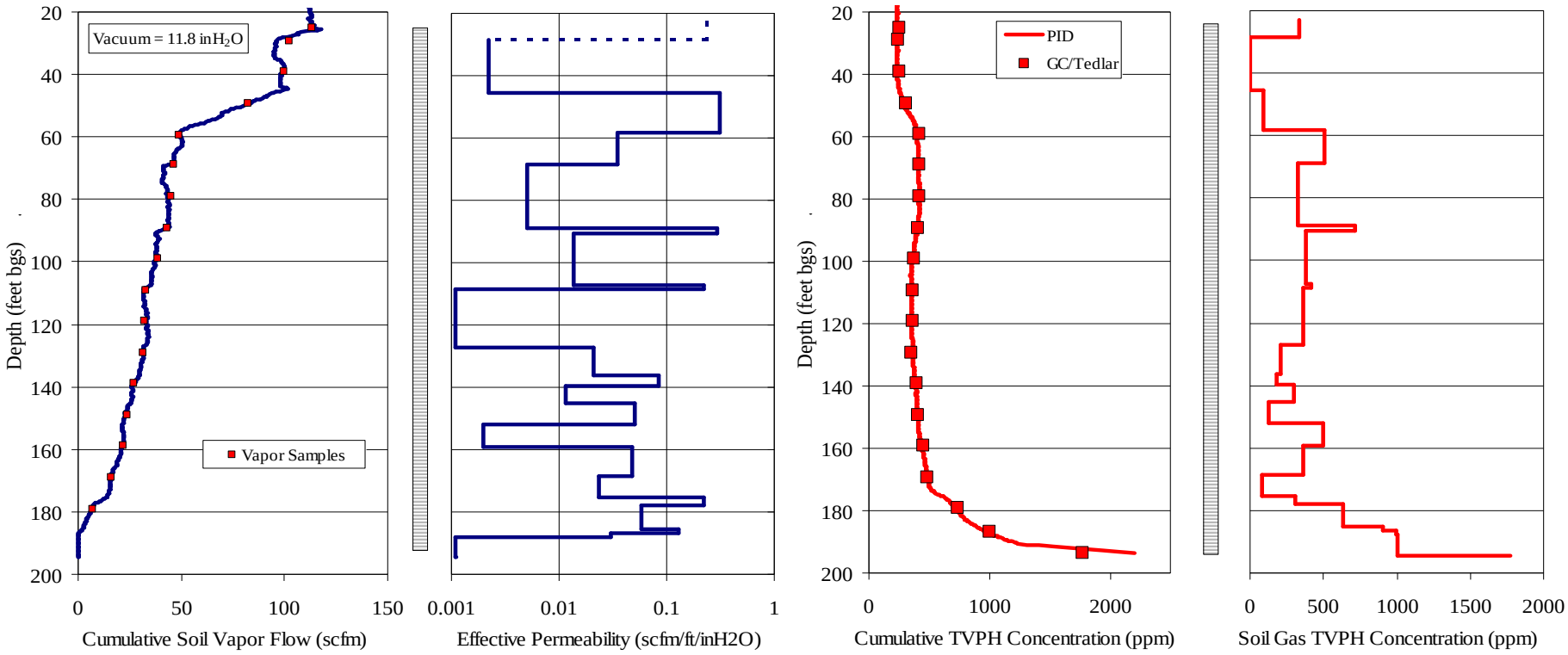




WELL	KAFB-106-150-S
SCREEN	25 – 200 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	20-APR-12

	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	11.8	113
FINAL	11.5	112.3

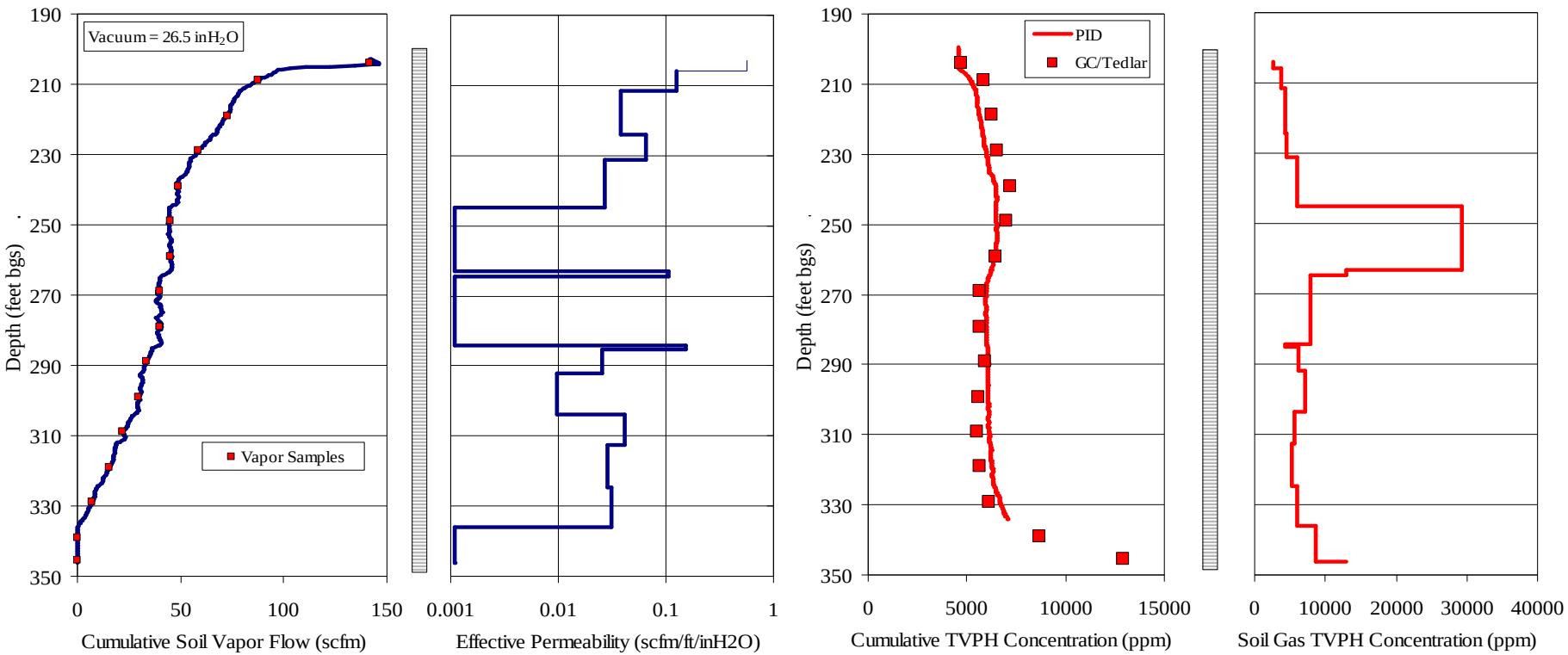
PROFILES:



WELL	KAFB-106-150-M
SCREEN	206 – 350 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	20-APR-12

	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	16.5	96.3
FINAL	26.5	137.3

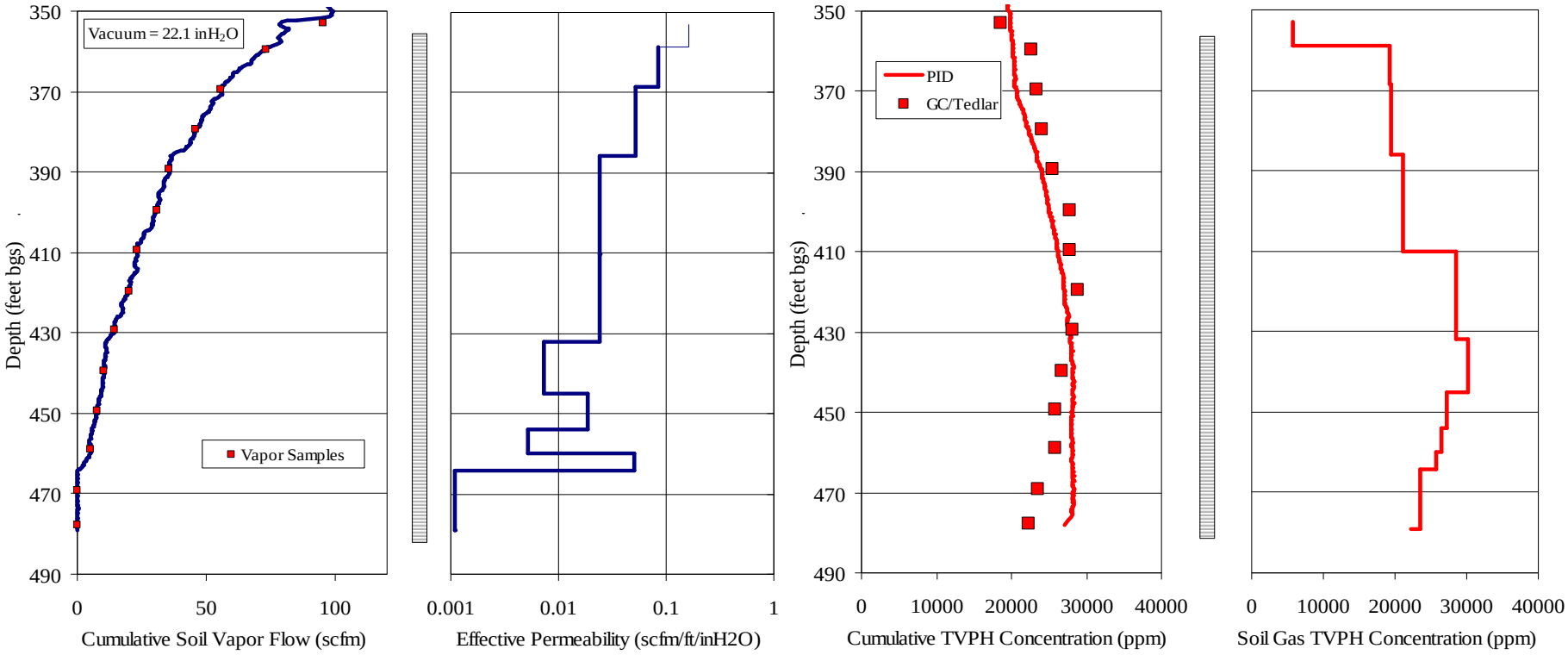
PROFILES:



WELL	KAFB-106-150-D
SCREEN	355 – 484 FT BGS
SITE	KIRTLAND AFB
	ALBUQUERQUE, NM
DATE	20-APR-12

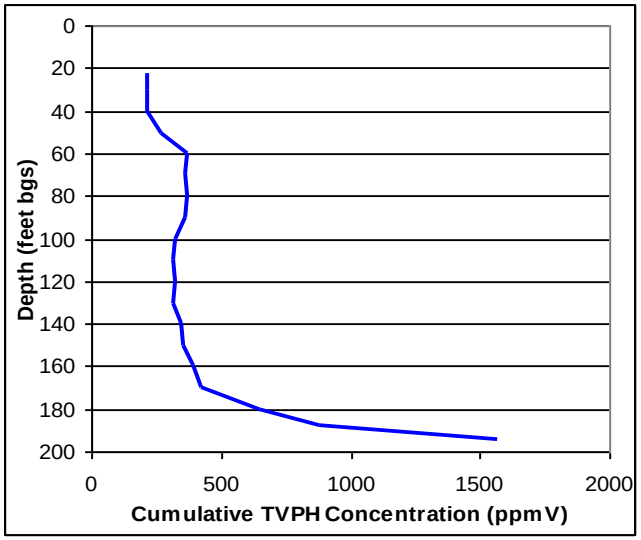
	APPLIED VACUUM (inH_2O)	EXTRACTION RATE (SCFM)
INITIAL	22.1	94.9
FINAL	22.0	95.4

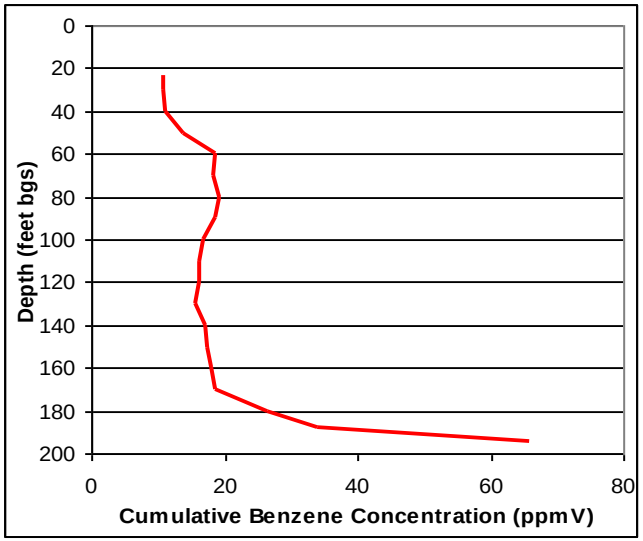
PROFILES:

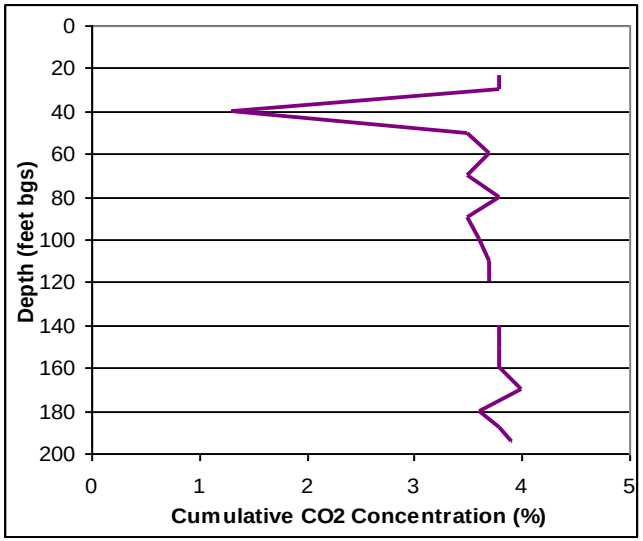


Vapor Analytical Results for 106-150-S

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/20/2012	17:49	243	150-S	12.7	3.1	8.1	11	9.4	0.3	1.1	0.5	0.2	221	na	na	na
4/20/2012	16:45	244	150-S	194.7	0.6	21	23	26	0.7	2.3	0.7	0.3	617	12	3.9	15.4
4/20/2012	16:49	245	150-S	187.9	1.9	29	34	35	1.1	3.6	2.9	0.3	884	9	3.8	15.5
4/20/2012	16:52	246	150-S	180.0	1.8	22	26	26	0.8	2.6	0.9	0.2	652	5	3.6	15.7
4/20/2012	16:55	247	150-S	170.2	3.7	14	19	17	0.5	1.8	0.7	0.2	423	3	4.0	15.6
4/20/2012	16:58	248	150-S	160.0	3.6	13	18	16	0.5	1.8	8.0	0.2	395	3	3.8	15.6
4/20/2012	17:01	249	150-S	150.2	3.5	13	18	15	0.4	1.6	0.7	0.2	357	3	3.8	15.6
4/20/2012	17:04	250	150-S	140.0	3.6	12	17	14	0.4	1.6	0.7	0.2	347	4	3.8	15.5
4/20/2012	17:07	251	150-S	130.2	3.5	11	16	13	0.3	1.3	0.6	0.2	314	bad bag	-	-
4/20/2012	17:11	252	150-S	120.0	3.6	12	16	13	0.4	1.4	0.7	0.2	322	3	3.7	15.7
4/20/2012	17:14	253	150-S	110.2	3.4	12	16	13	0.4	1.4	0.6	0.2	318	3	3.7	15.6
4/20/2012	17:18	254	150-S	100.0	3.4	12	17	13	0.4	1.4	0.6	0.2	326	4	3.6	15.7
4/20/2012	17:21	255	150-S	90.2	2.2	13	18	15	0.4	1.6	0.7	0.2	360	4	3.5	15.9
4/20/2012	17:24	256	150-S	80.0	2.0	13	19	16	0.4	1.6	0.7	0.2	368	0	3.8	15.8
4/20/2012	17:29	257	150-S	69.9	3.5	13	18	15	0.4	1.6	0.7	0.2	364	0	3.5	16.2
4/20/2012	17:32	258	150-S	60.3	3.2	14	19	16	0.4	1.6	0.7	0.2	370	0	3.7	15.8
4/20/2012	17:36	259	150-S	50.4	2.8	9.9	14	11	0.3	1.2	0.6	0.2	268	0	3.5	15.9
4/20/2012	17:39	260	150-S	40.0	3.0	8.1	11	9.4	0.2	1.0	0.5	0.1	220	0	1.3	19.2
4/20/2012	17:42	267	150-S	30.1	3.0	7.9	11	8.9	0.2	1.0	0.4	0.1	213	0	3.8	15.8
4/20/2012	17:48	262	150-S	12.7	1.7	7.9	11	8.8	0.2	0.9	0.4	0.1	213	0	3.8	15.8
4/20/2012	18:20	263	Equip B	QAQC	0.5	0.2	0.2	0	0.0	0.1	0.1	0.1	8.4	na	na	na
4/20/2012	16:45	264	150-S	194.7	1.9	59	66	74	2.8	8.0	2.6	0.8	1565	na	na	na

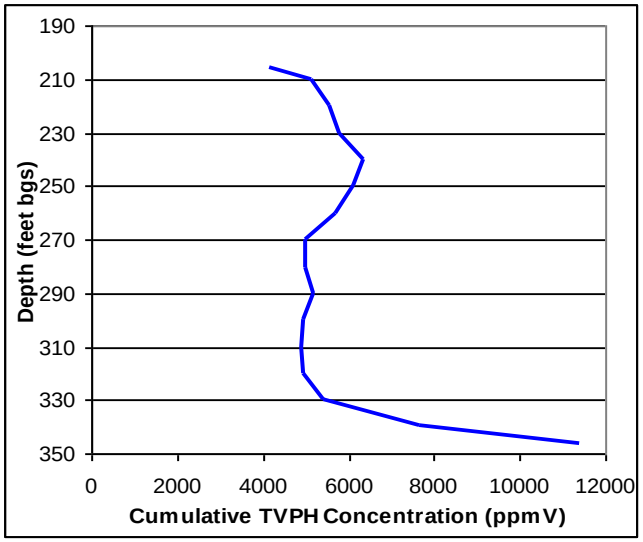


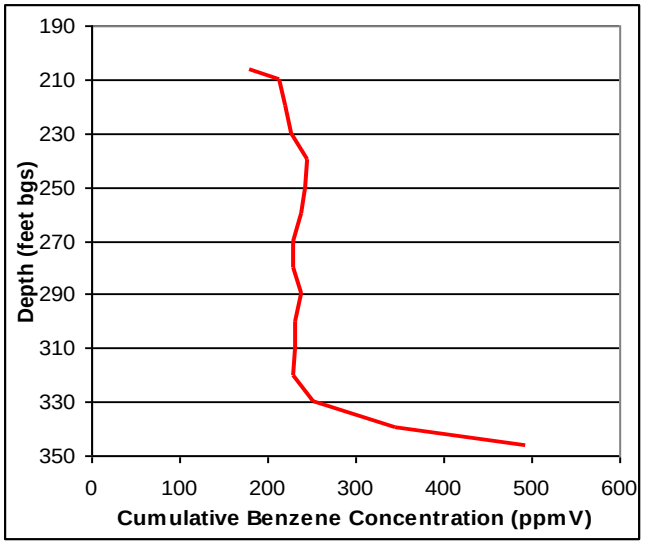


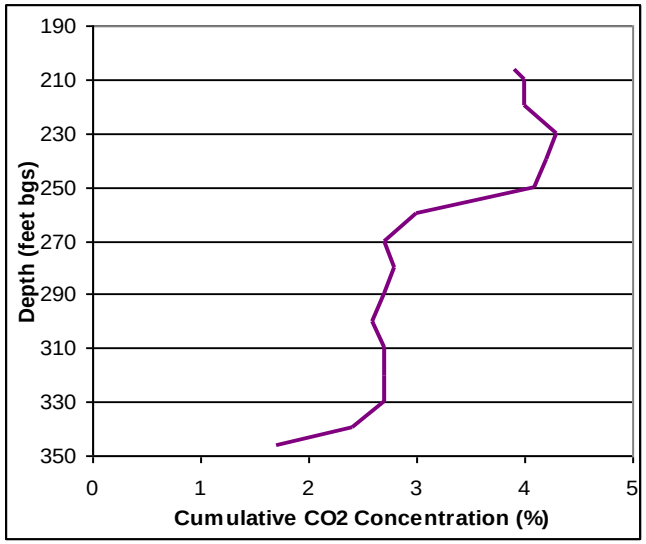


Vapor Analytical Results for 106-150-M

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/20/2012	13:46	226	150-M	346.5	0.0	730	448	408	17	40	11	4	10117	>100	1.7	16.9
4/20/2012	13:47	227	150-M	346.5	0.0	816	493	460	20	47	13	5	11374	na	na	na
4/20/2012	13:52	228	150-M	339.9	0.0	501	345	333	13	34	9.2	3.6	7661	>100	2.4	16.0
4/20/2012	13:56	229	150-M	330.0	2.7	316	252	262	10	26	7.1	2.7	5394	>100	2.7	15.7
4/20/2012	14:00	230	150-M	320.2	2.8	273	230	251	9.0	24	6.5	2.5	4958	85	2.7	15.7
4/20/2012	14:04	231	150-M	310.0	2.8	258	233	253	8.7	24	6.3	2.2	4882	85	2.7	15.8
4/20/2012	14:08	232	150-M	300.2	2.9	256	231	254	8.5	23	7.1	2.1	4943	83	2.6	15.8
4/20/2012	14:12	233	150-M	290.0	3.0	264	239	271	9.1	25	7.2	2.3	5203	85	2.7	15.7
4/20/2012	14:15	234	150-M	280.2	2.9	250	230	260	8.5	23	6.4	1.9	4983	84	2.8	15.7
4/20/2012	14:20	235	150-M	270.0	2.8	250	229	261	8.5	23	6.4	1.9	5002	84	2.7	15.6
4/20/2012	14:23	236	150-M	260.1	2.9	262	239	276	10	27	8.1	2.4	5691	87	3.0	15.4
4/20/2012	14:27	237	150-M	250.0	3.1	267	244	273	9.4	27	7.3	2.5	6138	>100	4.1	14.4
4/20/2012	14:30	238	150-M	240.1	0.0	272	246	284	10	29	8.6	2.9	6332	>100	4.2	14.3
4/20/2012	14:34	239	150-M	230.0	3.0	245	226	260	9.3	27	7.9	2.8	5776	>100	4.3	14.2
4/20/2012	14:38	240	150-M	219.9	2.9	233	220	256	8.9	26	7.1	2.7	5535	94	4.0	14.5
4/20/2012	14:41	241	150-M	210.0	3.0	214	213	248	8.7	25	7.1	2.3	5154	91	4.0	14.3
4/20/2012	14:45	242	150-M	202.7	2.7	169	180	210	7.3	21	6.3	2.1	4150	76	3.9	14.5

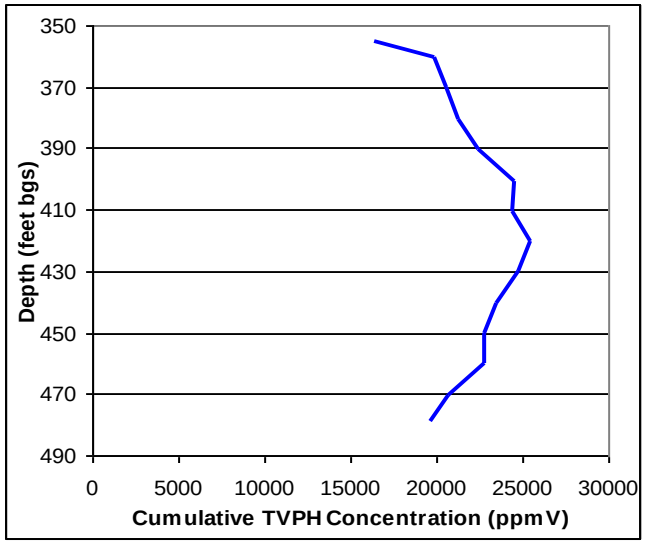


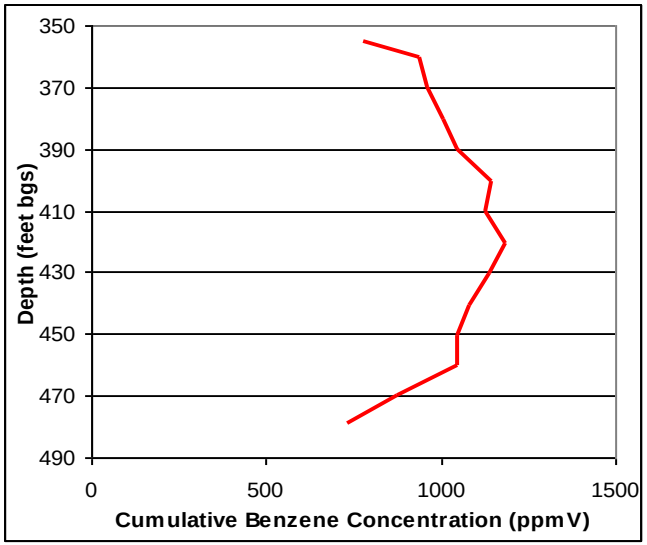


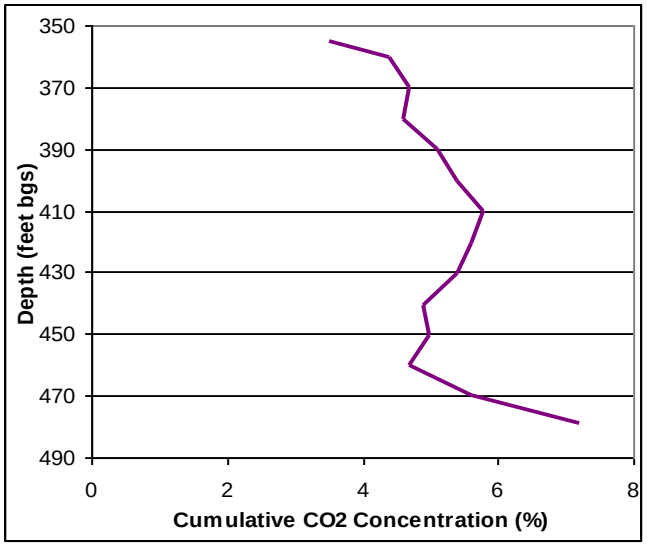


Vapor Analytical Results for 106-150-D

Date	Time	ID	Well	Depth	Methane	Hexane	Benzene	Toluene	Ethylbzne	p-Xylene	o-Xylene	1,2,4-TMB	TVPH	LEL	CO2	O2
									(ppmV)					(%)	(%)	(%)
4/20/2012	9:52	211	150-D	478.8	na	850	730	705	31	85	26	7.7	19628	94	7.2	4.9
4/20/2012	9:56	212	150-D	470.2	na	1310	874	773	36	86	34	8.6	20710	>100	5.6	7.7
4/20/2012	9:59	213	150-D	460.0	na	1921	1047	817	36	80	29	7.5	22779	>100	4.7	10.2
4/20/2012	10:10	214	150-D	450.4	na	2005	1048	792	36	79	43	7.5	22830	>100	5.0	9.9
4/20/2012	10:13	215	150-D	440.5	na	2088	1082	820	37	82	32	7.0	23498	>100	4.9	10.3
4/20/2012	10:17	216	150-D	430.4	na	2185	1137	862	38	82	26	6.9	24728	>100	5.4	9.6
4/20/2012	10:21	217	150-D	420.5	na	2184	1184	904	38	84	27	6.9	25452	>100	5.6	9.9
4/20/2012	10:25	218	150-D	410.4	na	2039	1130	877	35	80	25	6.4	24439	>100	5.8	10.0
4/20/2012	10:29	219	150-D	400.5	na	2003	1145	893	34	78	28	6.1	24543	>100	5.4	10.5
4/20/2012	10:33	220	150-D	390.4	na	1791	1045	830	30	71	23	5.2	22452	>100	5.1	11.0
4/20/2012	10:36	221	150-D	380.5	na	1640	1005	807	28	68	19	5.0	21235	>100	4.6	11.7
4/20/2012	10:41	222	150-D	370.4	na	1541	963	796	27	67	18	5.4	20542	>100	4.7	11.5
4/20/2012	10:44	223	150-D	360.5	na	1447	937	802	27	69	19	5.8	19890	>100	4.4	12.2
4/20/2012	10:49	224	150-D	345.1	na	1153	779	686	23	60	16	5.8	16445	>100	3.5	13.5
4/20/2012	10:50	225	150-D	345.1	na	1195	808	699	23	59	16	5.1	16925	na	na	na







Attachment B

Subsurface Vapor Flow Model for SVE

B. Subsurface Vapor Flow Model for SVE

The permeability of each soil layer was determined by applying a subsurface air flow model with the measured flow profiles from PneuLog and varying the permeabilities until a best-fit was achieved to the applied well vacuum and observed vacuum responses at nearby monitoring probes. The mathematical air flow model is an extension to the steady-state solution of *Baehr and Hult* [1991] for a surface open to the atmosphere and includes multiple soil layers and a more general boundary condition at the extraction well. For steady flow, a constant atmospheric pressure, and two-dimensional axisymmetric air flow into a single well, the following set of governing equations for M parallel soil layers each of which is homogenous and anisotropic applies:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta_i}{\partial r}\right)+\alpha_i\frac{\partial^2\theta_i}{\partial z^2}=0 \qquad \text{in } L_{i-1} < z < L_i,\ i = 1 \text{ to } M \tag{2}$$

where θ_i represents the soil gas pressure relative to the atmospheric pressure, P_{atm} and P_i is the absolute gas pressure in layer i:

$$\theta_i = P_i^2 - P_{atm}^2$$

and:

$$\alpha_i = \frac{k_{z,i}}{k_{r,i}}$$

where $k_{r,i}$ is the horizontal air permeability and $k_{z,i}$ is the vertical air permeability in soil layer i. The domain and boundary conditions for the general solution of equation (2) are illustrated in Figure A4-1. The upper surface is open to the atmosphere. The bottom surface is considered impermeable to air and may be the water table or a confining soil layer. The boundary condition at the well specifies a variable flow along the length of the borehole (e.g., multiple screens). The ground surface and far field are assumed to be at atmospheric pressure. At the interface between adjacent layers, the pressure is continuous and mass is conserved. The mathematical interpretations of these conditions are:

$$
\begin{aligned}
&\frac{\partial \theta_i}{\partial r} = -q_i(z) && \text{at } r = r_w;\ i = 1 \text{ to } M \\
&\theta_i = 0 && \text{for } r \to \infty;\ i = 1 \text{ to } M \\
&\theta_1 = 0 && \text{at } z = 0 \\
&\theta_i = \theta_{i+1} && \text{at } z = L_i;\ i = 1 \text{ to } M-1 \\
&k_{z,i} \frac{\partial \theta_i}{\partial z} = k_{z,i+1} \frac{\partial \theta_{i+1}}{\partial z} && \text{at } z = L_i;\ i = 1 \text{ to } M-1 \\
&\frac{\partial \theta_M}{\partial z} = 0 && \text{at } z = L_M
\end{aligned}
\tag{3}
$$

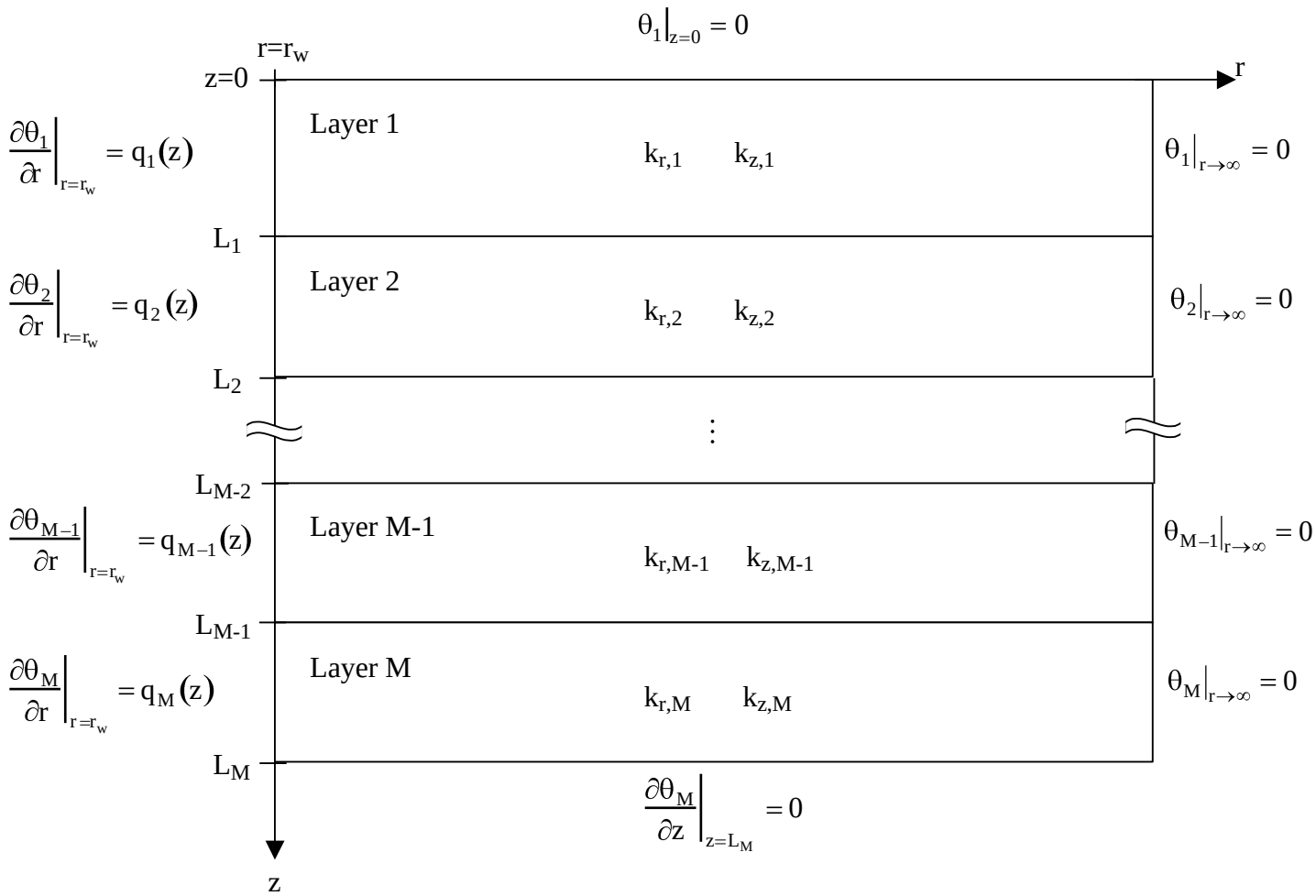


Figure B-1. Mathematical Representation of Flow through a Single Borehole in a Layered Vadose Zone

The function $q_i(z)$ represents an arbitrary steady flow rate along a well screen and r_w is the radius of the extraction well. For unscreened intervals, q_i equals 0. The value of q_i may be either positive (injection) or negative (extraction). This general function can accommodate multiple screens in a nested well and screens extending over multiple soil layers. The solution to (2) subject to (3) is derived using a generalized integral transform and the general solution in terms of an eigenvalue problem is:

$$\theta_i(r,z) = \sum_{n=1}^{\infty} \frac{Z_i(\beta_n, z)}{\beta_n N(\beta_n)} \frac{K_0(\beta_n r)}{K_1(\beta_n r_w)} \bar{q}(\beta_n)$$

where K_0 and K_1 are modified Bessel functions of the second kind. The accompanying streamfunction is solution is:

$$\psi_i(r,z) = \frac{r k_{r,i}}{2\mu RT} \sum_{n=1}^{\infty} \frac{\bar{q}(\beta_n)}{N(\beta_n)} \frac{K_1(\beta_n r)}{K_1(\beta_n r_w)} \int Z_i(\beta_n, z')\, dz'$$

The eigenvalue problem for the space variable z is:

$$\frac{d^2 Z_i}{dz^2} + \frac{\beta_n^2}{\alpha_i} Z_i = 0 \qquad \text{in } L_{i-1} < z < L_i,\ i = 1 \text{ to } M \tag{4}$$

where Z_i are the eigenfunctions and β_n are the eigenvalues. The separated boundary conditions are:

$$\begin{aligned}
&Z_1 = 0 && \text{at } z = L_0 = 0 \\
&Z_i = Z_{i+1} && \text{at } z = L_i;\ i = 1 \text{ to } M-1 \\
&k_{z,i} \frac{\partial Z_i}{\partial z} = k_{z,i+1} \frac{\partial Z_{i+1}}{\partial z} && \text{at } z = L_i;\ i = 1 \text{ to } M-1 \\
&\frac{\partial Z_M}{\partial z} = 0 && \text{at } z = L_M
\end{aligned} \tag{5}$$

The general eigenfunctions satisfying (4) are:

$$Z_i(\beta_n, z) = A_{n,i} \sin\left(\frac{\beta_n z}{\sqrt{\alpha_i}}\right) + B_{n,i} \cos\left(\frac{\beta_n z}{\sqrt{\alpha_i}}\right) \qquad \text{in } L_{i-1} < z < L_i,\ i = 1 \text{ to } M \tag{6}$$

To determine the coefficients A and B in (6), a standard numerical matrix evaluation routine is employed. The eigenvalues, β_n, are calculated from the requirement that for nontrivial solutions to exist the determinant of the matrix vanishes. Hence, the eigenvalues are the roots of the equation resulting from setting the determinant equal to zero. The normalization integral and transformed boundary conditions are then calculated to complete the solution from:

$$N(\beta_n) = \sum_{i=1}^{M} \frac{k_{z,i}}{\alpha_i} \int_{L_i}^{L_{i+1}} Z_i^2(\beta_n, z')\,dz' \tag{7}$$

$$\bar{q} = \sum_{i=1}^{M} \frac{k_{z,i}}{\alpha_i} \int_{L_i}^{L_{i+1}} Z_i(\beta_n, z')\,q_i(z')\,dz' \tag{8}$$

References

Baehr, A. L., and M. F. Hult, Evaluation of unsaturated zone air permeability through pneumatic tests, *Water Resour. Res.*, *27*(10), 2605-2617, 1991.

Attachment C

Model of Residual Fuel Evaporation to Estimate SVE Performance

C. Model of Residual Fuel Evaporation to Estimate SVE Performance

Soil vapor extraction removes contamination from the vadose zone by extracting volatilized contaminants in the soil gas. The induced flow of air during SVE acts to promote volatilization of contaminants from any liquid fuel (i.e., residual NAPL) in the pore spaces. To evaluate this process for the sizing of an SVE system, a simple, multi-component evaporation model can be used to predict NAPL component volatilization. In general, the model has the following attributes:

- Model estimates evaporation of individual compounds in NAPL.
- Model is based on a mass balance and thermodynamic equilibrium.
- Model assumes the soil is a "black box" (i.e., the pore volume exchange rate is rapid compared to the timescale for the cleanup).
- Model assumes equilibrium in the NAPL at all times (i.e., no inner NAPL diffusion constraints).
- Equilibrium between NAPL and vapors can be mass transfer constrained.
- Mass transfer constraints of the soil matrix are lumped into a "removal efficiency."
- Removal rate is proportional to mass extracted.
- Partitioning of vapors into other phases and degradation are neglected (i.e., all volatilized compounds are assumed to be extracted).

The model treats the subsurface as a well-mixed continuum. This implies any subsurface heterogeneities, dilutions, dis-equilibrium, diffusion limitations, phase partitioning, etc. are averaged over the domain volume and are included in an overall removal efficiency. An overall removal efficiency less than one implies the vapor concentration is less than the thermodynamic equilibrium value between the NAPL and the carrier vapor (e.g., air). Thermal enhancements can be included by adjusting temperature-dependent properties (e.g., vapor pressure). The model assumes the evaporation process is slow (i.e., mass changes are small for each pore volume of air passed through the contaminated medium). The model is illustrated in Figure C-1.

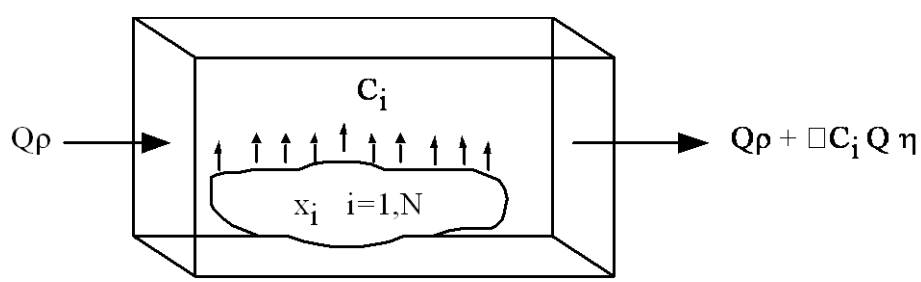


Figure C-1. Conceptual Illustration of Well-Mixed Evaporation Model

Invoking the assumption of a well-mixed model allows the following equation to predict the mass removal rate of individual compounds from the NAPL:

$$\frac{dm_i}{dt} = C_i \, Q \, \eta$$

where:

m_i = mass of the i-th component in the NAPL (mg)
t = time (min)
Q = the volumetric flow rate of the carrier gas through the medium (m^3/min)
η = the removal efficiency factor (dimensionless)
C_i = vapor concentration of the i-th component in the carrier gas (mg/m^3)

For an order-of-magnitude evaluation, the removal efficiency is assumed to remain constant; although, in field application the value would decrease slowly over time. The vapor concentration of component i can be estimated using the ideal gas law:

$$C_i = x_i \, C_{sat,i} = x_i \, \frac{P_{v,i} \, M_i}{R_u \, T} \left(10^6 \, \frac{mg}{kg} \right)$$

where:

x_i = liquid mole fraction of component i in the NAPL (dimensionless)
$C_{sat,i}$ = saturated vapor concentration of component i at temperature T (mg/m^3)
$P_{v,i}$ = vapor pressure of component i at the system temperature T (bar)
M_i = molecular weight of component i (kg/kg-mol)
R_u = ideal gas constant (0.08315 bar m^3 / kg-mol K)
T = system temperature (K)

For a given system temperature T, the pure-component vapor pressures are calculated using the correlations of Reid et al. (1989). If the system temperature is below the minimum value for the Reid et al. correlations, the Lee-Kesler equation is used to estimate the vapor pressure.

For N components in the NAPL, the system of equations is solved numerically by discretizing as follows and marching through time:

$$\Delta m_i = C_i \, Q \, \eta \, \Delta t$$

where the total mass of NAPL remaining in the system at each time step is calculated from:

$$m_{NAPL}(t + \Delta t) = m_{NAPL}(t) - \sum_{i=1}^{N} \Delta m_i (t + \Delta t)$$

and the mass of each individual compound remaining is:

$$m_i (t + \Delta t) = m_i (t) - \Delta m_i (t + \Delta t)$$

After calculating the mass removed, the mole fractions of each compound are recalculated from the new mass fractions of each compound:

$$x_i(t) = \frac{\dfrac{f_i(t)}{M_i}}{\displaystyle\sum_{j=1}^{N} \frac{f_j(t)}{M_j}}$$

where the mass fraction (f) of each compound is defined by:

$$f_i(t) = \frac{m_i(t)}{\displaystyle\sum_{j=1}^{N} m_j(t)}$$

The new mole fractions are used in calculating new vapor concentrations for the next time step. The calculation is performed to a second order in accuracy by taking half a time step and using the mole fractions at the half time step to estimate the vapor concentrations for the full time step. Note that an implicit assumption in this formulation is that the mass of each component dissolved in pore water and adsorbed to soil solids is assumed to be very small compared to its mass in the NAPL phase.

For this work, the evaporation model was used to provide engineering estimates for mass recovery and vapor concentration behavior during full-scale SVE applied at Bulk Fuels Facility Spill. The NAPL makeup at the site was estimated from previous analyses of NAPL samples from the site and observed vapor concentrations.

References

Reid, R. C., J. M. Prausnitz and B. E. Poling, 1989, The Properties of Gases & Liquids, McGraw-Hill Book Company, New York, pp. 741.

Attachment D

PneuLog Standard Operating Procedure

This project will utilize a procedure combining site characterization and the collection of soil vapor extraction (SVE) data in vadose zone soils containing volatile organic compounds (VOCs). The procedure developed by PRAXIS Environmental Technologies, Inc. uses pneumatic well logging, known as PneuLog®, to measure the vertical air permeability and chemical concentration profiles in wells screened for SVE. The field procedures associated with PneuLog® are described in this attachment. All field activities will adhere to the procedures and specifications contained in the project Field Sampling Plan (FSP) and Quality Assurance Project Plan (QAPP) prepared as separate documents.

Pneumatic well logging is used to develop a detailed conceptual site model to aid in the design, optimization, or closure of SVE systems. The following data are collected in addition to lithologic logging and conventional sample analyses to build the conceptual site model:

- Flow and vacuum data from extraction wells,
- Vertical vapor concentration data from extraction wells, and
- Vertical air production profiles from extraction wells.

This attachment describes the PneuLog® technology and the collection of the data listed above.

This project will employ an expedited approach to vadose zone characterization with simultaneous collection of data for optimized SVE design and operation. For both vadose zone characterization and remedial design, Praxis has developed, field-tested and commercialized a pneumatic well logging process. Known as PneuLog®, the well logging is performed by simultaneously measuring the cumulative air flow and chemical vapor concentrations along the depth of an extraction well screen during active SVE. To make these measurements, a flow sensor is moved through the well during vapor extraction and soil gas samples are collected and

analyzed continuously. Performing these measurements at a representative number of wells can yield a three-dimensional picture of the extent of chemicals in soils at a site as well as the soil permeability distribution. These measurements, in conjunction with traditional measurements, yield a thorough site evaluation.

The equipment for the pneumatic logging is illustrated in Figure 1. The Pneulog® instrumentation is attached to a cable, which passes through alignment pulleys and a vacuum-tight fitting at the wellhead. The instrumentation is raised or lowered by a motorized reel around which the cable is wound. The logging proceeds at roughly eight feet per minute along the screen in the SVE well. Sensors in the pulley assembly indicate the depth of the measurement. Electrical leads connect the flow sensor to a data acquisition system located on the motorized reel. A vapor sampling tube connects the sample port on the instrument to a vacuum pump, also on the reel. The sampling pump draws a continuous stream of air through the sampling tube to the surface where it is analyzed for VOCs and other compounds of interest (e.g., oxygen and carbon dioxide). A photoionization detector (PID) is used to provide a continuous reading of total VOC concentration. Canister samples can be collected for off-site gas chromatographic and mass spectrometer analyses to determine compound-specific concentrations at discrete depths and to calibrate the PID readings. Supplemental vapor samples can be collected and analyzed on-site with a field gas chromatograph.

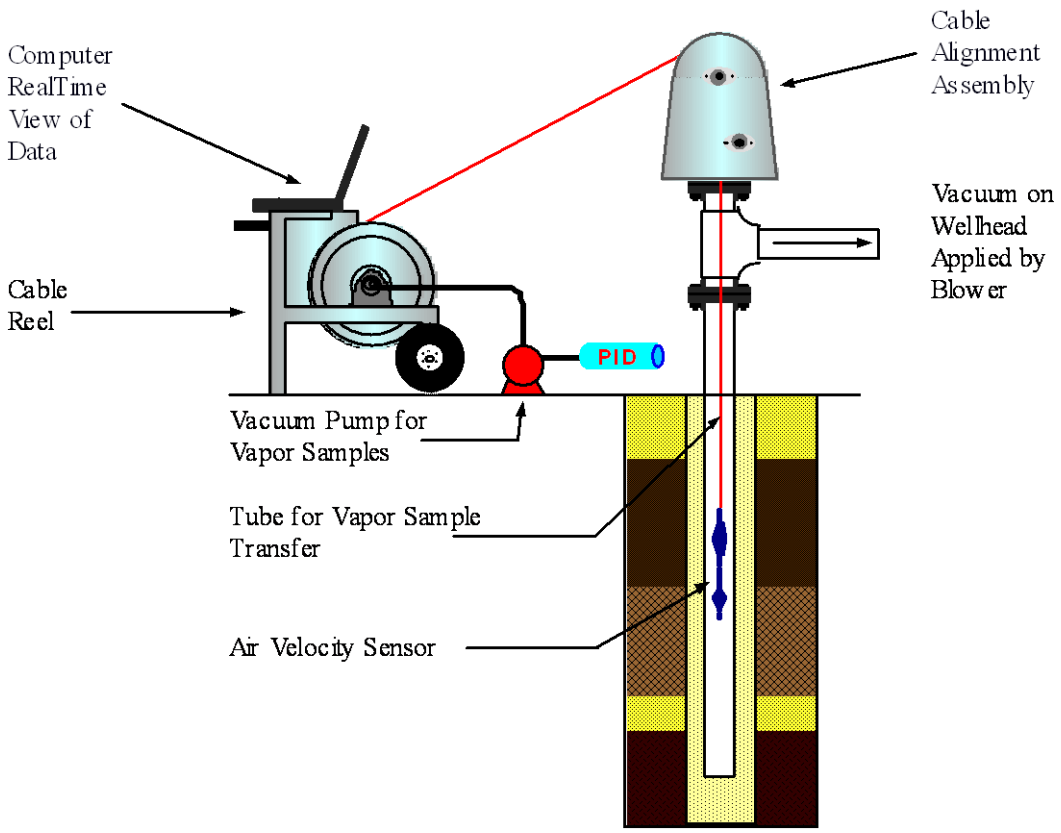


Figure 1. Schematic of Pneumatic Well Logging Equipment

The airflow from each soil layer is related to the cumulative airflow by a simple mass balance. To determine the airflow from a given soil layer, the cumulative airflow measured below the soil layer is subtracted from the cumulative airflow measured above the soil layer. The soil permeability of the interval is then determined from Darcy's law. The data and the analyses appear similar to output from borehole flowmeter testing in water wells (Molz et al., 1989). A typical cumulative airflow measurement from PneuLog® is provided in Figure 2a. In this example, the well is screened from 12 to 32 feet below the ground surface (bgs). The screen interval is indicated by the green (dark) and yellow (light) blocks together. As shown, the airflow from the bottom half of the well is practically zero. The airflow increases steadily from 0 to 28 standard cubic feet per minute (scfm) between 23 and 16.5 feet bgs as the instrument is raised through the screen. The steady flow increase indicates this soil interval has a relatively uniform permeability to air. From 16.5 to 15 feet, only 2.5 scfm of soil gas are added. 15 scfm are then added in the next 1.5-foot interval up to 13.5 feet. The top 1.5 feet of the screen adds only one scfm to the total.

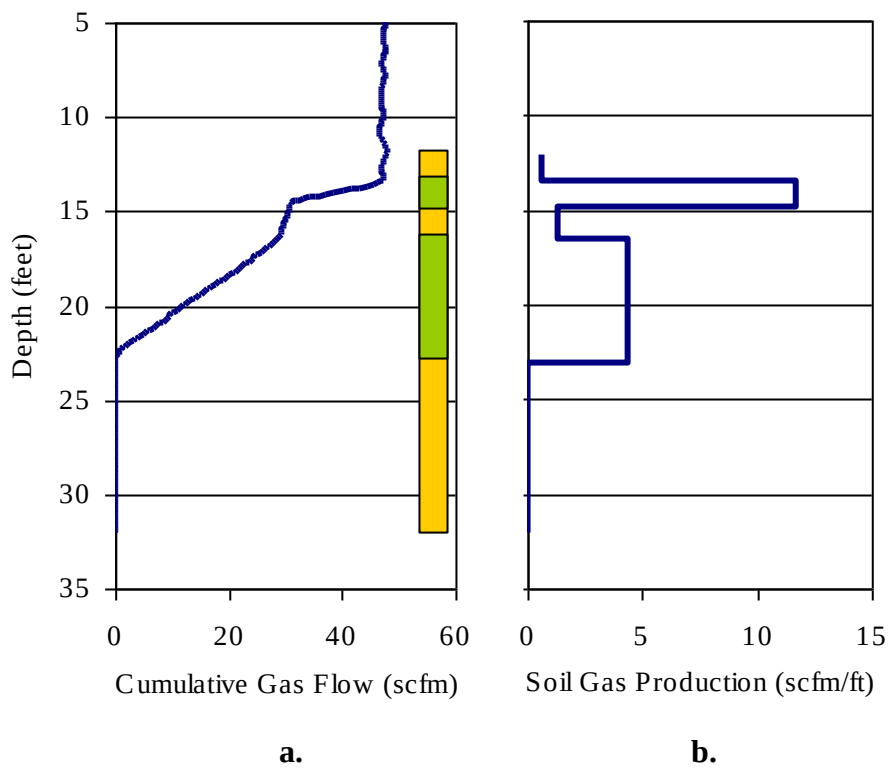


Figure 2. Example Pneumatic Well Logging Results for Soil Permeability to Air

Figure 2b presents an interpretation of the cumulative flow measurements as soil gas production. An effective air permeability profile can be generated using the soil gas production

profile with multi-dimensional analytical or numerical airflow models. The permeability of an interval is proportional to the change in flow across the interval, its thickness, its depth below the surface and the well vacuum according to Darcy's law. Figure 2b reveals roughly five soil strata along the screen. The stratum intersected by the bottom half of the screen has a relatively low permeability since no measurable soil gas was produced. The geologist characterized the soils of this interval as silts. The soil intervals from 16.5 to 23 feet and 13.5 to 15 feet have air productions indicative of coarse sands. These two sand intervals are separated by a 1.5-foot-thick silt interval. The soil at the top of the screen would also be characterized as silt. This characterization of the physical properties is superior to a geological log and a typical air permeability test. The PneuLog® results were qualitatively consistent with the geological log; however, the geological log provided little indication of air permeability. Without the pneumatic logging data, the permeability determined by typical testing would be averaged over the screen interval and dominant features of the subsurface flow during SVE would not be quantified.

The characterizations of zones containing chemicals and soil gas concentrations result from the measurement of VOC concentrations along the well screen. An example concentration log, which was collected simultaneously with the previously discussed air flow log, is presented in Figure 3a. This concentration profile was obtained from a continuous PID reading which was calibrated to trichloroethylene (TCE) concentrations with on-site and off-site gas chromatographic analyses of vapor samples from discrete depths and the wellhead. The measured vapor concentration is lowest near the bottom of the screen and increases slightly up to a depth of about 28 feet. As the instrumentation is raised higher in the well, the concentration increases sharply to a maximum and remains relatively steady into the soil gas production interval starting at 23 feet. The concentration then decreases steadily from 22 to 15 feet bgs. Between 15 feet and the top of the screen, the concentration increases very slightly.

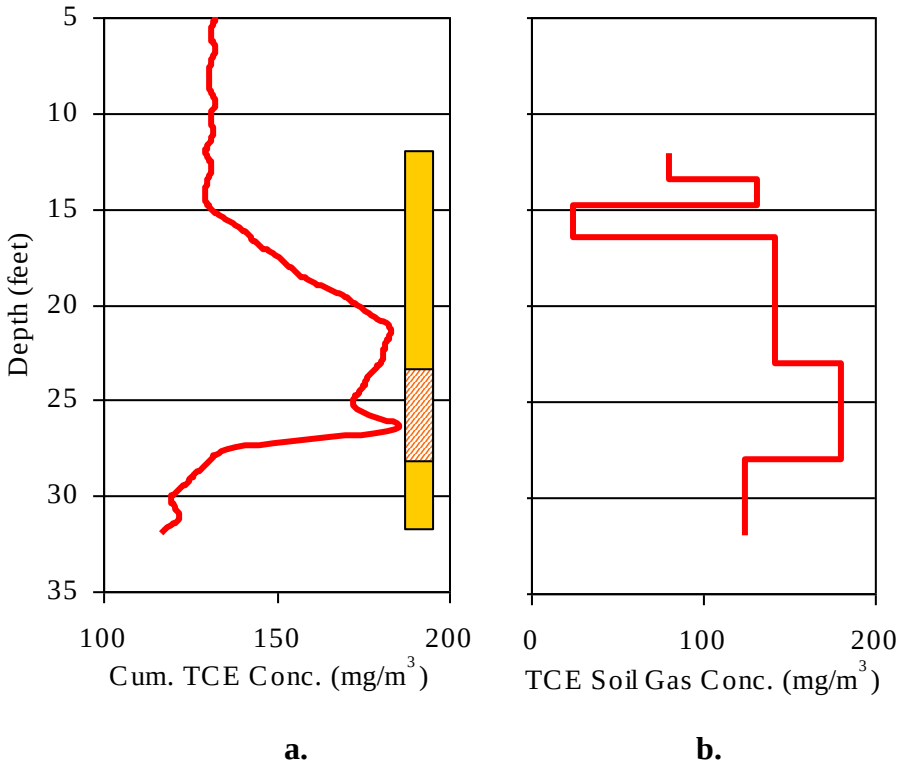


Figure 3. Sample Pneumatic Well Logging Results

The observed increases and decreases in concentration can be combined with the depth-specific air production in a mass balance to estimate depth-specific soil gas concentrations. The PneuLog® device simultaneously measures the flow rate and concentration versus depth. The change in the product of these two variables over a specified depth interval divided by the flow change is equal to the chemical vapor concentration in the soils of that depth interval. Application of this relationship to the data shown in Figures 2a and 3a yields the chemical vapor concentration profile presented in Figure 3b. The highest concentration occurs in the low permeability material underlying the deep sand interval. This high concentration indicates the low permeability interval creates a mass transfer constraint to SVE. Compounds must migrate slowly out of this interval into the flow interval above. The silt interval at 15 feet does not appear to be a barrier to chemical migration between the sands.

As illustrated by this example, pneumatic logging provides a more thorough and appropriate site characterization than traditional methods alone. Repeating the process in a representative number of wells can generate a three-dimensional description of the physical and chemical subsurface by correlating between locations. The technique also provides data to more effectively design and optimize an SVE system. Soil strata near or below cleanup goals are quickly identified and the extraction flow rate can be lowered or terminated from these layers. The operation can then be focused on strata remaining above cleanup goals. This optimization could lead to cost savings by accelerating cleanup and lowering operation & maintenance costs.

3. FIELD TASKS AND PROCEDURES

This section describes the field activities and procedures to collect data for site characterization and SVE design using PneuLog®. The activities adhere to the procedures and specifications contained in the project Field Sampling Plan (FSP) and Quality Assurance Project Plan (QAPP) prepared as separate documents. Site evaluation includes measurements of flow and vacuum in extraction and monitoring wells during pneumatic logging. Concentrations during the tests are monitored with a PID and two samples from each screen interval are collected and analyzed for VOCs. During the testing, vacuum responses are monitored in other available screens to aid in the calculation of permeabilities at the site. Vacuum responses depend on the soil properties and well spacing and may not be measurable in all monitored screen intervals.

The PneuLog® technique was described in detail in Section 2. During the pneumatic logging, a small flow of air is extracted through the Teflon® tubing attached to the flow instrument in the well. The total organic compound concentration in this air flow will be measured with a calibrated photoionization detector (PID) to yield the chemical concentration in soil gases extracted along the well screen depth. The pneumatic log will then be repeated and the instrument will be paused at a depth of major change in flow or concentration, generally at the maximum concentration. At this discrete depth, a sample of the soil gas may be collected in a canister or Tedlar® bag. A second canister or Tedlar® sample will be collected at the top of the well. Canisters will be packaged and shipped to a state-certified, off-site laboratory for analysis by GC/MS. The flow data from the pneumatic well log will immediately be analyzed to yield an air production profile along the well screen and the concentration log will be analyzed to indicate the intervals with the highest chemical concentrations. In wells with lower concentrations, a meaningful maximum concentration along the screen may not be identified. In these screens, a vapor sample will be collected from the bottom of the screen.

Any point or non-point discharge to air generally requires review and permission from the local air board. This includes any process that volatilizes materials from the ground (e.g., soil vapor extraction) or uses volatilization as a means of disposal for unwanted materials or constituents. The SVE aspect of this fieldwork will require the extraction of vaporous chemicals from the subsurface. The SVE discharge from each well will be treated with existing vapor abatement equipment on each site.

4. VAPOR SAMPLING AND ANALYSES

This section summarizes the procedures for collecting and analyzing vapor samples during the field tests. The equipment that will be used to collect vapor samples is also described. The sample locations, frequencies, and procedures presented are subject to change based on site-specific conditions.

Vapor concentrations will be monitored continuously during extraction periods with a calibrated PID as described in Section 3. Vapor samples will be collected in Summa® canisters for off-site analysis via method TO-14 (VOCs) or TO-15 (VOCs), and/or method TO-3 (total

volatile petroleum hydrocarbons) at a state-certified laboratory or in Tedlar bags for on-site analyses of VOCs using a modified EPA Method 18. Approximately 2 samples will be collected during the pneumatic log of each screen in each well location. Samples will be collected through the pneumatic logging instrumentation and will provide depth-specific concentrations from inside the extraction wells. One sample will be collected from above the screen interval and one sample from the depth in the screen yielding the highest concentration or the bottom.

Depth-specific samples will be drawn by a small, oilless diaphragm pump through a Teflon® tube attached to the flow instrumentation for pneumatic logging. The vapor sample will be monitored by a PID on the surface and collected near the discharge of the Teflon® tube in a stainless steel SUMMA® canister or Tedlar® bag. The majority of samples collected in Tedlar bags will be analyzed on-site with a portable GC. Canisters will also be used to directly collect vapor samples at the wellhead to validate on-site analyses. The canisters will be submitted for offsite chemical analysis. Samples will be collected following the guidance offered in EPA's *"Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*," EPA 4-84-041-April 1984. The specific methods to be used are TO-14, "Determination of Volatile Organic Compounds (VOCs) in Ambient Air Using SUMMA Passivated Canister Sampling and Gas Chromatography Analysis" or TO-15 and/or TO-3 for total volatile petroleum hydrocarbons. The canisters will be used and samples collected in the vacuum mode. The vacuum in the clean canister (near 30 inches Hg) will be sufficient to pull the sample out of the gas line. A slow flow rate into the canister will be controlled manually by slightly cracking open its valve. The rate is checked by monitoring the canister vacuum gauge and comparing the value to the elapsed time and the wellhead vacuum. The final canister vacuum will be approximately equal to the vacuum in the vapor extraction line. The final vacuum will be recorded on the chain-of-custody and then measured at the laboratory after shipment and before analysis. The two recorded vacuums will be approximately equal if the canister has not leaked. Each canister will be cleaned in the laboratory before delivery.

The purpose of a field quality control program is to provide a measure of data quality. QA samples to be collected include field duplicates, equipment blanks, trip blanks, ambient condition blanks, and material for matrix spike/matrix spike duplicate (MS/MSD) analyses. Collection of the QA samples during the project is described in the project Work Plan. A summary of the quality control sampling for vapor sampling during PneuLog® is provided in Table 1. The sample handling, preservation and shipment procedures are described in the Work Plan along with sample custody and decontamination procedures.

TABLE 1
QUALITY CONTROL SAMPLES

Sample Matrix		Number of Samples

Analysis	Analysis Level	Primary	Duplicate	Ambient Blank	Trip Blank	Equipment Blank	Matrix Spike /MSD	Total
Soil Vapor								
VOCs (Offsite TO-14)	III	TBD[1]	1 per 10	0	0	0	0	TBD[1]
VOCs (Offsite TO-15)	III	TBD[1]	1 per 10	0	0	0	0	TBD[1]
VOCs (Onsite TO-18)	I	2 per well	1 per 10	1 per 10	0	1 per 10	0	13 per 5 wells
TVPH (Offsite TO-3)	III	TBD[1]	1 per 10	0	0	0	0	TBD[1]

[1] TBD = To Be Determined

5. DATA MANAGEMENT

The data to be collected during PneuLog® include:

- Soil vapor concentrations,
- Extraction air flowrates,
- Wellhead vacuums,
- Vertical air flow profiles, and
- Vertical concentration profiles.

These data can be used to define the vertical and horizontal extent of chemicals at the various sites if a sufficient number of representative wells are logged. The data will also yield the disposition of the chemicals (e.g., found primarily in low permeability soil, found near the groundwater, suspected non-aqueous phase liquid present, etc.). The pneumatic logging data, combined with historical data can provide information on optimal SVE system operation and possibly the optimal locations for new SVE wells.

A general chronicle of field activities and personnel on site will be recorded daily. The following information shall be recorded for all field activities: (1) location, (2) date and time, and (3) identity of people performing activity. The information shall be recorded in a field notebook or on data logging sheets. These records shall be archived in an easily accessible form and made available to the Air Force upon request.

The collection of soil vapor samples will be documented in a field notebook or on appropriate data logging sheets. These records shall be archived in an easily accessible form and made available to the Air Force or its contractors upon request. The following additional information shall be recorded for all sampling activities: (1) sample type and sampling method, (2) the identity of each sample including location and depth(s), where applicable, from which it was collected, (3) the date and time of collection, (4) the amount of each sample or sample container volume, (5) sample description (e.g., color, odor, clarity), and (6) identification of

conditions that might affect the representativeness of a sample (e.g., refueling operations, damaged casing).

Field measurements will be recorded on data sheets specific to each measurement (e.g., air flow rates and wellhead vacuums). For each field instrument the following shall also be recorded: (1) the numerical value and units of each measurement, and (2) calibration results

6. HEALTH AND SAFETY

The health and safety plan for the fieldwork is prepared separately and is adhered to during all field activities.

7. MANAGEMENT AND STAFFING

Key staff from PRAXIS assigned to the project are shown in Table 2 with their responsibilities. Team members include:

Ms. Mary Scarpetti is the President of PRAXIS. She is responsible for the administrative, contractual and fiscal aspects of all PRAXIS projects. All significant changes in scope or cost must have her approval. Ms. Scarpetti received her law degree from the University of San Francisco in 1990 and is a member of the California Bar Association. Ms. Scarpetti has seven years of experience in the operations and financing of small firms and, in particular, government contracting and accounting. She worked in the securities industry prior to law school.

Dr. Lloyd "Bo" Stewart is the Principal Engineer for the pneumatic well logging and a Vice President of PRAXIS. Dr. Stewart has ten years of experience overseeing the development and implementation of innovative technologies for the remediation and characterization of hazardous waste sites. Dr. Stewart also develops and implements computer models for risk assessments and cleanup actions. Remedial technologies under development at Praxis include steam injection combined with vacuum extraction, dual-phase extraction, and hydraulic fracturing. Dr. Stewart received his Ph.D. in Mechanical Engineering from the University of California Berkeley in 1989.

Mr. Mike Chendorain in the Soil Hydrologist for the subsurface investigation, data analysis, and modeling. Mr. Chendorain received an MS in Soil and Environmental Sciences from the University of California at Riverside. He received a BS in Environmental Sciences from Virginia Institute of Technology. He has three years of experience in modeling the fate and transport of chemicals in the subsurface. While working on his MS, he also worked as a teaching assistant and as a research assistant.

Table 2 PRAXIS Project Team Members	
Responsibility	**Team Member**
Program Manager / Contracts	Mary Scarpetti
Project Manager / Principal Engineer	Bo Stewart
Subsurface Modeling/Data Analysis	Mike Chendorain
Equipment Installation & Maintenance	Steven Scarpetti

8. REFERENCES

Molz, F.J., R. H. Morin, A. E. Hess, J. G. Melville, and O. Guven, 1989, "The Impeller Meter for Measuring Aquifer Permeability Variations: Evaluation and Comparison with Other Tests," *Water Resources Research*, Vol. 25, No. 7, pp. 1677-1683.