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Passive Soil Venting at the Chemical Waste Landfill Site at Sandia National Laboratories, Albuquerque, New Mexico

J. M. Phelan, B. Reavis, W. C. Cheng

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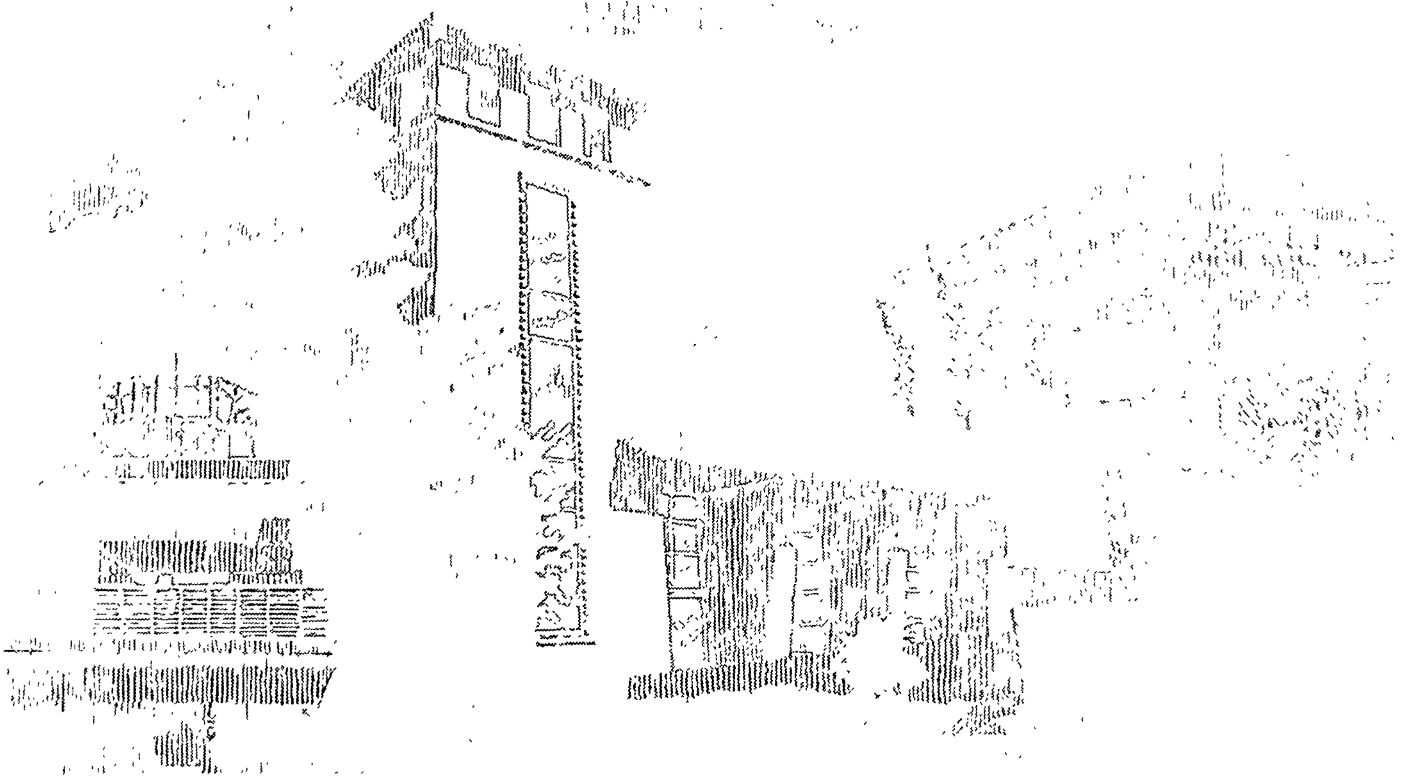

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Passive Soil Venting at the Chemical Waste Landfill Site at Sandia National Laboratories, Albuquerque, New Mexico

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ABSTRACT

Passive Soil Vapor Extraction was tested at the Chemical Waste Landfill (CWL) site at Sandia National Laboratories, New Mexico (SNL/NM). Data collected included ambient pressures, differential pressures between soil gas and ambient air, gas flow rates into and out of the soil and concentrations of volatile organic compounds (VOCs) in vented soil gas. From the differential pressure and flow rate data, estimates of permeability were arrived at and compared with estimates from other studies. Flow, differential pressure, and ambient pressure data were collected for nearly 30 days. VOC data were collected for two six-hour periods during this time. Total VOC emissions were calculated and found to be under the limit set by the Resource Conservation and Recovery Act (RCRA).

Although a complete process evaluation is not possible with the data gathered, some of the necessary information for designing a passive venting process was determined and the important parameters for designing the process were indicated.

More study is required to evaluate long-term VOC removal using passive venting and to establish total remediation costs when passive venting is used as a polishing process following active soil vapor extraction.

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ABBREVIATIONS AND NOMENCLATURE

OSHA - Occupational Safety and Health Administration

PEL - permissible exposure limit

PVC - polyvinyl chloride

SEAMIST - Science and Engineering Associates Membrane Instrumentation

TEVES - Thermal Enhanced Vapor Extraction System

D - inside pipe diameter

E - energy loss due to friction

f - friction factor for fluid flow, a function of Reynold's number

g - gravitational acceleration - 9.8 m/s^2

k - air permeability

P - absolute pressure

Q - volumetric air flow

R - Gas Constant = 0.0821 L- atm/g-mole-K

S - Cross-sectional area for fluid flow, S_a for upstream, S_b for downstream of a constriction or expansion

V - velocity

Z - height

ΔL - length of the pipe

ΔP_{trand} - pressure difference across the transducer

μ – gas viscosity

ρ - air density

1.0 INTRODUCTION

Barometric pumping, or passive soil vapor extraction, refers to the inhaling of ambient air into the vadose zone and the exhaling of soil gas from the vadose zone to ambient air upon diurnal and climate-induced atmospheric pressure differences between ambient air and soil gas. Passive soil vapor extraction has been proposed as a complementary technology to active vapor extraction (AVE) in which either vacuum or pressure is applied to vadose zones to remove volatile organic compounds (VOCs) from contaminated soils. The simplicity of the technology and the low costs make passive vapor extraction an attractive polishing step when cleanup by AVE reaches diffusion limitations.

At the chemical waste landfill (CWL) site at Sandia National Laboratories in Albuquerque, New Mexico (SNL/NM), various VOCs have been detected in the soil gas. This study was conducted to provide quantitative data on ambient pressure and differential pressure cycles, gas flow rates, and VOC concentrations in vented soil gas. From the differential pressure and flow rate data, estimates of permeability were compared with estimates from other studies. Although the data are incomplete for estimating process performance, some of the necessary information for designing a passive venting process was determined, and some of the important parameters for designing the process are indicated.

2.0 BAROMETRIC PUMPING TECHNOLOGY

Wells with openings in unsaturated soil have been observed to "breath"—that is, inhale ambient air and exhale soil gas. The driving force for air and gas flow results from the difference between the barometric pressure and soil gas pressure are illustrated in Figure 1. Resistance to flow is offered primarily by the soil matrix and the well inlet. Thus, with variations in barometric pressure due to diurnal as well as climatological changes, the net effect is alternating inflow and outflow (venting) at the well. Delays and damping of the response are possible.

Figure 2 illustrates a configuration for the purpose of analyzing the flow. The steady-state mechanical energy balance for flow without mechanical work and heat addition is:

$$\frac{P_2}{\rho} + Z_2 g + \frac{1}{2}V_2^2 = \frac{P_1}{\rho} + Z_1 g + \frac{1}{2}V_1^2 + E \qquad (1)$$

where E is the energy loss due to friction per unit mass of air or soil gas. A sample calculation in Appendix A indicates that the maximum velocity head changes are in the order of 3.4% of the average observed pressure difference. Therefore, for first-order estimates, the mechanical energy equation for this application is reduced to:

$$\frac{P_2}{\rho} + Z_2 g = \frac{P_1}{\rho} + Z_1 g + E \quad . \qquad (2)$$

For more accurate calculations, one can use $V_1=0$ and V_2 from observed values. The datum can be set so that $Z_1 = 0$. P_2 is the absolute pressure at the surface or P_{atm}. P_1 can be measured with a differential pressure transducer located at the surface with one side of the diaphragm in contact with atmospheric pressure and the other side in contact with soil gas at a capped well as shown in Figure 2. The relationship is:

$$P_1 = P_{atm} + \Delta P_{transd} + \rho g \Delta Z \qquad (3)$$

where ΔP_{transd} is the differential pressure across the transducer, P_{inside}-P_{atm} and ΔZ is the height difference between the transducer and the well inlet, that is Z_2-Z_1. With the substitution for ΔZ into Equation 3 and substitution of Equation 3 into Equation 2, the result is:

$$E = -\frac{\Delta P_{transd}}{\rho} \qquad (4)$$

(details of the derivation are given in Appendix B). Therefore, by measuring the differential pressure at a capped well, one can measure the driving force for flow of soil vapor from the soil matrix under the capped well out to the breathing well and from the breathing well to the soil matrix.

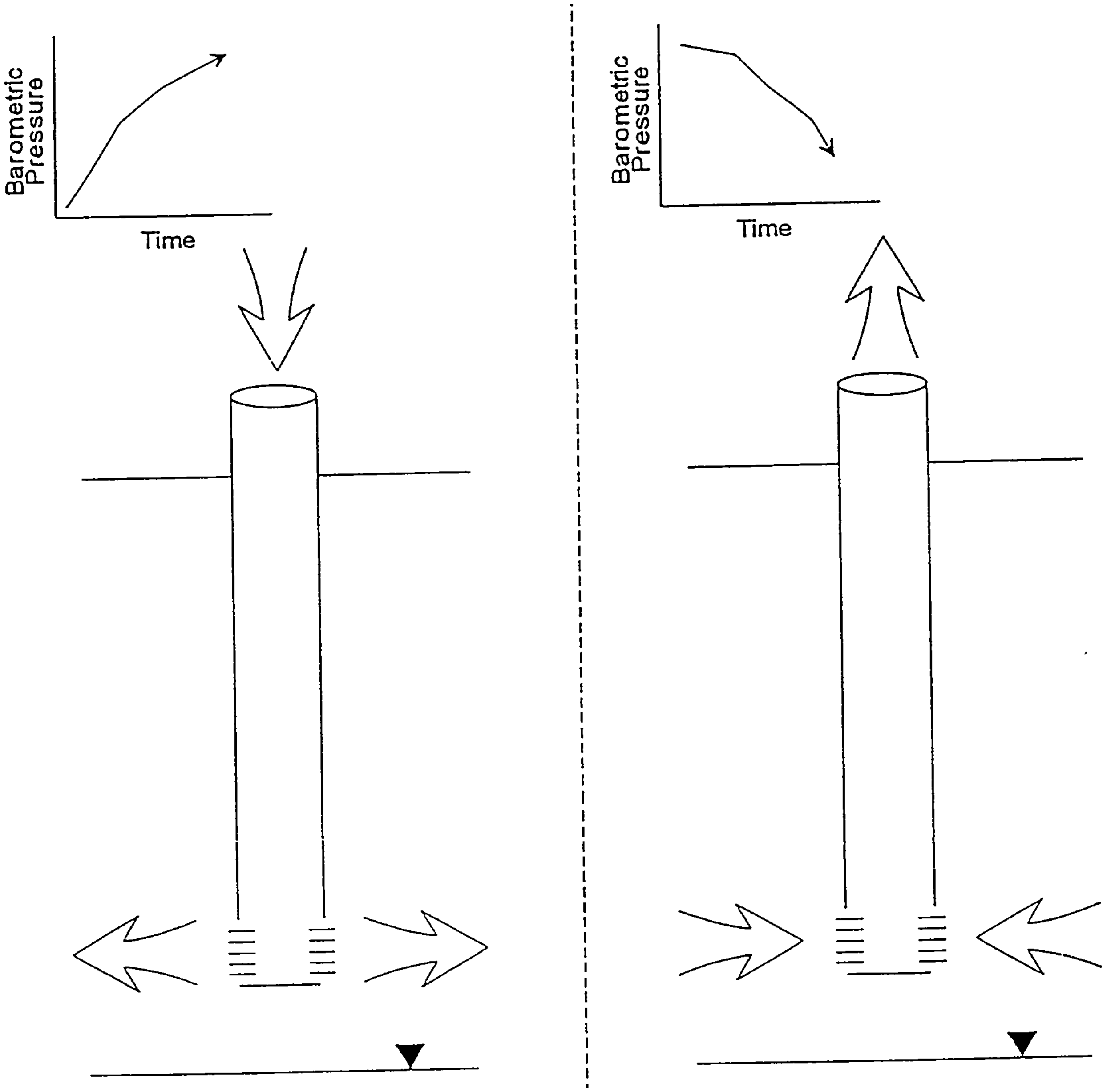


Figure 1. Passive venting cycle.

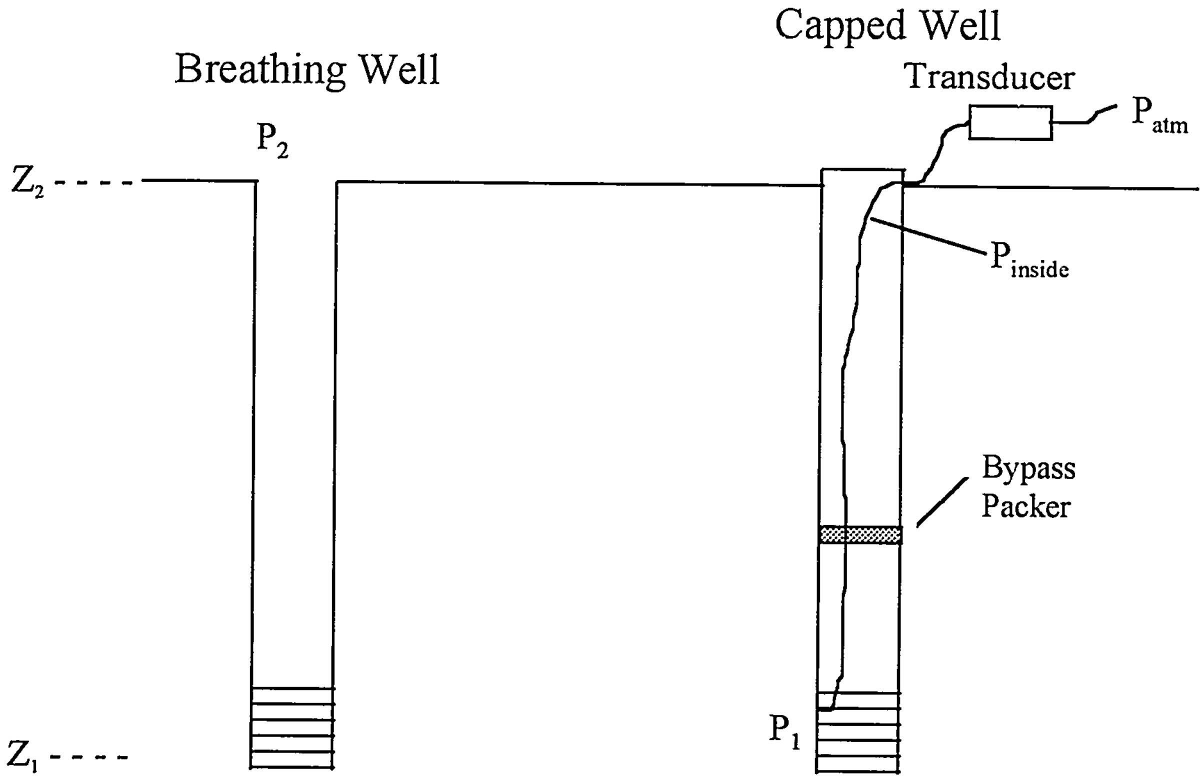


Figure 2. Diagram of locations of pressure and height measurements.

3.0 MEASUREMENT SYSTEM

The measurements taken for the study included ambient pressure, differential pressure, air flow, and concentrations of specific organic compounds in the exiting gas. A data logger was used to collect values of the measured parameters. Table 1 gives the instruments used for each parameter.

Table 1. Instrumentation

Parameter	Instrument	Vendor/Model	Range
Differential Press.	Diaphragm Press. Transd.	Setra 264100-24	±5 mbar
Absolute Pressure	Diaphragm Press. Transd.	Visala PTA427A	500 to 1100 mbar
Power Supply	-----	Omega PST-4130	4 to 15 Vac
Air Velocity	Thermal Anenometer	TSI 8470-52E-V	±500 fpm
Organic Gases	Gas Chromatograph	Analysis by ENCOTEC	-----
Press. and Flow	Data Logger	Campbell Sci. 21X	8 channel

4.0 SITE, CONFIGURATION, AND PROCEDURE

4.1 Site and Configuration

Field data were collected from existing wells used for the Thermal Enhanced Vapor Extraction System (TEVES), designated as TEVES1 and TEVES2 boreholes. Figure 3 is a photograph of the CWL where the boreholes were located. It shows the breathing well (distant) and the capped well (near). The photo shows the Science and Engineering Associates Membrane Instrumentation and Sampling Technique (SEAMIST) apparatus being inserted into the far well; the SEAMIST tool was used to measure soil permeability in 1993. Figure 4 illustrates the components of the apparatus for the passive venting tests. Well construction diagrams are provided in Figures 5 and 6. The TEVES wells are screened from 3 to about 50 ft and from 55 to 130 ft (TEVES1) and from 55 to 80 ft (TEVES2). Both wells are connected with 4-in. pipe. At about 40 ft in depth, there is a soil horizon that has small permeability in contrast to layers above and below. This layer may limit the propagation of changes in the surface atmospheric pressure and allow greater pressure differentials, and thus greater air flow rates.

A 2-in. polyvinyl chloride (PVC) well insert was used with a flexible annular seal material (neoprene) in TEVES1 down to the blank section at the 50 to 55 ft depth. The 2-in. well insert was used to measure flow rates into and out of the well. A bypass packer was placed into TEVES2 at the location of the blank section. Thus, the active venting region was from 55 to 130 ft. A pressure monitoring point was located below the packer in TEVES 2. Surface atmospheric pressure was measured with an absolute pressure transducer.

4.2 Procedure

Air flow rates were measured with a thermal anenometer mounted into a riser pipe attached to the top of TEVES1. This method did not provide a directional response; therefore, the pressure differential was used to determine the flow direction.

Pressure and flow rates were measured every 15 minutes with data captured on a Campbell-Scientific data logger. The instrumentation array was installed for four weeks of data collection. Air flow data were collected starting 4/1/94 using a 2-in. PVC pipe inserted into and sealed against the 4-in. copper pipe of TEVES1. On 4/11/94, a 3-in. PVC pipe was substituted in TEVES1 to lower the velocity because it was discovered that the thermal anenometer readings were off scale with the 2-in. pipe.

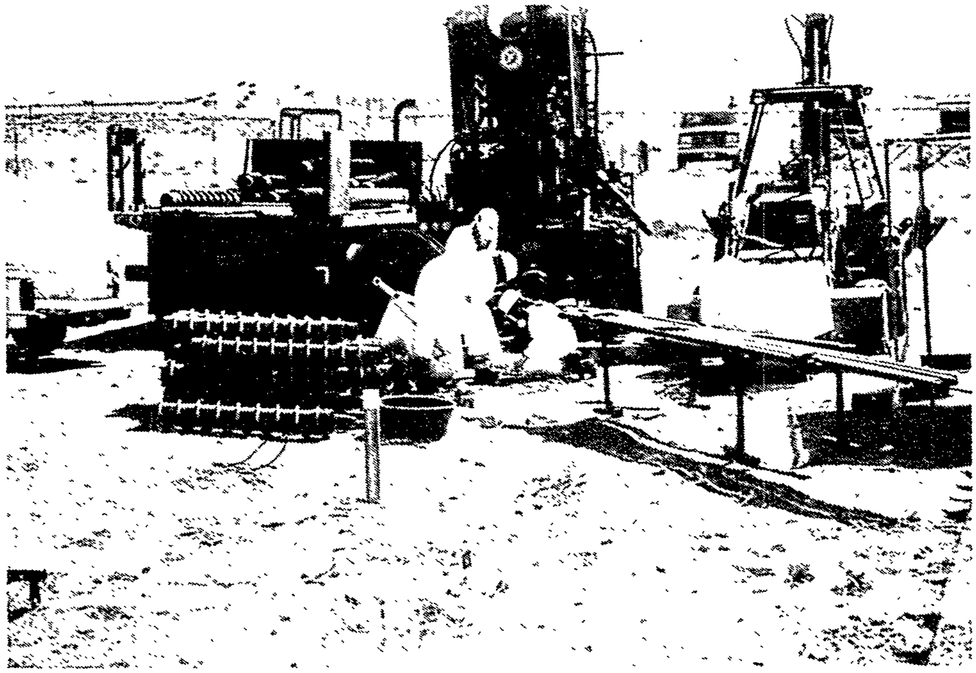


Figure 3. Chemical waste landfill site with TEVES1 and TEVES2 wells.

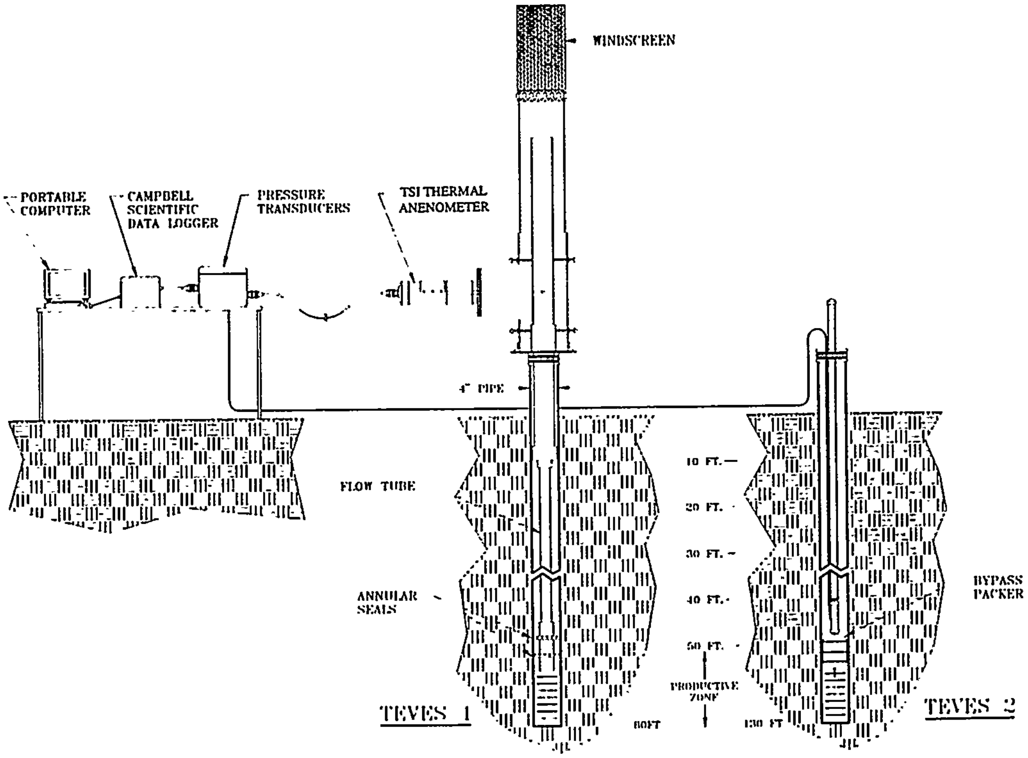
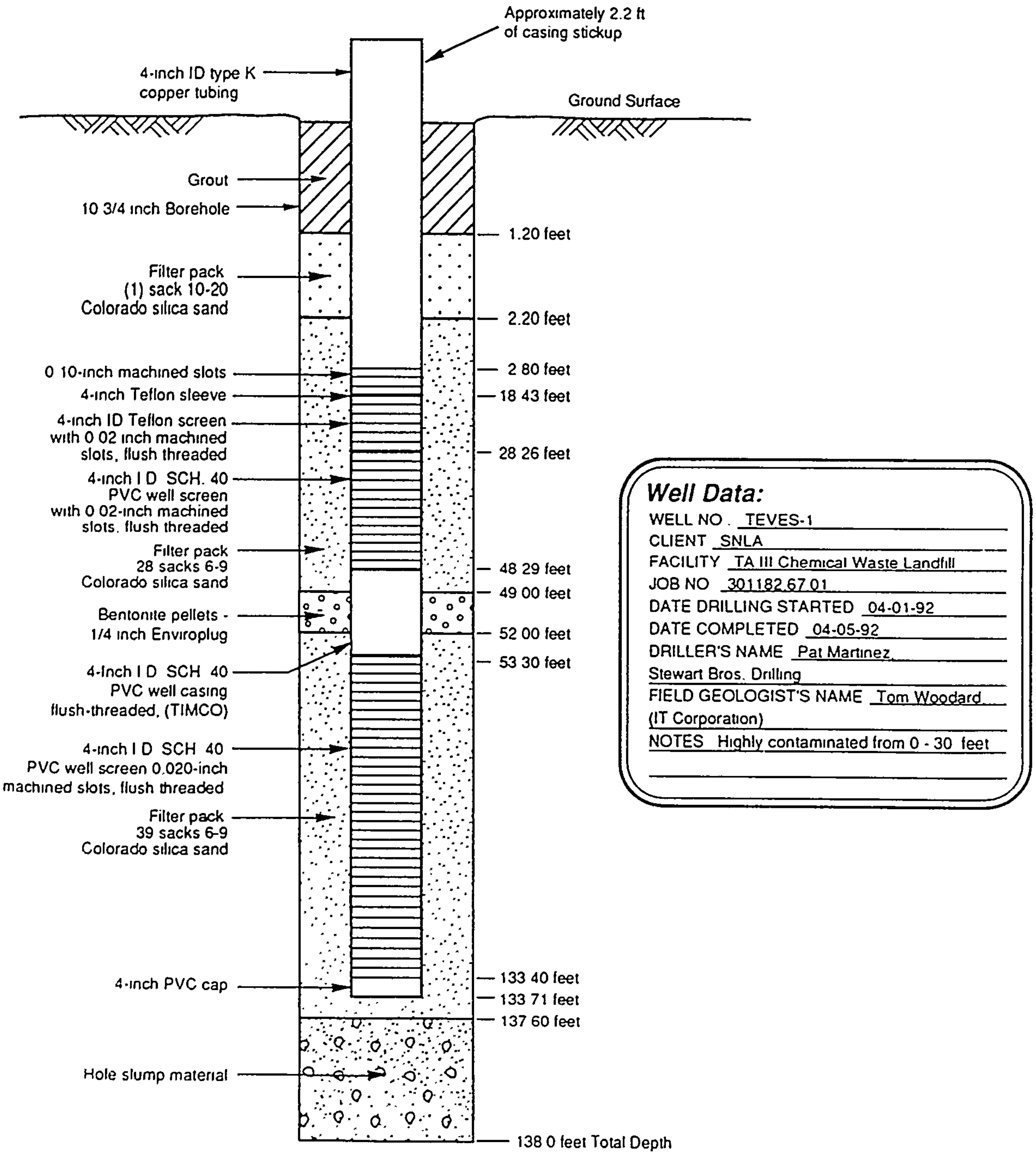


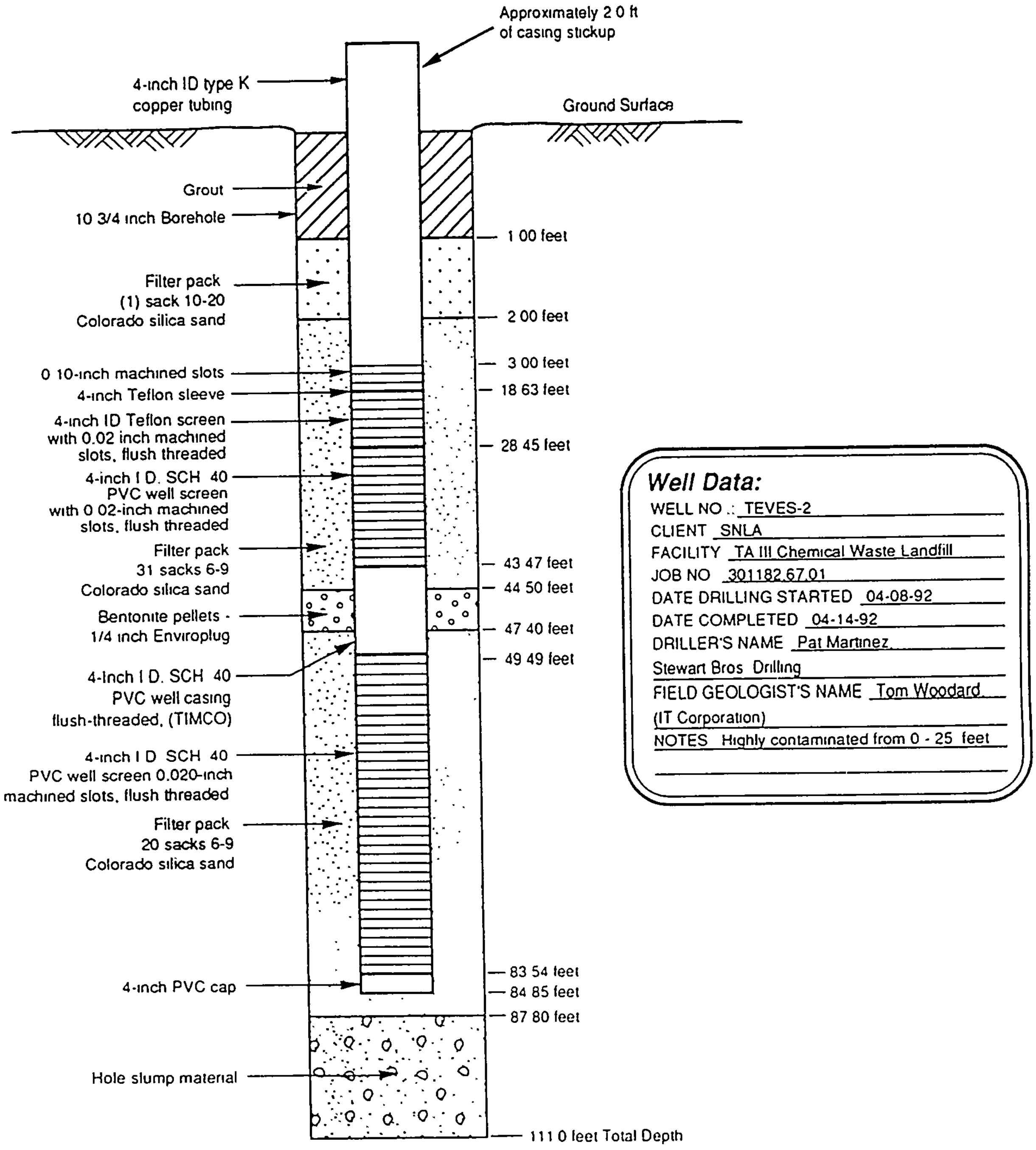
Figure 4. TEVES1 and TEVES2 wells and instrumentation.



Well Data:

WELL NO . TEVES-1
CLIENT SNLA
FACILITY TA III Chemical Waste Landfill
JOB NO 301182.67.01
DATE DRILLING STARTED 04-01-92
DATE COMPLETED 04-05-92
DRILLER'S NAME Pat Martinez,
Stewart Bros. Drilling
FIELD GEOLOGIST'S NAME Tom Woodard
(IT Corporation)
NOTES Highly contaminated from 0 - 30 feet

Figure 5. Well construction schematic, TEVES1.



Well Data:

WELL NO .: TEVES-2
CLIENT SNLA
FACILITY TA III Chemical Waste Landfill
JOB NO 301182.67.01
DATE DRILLING STARTED 04-08-92
DATE COMPLETED 04-14-92
DRILLER'S NAME Pat Martinez
Stewart Bros Drilling
FIELD GEOLOGIST'S NAME Tom Woodard
(IT Corporation)
NOTES Highly contaminated from 0 - 25 feet

Figure 6. Well construction schematic, TEVES2.

The differential subsurface and absolute surface pressures were plotted versus time to evaluate the magnitude of the pressure front at depth and to determine if there was any significant time lag in the appearance of surface pressure changes. The differential pressure of the subsurface and surface pressure was plotted with flow rate versus time to map the direction of flow rate and sign of the pressure difference.

Air samples were collected in SUMMA canisters at TEVES1 during a venting cycle to determine if contaminant concentrations stayed constant or were depleted during the cycle. Three samples were collected, roughly two hours apart. Then TEVES1, the flow well, was capped for about four days before the second set of three samples (again about two hours apart) were collected. All samples were analyzed by ENCOTEC, using EPA Method TO-14 (US EPA, 1988).

5.0 RESULTS AND DISCUSSION

5.1 Ambient Pressure

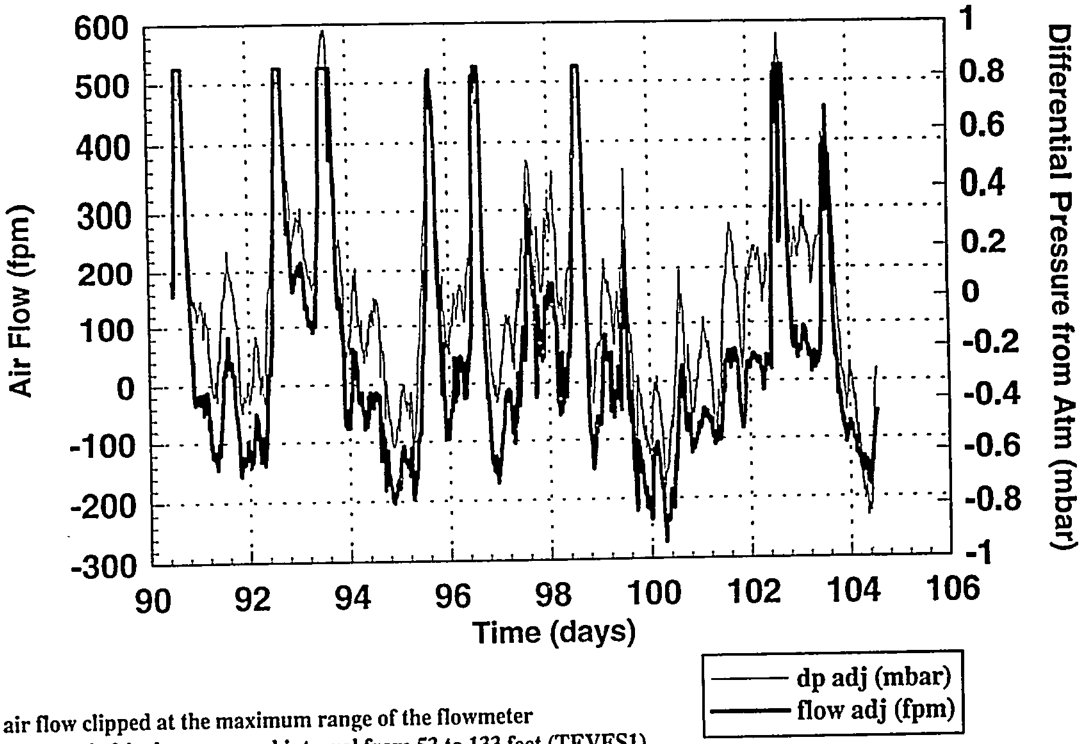
Diurnal pressure changes are in the order of 5 to 10 mbar in Albuquerque as previously determined by Phelan (1993). There is about a three-hour lag between the time of lowest temperature and the time of highest pressure. At lower temperatures, the density of the air is greater and thus the pressure is greater. There is also a three-hour lag between the time of highest temperature and lowest pressure. Thus, the highest and lowest atmospheric pressures occur between 8 and 9 am and between 5 and 6 pm, respectively. Ambient pressure changes larger than 10 mbar can then be considered to be pressure fronts induced by weather systems. Figure 7 shows the variation of atmospheric pressure and differential pressure between the TEVES2 well and ambient pressure in the period of day 90 through day 106 (calendar days).

5.2 Flows and Differential Pressures

From calendar day 90 to calendar day 100, TEVES1 (the flow well) was fitted with a 2-in. pipe. It was found that the maximum velocity measurement possible using the thermal anenometer, 500 fpm, was exceeded when the 2-in pipe was used. Therefore, on day 100, TEVES1 was fitted with a 3-in. pipe for velocity and flow measurement. Figure 8 shows a plot of volumetric air flow rate and differential pressure. The air velocity and air flow rate plots parallel the differential pressure plots, indicating no delays in flow response to the presence of a differential pressure.

Figure 9 shows a plot of differential pressure versus flow for the period in which the 3-in. pipe outlet was used. Taken as a whole, the plot is non-linear, indicating that something other than darcy flow is occurring. Calculations of pressure drops at the screen and through the well piping, as shown in Table 2 and detailed in Appendix C, indicate that these are significant, especially at the higher flow rates. It is therefore counter-intuitive that Figure 9 should show a higher slope for larger differential pressures than for smaller differential pressures.

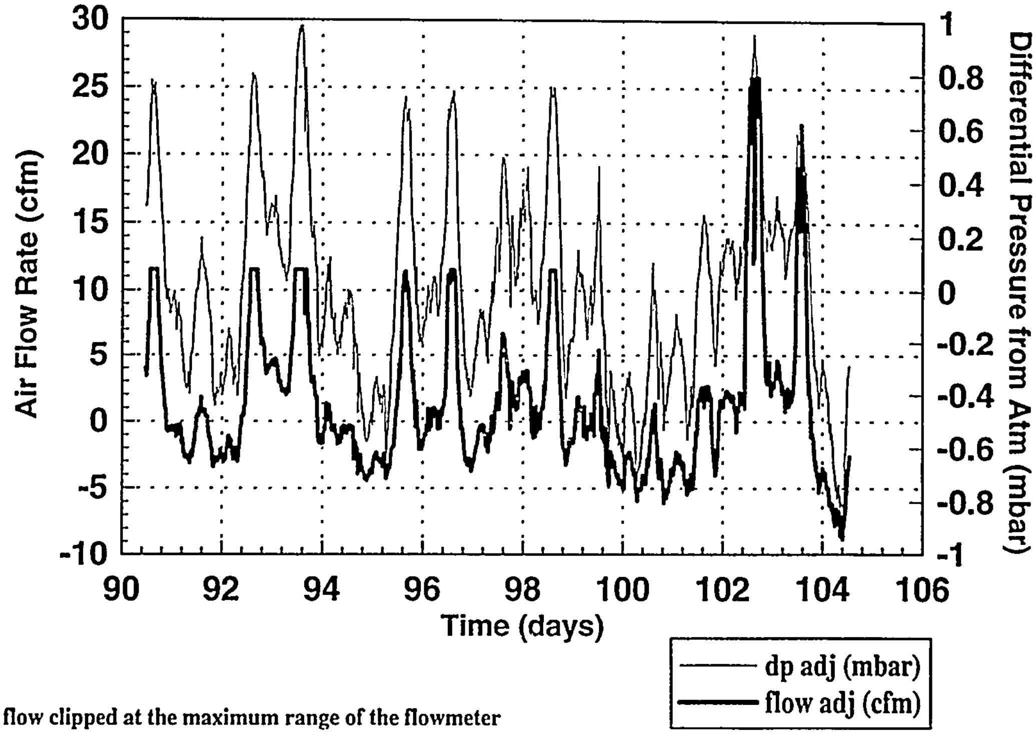
From another perspective, the plot can be seen as two linear sections: one for flow into the well at the negative air flows, and one for flow out of the well at the positive flows. The difference in the two slopes would then indicate two different apparent permeabilities for inflow and outflow. Because the permeabilities vary with depth at the site, one possible explanation would be a different path taken for inflow versus for outflow. However, there does not appear to be a reason for a different flow path.



Notes:

1) Maximum air flow clipped at the maximum range of the flowmeter
2) Flow pipe diameter is 2 inches, screened interval from 53 to 133 feet (TEVES1)
3) Differential pressure measured at 50 to 83 feet (TEVES2)

Figure 7. Variation of atmospheric and differential pressure between the TEVES2 well and ambient pressure.



Notes:

1) Maximum air flow clipped at the maximum range of the flowmeter
2) Flow pipe diameter is 2 inches, screened interval from 53 to 133 feet (TEVES1)
3) Differential pressure measured at 50 to 83 feet (TEVES2)

Figure 8. Plot of volumetric air flow rate and differential pressure.

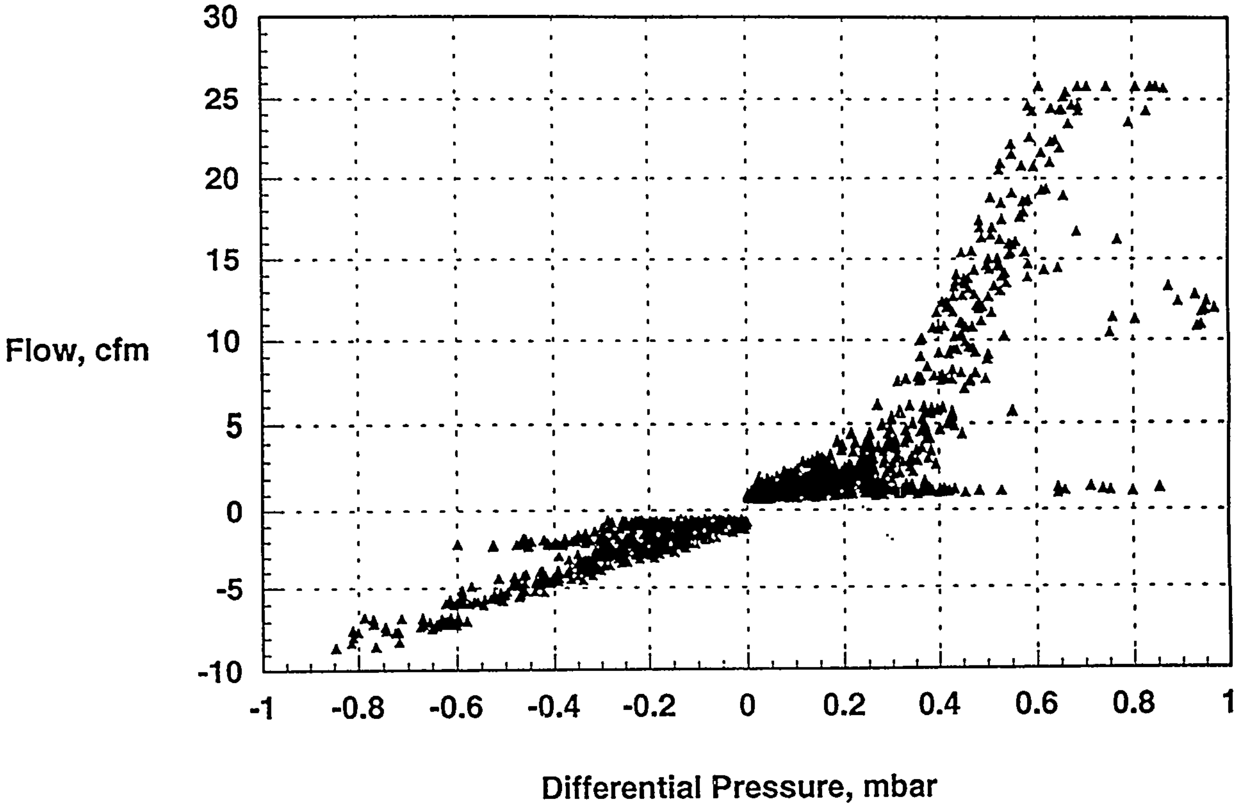


Figure 9. Differential pressure versus flow.

Table 2. Contributions to Pressure Drop at Various Flows

Component	5 cfm	10 cfm	15 cfm	20 cfm	25 cfm
Screen/Packing	5.8	9.3	11.9	14.6	15.5
4" Pipe (80 ft)	1.2	4.9	7.2	11.0	13.6
3" Pipe (50 ft)	3.4	10.3	17.8	26.9	33.8
4" to 3" reduct.	0.1	0.2	0.4	0.1	0.1
Velocity Head	0.3	0.4	0.8	1.3	1.8
Soil Matrix (by Difference)	89.2	74.8	61.9	46.1	35.2
Total ΔP (mbar)	0.32	0.40	0.47	0.51	0.60

Note: Numbers are Percentages of Differential Pressure

From a previous study by Phelan (1993), soil permeabilities were determined at the same site using the SEAMIST tool, which allowed for the measurement of pressure and flow at different depths in the well. Using three flow models, the permeability was determined. The first model is the one-dimensional spherical steady-state gas flow model; the relationship between flow and pressure drop is:

$$k = \frac{Q\mu P_2}{2\pi(P_2^2 - P_1^2)r_2} \qquad (5)$$

where k is air permeability

r_2 is the borehole radius

P_1 is pressure at the source location

P_2 is pressure at the sink location

μ is air viscosity

and Q is volumetric flow.

Phelan (1993) found that permeabilities varied about an order of magnitude with depth of the soil, from 5 to 63 darcies. When pressure and flow data gathered in the present study are used to calculate permeability using the radial model, the results are in the range of 400 to 1700 darcies as detailed in Appendix D. These values are significantly higher than those previously determined by Phelan (1993) using the SEAMIST tool with the spherical flow model.

Using the second flow model—the one-dimensional cylindrical steady-state gas flow model—the flow versus pressure relationship is

$$k = \frac{QP_2\mu \ln(r_w / r_i)}{\pi L(P_2^2 - P_1^2)} \tag{6}$$

where L is the length of the withdrawal zone

r_i is the radius of influence

r_w is the radius of the collector well

P_2 is the pressure at the collector well

P_1 is the pressure at the source

and Q is the flow.

Permeability data from Phelan (1993) for wells located near TEVES1 and TEVES2 show values from 8 to 400 darcies using this model. With this model, an estimate must be made for r_i, the radius of influence. Since r_i appears in a logarithmic function, the model is not very sensitive to the estimate.

From the differential pressure and flow data of this study, one can estimate a permeability using the cylindrical model. As detailed in Appendix D, an estimated value for permeability is about 10 to 30 darcies, assuming various values for radius of influence and losses not due to flow through the soil. These values are near the low end of the values determined previously by Phelan (1993). Table 3 shows a summary of permeability variations determined from the SEAMIST tool and values determined from the present study for comparison.

Table 3. Comparison of Values for Permeability of Soil Matrix Values in Darcies

	SEAMIST Tool	Present Study
Spherical Model	5 to 63	400 to 1700
Cylindrical Model	8 to 400	10 to 30

5.3 Cumulative Flows

Figure 10 shows the measured cumulative flows into and out of the TEVES1 well. The cumulative flows into the well are significantly lower than the cumulative flows out of the well. The plot is not surprising because it is derived from the same data as Figure 9, which shows larger flows for exhalation than for inhalation. Because for a mass balance to be maintained in the soil, there must be flow into the soil that is not accounted for by the measurement. This could be

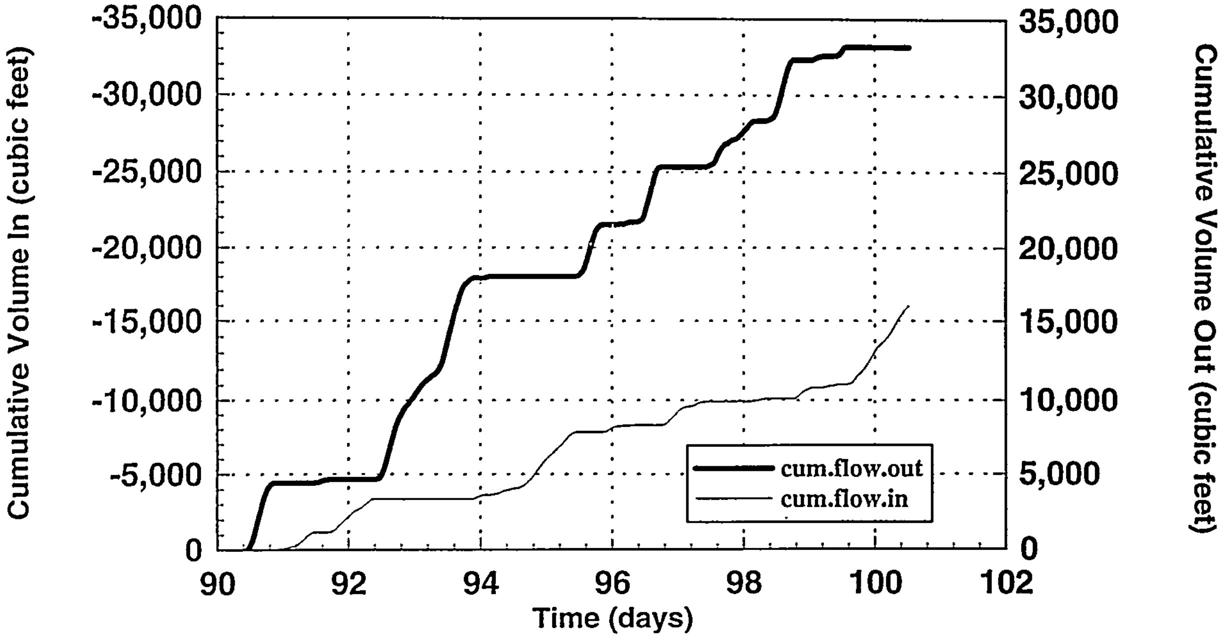


Figure 10. Cumulative flows in and out of TEVES1 well.

accounted for by flow via another path. However, it is not clear why the vapor flow for such a leak would be directional in nature.

5.4 Factors Considered Non-Critical to Flow and Permeability Determinations

The Klinkenberg Effect, or slip flow of vapor at low pressure when the mean free path is the same order of magnitude as the pore diameter, is not in effect in the flows of this study. The calculation, based on the relationship between the mean free path and ideal gas viscosity, which are tabulated values, is:

$$\lambda = \frac{3\mu}{\rho}\sqrt{\frac{\pi m}{8kT}}$$

where λ is mean free path
μ is viscosity
ρ is density
m is the mass of a molecule
k is Boltzman's constant
T is temperature

(Bird, Steward, Lightfoot. *Transport Phenomena.* 1960 John Wiley and Sons, Inc. p. 21).

The calculation, shown in Appendix G, indicates that the mean free path is in the order of 3×10^{-6} µm. Sand particle sizes are in the order of a few to hundreds of µm. Therefore, the Klinkenberg Effect is not considered to be applicable.

Temperature changes are not considered to greatly affect flow velocity because the largest temperature change is in the order of about 30° Fahrenheit or Rankin, whereas absolute temperatures must be greater than 460° Rankin. Therefore, the order of flow velocity changes due to temperature changes is only 30/460 or 6.5% at most.

5.5 VOC Concentrations

Vapor samples were collected in 5-liter SUMMA canisters on two days: 4/28/94 and 5/4/94. On each day, three samples were collected, at roughly 2-hour intervals during an outflow cycle. On 4/28, samples were collected when the gas velocity was 50 to 150 fpm. Between 4/28 and 5/4, the TEVES1 (the flow well) was capped. On 5/4, the samples were collected when the gas velocity was 25 to 50 fpm. Table 4 shows a summary of the VOC analyses for the six samples. Only the species that had above detectable concentrations are listed in the table. Other analyzed species, all below detectable levels in the six samples, are listed in Table 5. The results indicate a general increase in VOC concentrations with time for all the components measured on

4/28 and only slight increases for 5/4. Figures 11 and 12 show the trend for five selected species. Concentrations are about three times as high for the 5/4 samples as for the 4/28 samples because during the five days when the well was capped, larger quantities of VOCs could vaporize from the liquid state without mixing with circulating air.

Table 4. VOC Measurements

			Concentrations in ppmv					
	Detectable	Sample No.	15831	15832	15833	15834	15835	15836
	Limits	Sample Date	4/28/94	4/28/94	4/28/94	5/4/94	5/4/94	5/4/95
Compound	ppmv	Sample Time	14:20	17:00	19:30	14:35	16:55	17:35
Benzene	0.1		U	0.22	0.41	0.70	0.82	1.00
Carbon Tetrachloride	0.1		U	U	U	0.12	0.12	0.13
Chloroform	0.1		U	0.22	0.4	0.95	0.96	1.00
Chloromethane	0.1		U	0.15	0.31	1.70	1.10	1.40
1,1 Dichloroethene	0.1		0.12	U	U	U	U	U
Dichloro,difluoromethane	0.1		U	0.14	0.29	0.60	0.65	0.77
1,1 Dichloroethane	0.1		U	U	0.13	0.31	0.30	0.35
1,2 Dichloroethane	0.1		U	U	0.17	0.44	0.45	0.56
1,1 Dichloroethene	0.1		U	1.00	2.20	4.20	5.00	6.30
1,2 Dichloropropane	0.1		U	0.25	0.46	1.00	1.10	1.40
Methylene Chloride	0.1		0.12	1.00	2.00	2.90	3.70	4.20
Tetrachloroethene	0.1		0.24	1.20	1.85	5.1 S	5.5 S	5.0 S
Toluene	0.1		U	0.29	0.63	0.25	0.71	0.97
1,1,1 Trichloroethane	0.1		0.36	2.4	4.60	9.0 S	10.0 S	9.5 S
1,1,2 Trichloroethane	0.1		0.15	U	U	0.17	0.16	0.19
Trichloroethene	0.25(2.0)		2.3	14	24	50.00	61.00	60.00
Trichlorofluoromethane	0.1		0.15	0.95	1.8	3.80	4.20	4.60
trichloro, tri-fluoroethane	0.1		0.34	2.5	5.3	8.7 S	11.0 S	10.0 S

Note: S designates the use of dilution to determine the concentration, U designates undetectable.

Table 5. Species Present Below Detectable Levels

Benzyl Chloride	1,4-Dichlorobenzene	Styrene
Bromomethane	cis-1,2-Dichloroethene	1,1,2,2-Tetrachloroethane
Chlorobenzene	1,2-Dichloro,1,1,2,2-tetra-fluoroethane	1,2,4-Trichlorobenzene
Chloroethane	cis-1,3-Dichloropropene	1,2,4-Trimethylbenzene
3-Chloropropene	trans-1,3-Dichloropropene	1,3,5-Trimethylbenzene
1,2-Dibromoethane	Ethylbenzene	Vinyl chloride
1,2-Dichlorobenzene	4-Ethyltoluene	xylene (o, m, and p)
1,3-Dichlorobenzene	Hexachlorobutadiene	

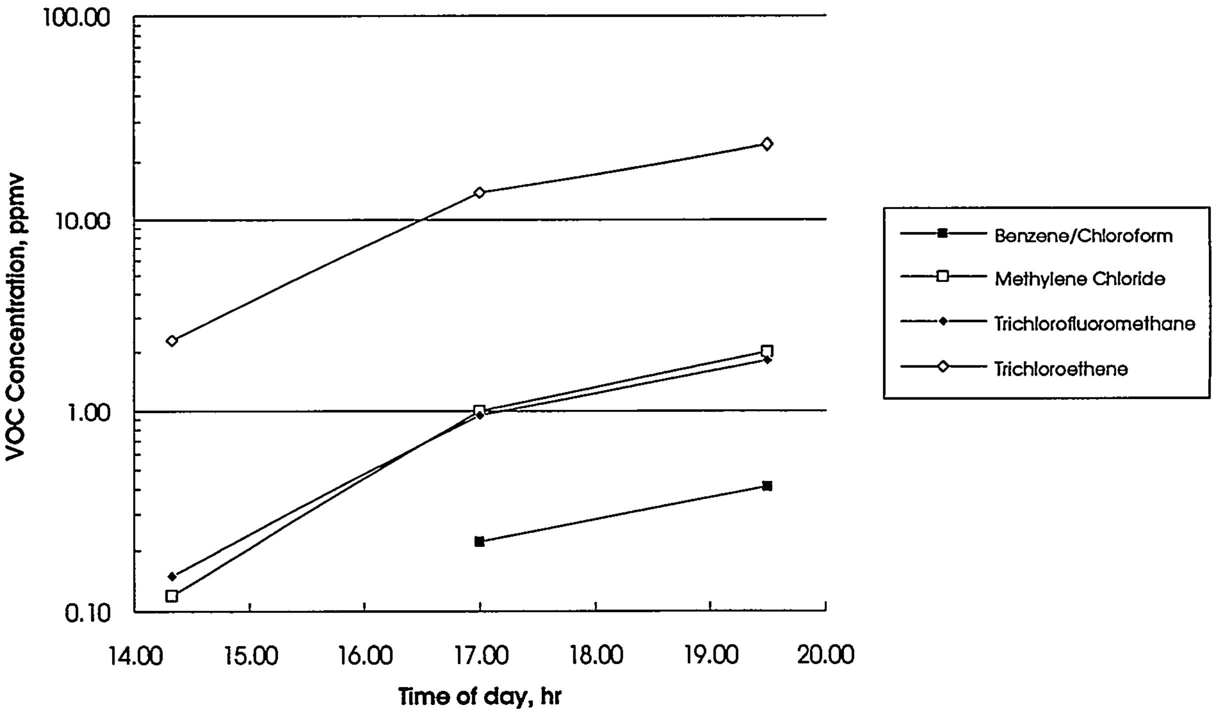


Figure 11. VOC measurements on 4/28/94 at vent.

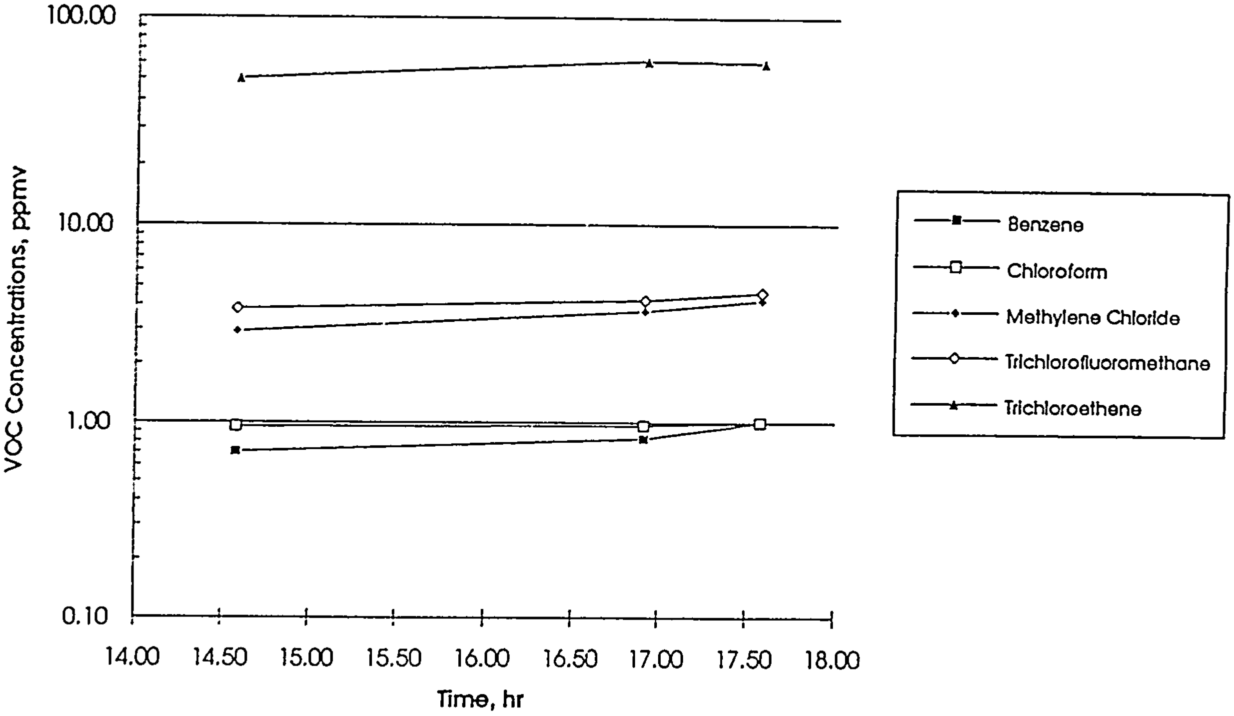


Figure 12. VOC mesaurements on 5/4/94 at vent.

Table 6 shows equilibrium concentrations for several species. Because the measured concentrations are significantly lower than would be indicated by the vapor pressures of the species, it can be concluded that vapor/liquid equilibrium is not present in the soil matrix. There are at least three possible reasons for non-equilibrium:

1. The rate of evaporation is slow relative to the gas flow either because
   a. there is insufficient heat in the soil gas to vaporize the liquid organic contaminants to the level required for equilibrium concentrations or
   b. at the given soil temperature the kinetics of evaporation is not favorable.
2. There is dilution of the VOCs due to flow of air from regions not containing VOCs; that is, the contaminant is not evenly distributed throughout the soil matrix.
3. There are mass transfer limitations hindering contaminant transport from micropores to macropores where the soil gas is flowing.

Table 6. Equilibrium Concentrations of VOCs

Species	Temperature (°F)	Equilibrium Concentration, ppmv
Benzene	66	95,200
Chloroform	51	158,730
Methylene Chloride	46	317,460
Trichlorofluoromethane	44	634,920
Trichloroethene	53	63,492

A calculation in Appendix E shows that the heat available from the air is not sufficient to vaporize enough of the VOCs to produce equilibrium concentrations; the difference is a factor of more than 10. However, the calculation also shows that the heat available is sufficient to vaporize more VOCs than is indicated by the sampled concentrations; the difference is a factor of more than 10. Thus, one would conclude that factors other than heat requirements are involved. Dilution of soil gas in contact with VOC liquid by soil gas not in contact with VOC liquid is a strong possibility.

6.0 IMPLICATIONS

6.1 System Sizing

From the flow versus time data, an annual gas exchange rate can be estimated. In addition, if the quantity of the initial spill and the concentration of VOCs in the exhaled gas (which varies with time) are known, it would be possible to calculate combinations of 1) remediation time, 2) numbers of wells, and 3) size of wells to accomplish the remediation. For example, Rohay et al. (1993) provided data on the Hanford Site from which the calculation can be done. Appendix F provides a rough estimate, indicating that for a 10-year remediation, assuming the VOC concentration remains constant in the effluent, one well would be needed for each plot of land with a 17-m radius.

VOC concentrations in exhaled gas as a function of time or amount of gas vented remain a key design parameter. They are sensitive to mass transfer limitations, which in turn depend on soil matrix parameters as well as soil and soil gas temperatures.

6.2 Air Emissions and Emissions Reduction by Active Carbon

Figure 13 shows a plot of gas flow rate versus VOC concentration that results in VOC emissions of 0.1 to 30 lb/hr. The Resource Conservation and Recovery Act (RCRA) standard for allowable VOC emissions at a site is 3 lb/hr. Calculation results in Table 7 indicate that for the CWL site, the total VOC emissions is 0.12 lb/hr, well below the 3.0 lb/hr RCRA standard.

At present, the City of Albuquerque establishes emissions standards in terms of concentrations rather than mass flow. The Albuquerque standard for exposed members of the general public is 1/100 the concentration established by the OSHA for prolonged exposure limit and 1/1000 the concentration established by OSHA if the species is known to be carcinogenic. Table 7 lists the maximum measured concentrations at TEVES1. For all species, the concentrations are below the OSHA standards for on-site workers. The nearest public access points are the SNL Solar Tower, 2.9 miles southeast of the CWL and a road approximately 1.2 miles east of the CWL. Previous modeling done for the TEVES project indicates that for an emission rate of 3.8 lb/hr of trichloroethylene (TCE), the highest 24-hour average concentration at the public access locations, over a 365-day period used for the analysis, is 29 $\mu g/m^3$ which is less than 1/10,000 of the OSHA standard of 335 mg/m^3 (New Mexico Environmental Department, 1994). Therefore, it is concluded that the passive venting operation, with a maximum emission of 0.12 lb/hr per well, would not exceed the City of Albuquerque standard

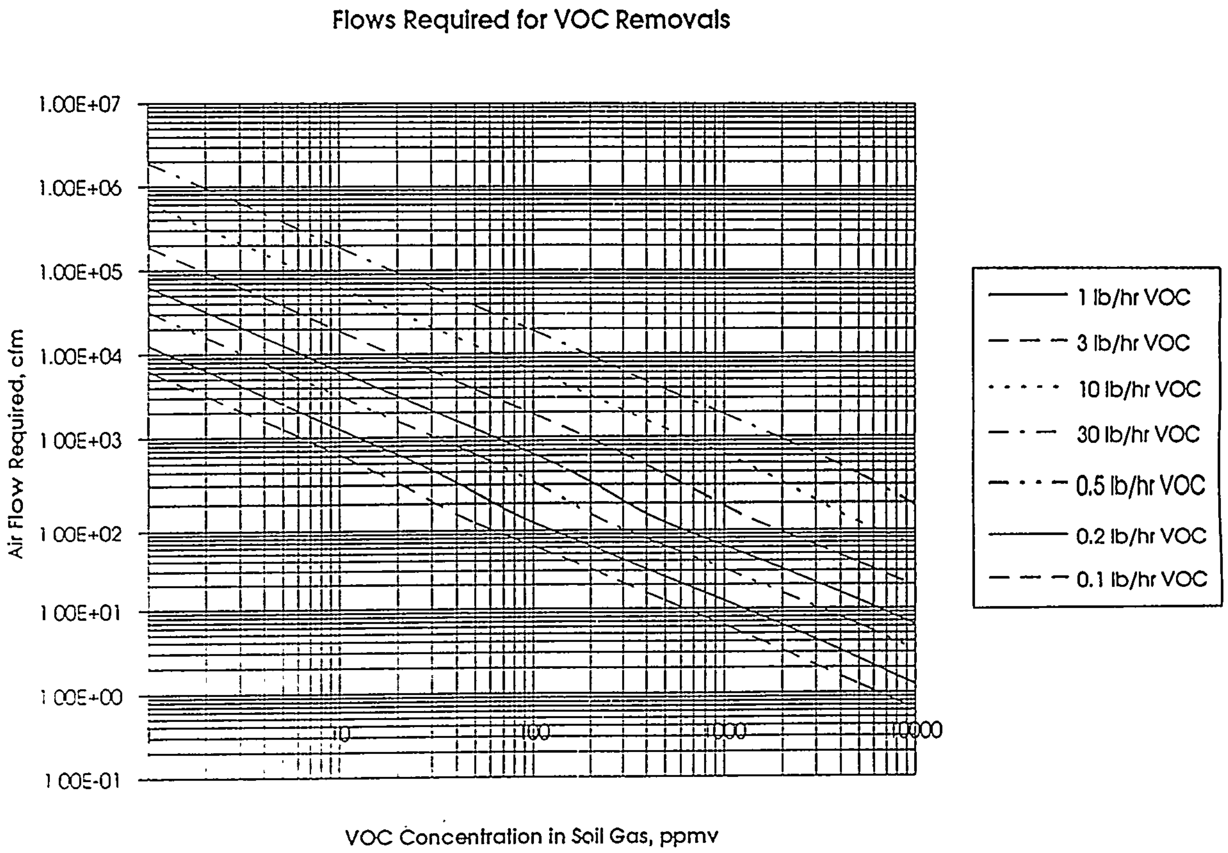


Figure 13. Gas flow rate versus VOC concentration.

Table 7. VOC Emissions Standards and Passive Venting Emissions

Compound	Molec. Wt.	Carcinogen?	OSHA PEL ppm	ACGIH TLV ppm	City of ALB ppm	RCRA lb/day	TEVES Conc. ppm	Pass. Vent Emission lb/d
Benzene	78.1	Human	10	10	0.010		2.693	6.34E-04
Carbon Tetrachloride	153.8	Suspect Human	10	5	0.005		0.689	1.62E-04
Chloroform	119.4	Suspect Human	10	10	0.010		4.117	9.69E-04
Chloromethane	50.5		100	50	0.500		2.960	6.97E-04
1,1 Dichloroethene	96.9	Experim. carcin.					0.401	9.44E-05
Dichloro, difluoromethane	120.9	No	1000	1000	10.000		3.210	7.56E-04
1,1 Dichloroethane	99		340				1.195	2.81E-04
1,2 Dichloroethane	99						1.912	4.50E-04
1,1 Dichloroethene	96.9	Experim. carcin.					21.051	4.96E-03
1,2 Dichloropropane	113	No	75	75	0.750		5.455	1.28E-03
Methylene Chloride			1460				0.000	0.00E+00
Tetrachloroethene	165.8	Experim. carcin.	100		1.000		31.445	7.40E-03
Toluene	92.2	No	200	100	1.000		3.084	7.26E-04
1,1,1 Trichloroethane	133.4	No	350		3.500		46.000	1.08E-02
1,1,2 Trichloroethane	133.4	Experim. carcin.	10	10	0.100		0.874	2.06E-04
Trichloroethene	131.4	Experim. carcin.	100	50	0.500		276.393	6.51E-02
Trichlorofluoromethane	137.4	Experim. carcin.	1000		10.000		21.794	5.13E-03
1,1,2 trichloro, 1,2,2, tri-fluoroethane	187.2		6400				71.007	1.67E-02
Sum						3.0	494.3	0.12

Note: Outflow = 377 9 ft³/d
City of Albuquerque Standard at present is 1/100 the OSHA PEL standard for VOCs and 1/1000 of OSHA PEL for carcinogenic VOCs
Passive Venting Emissions are based on maximum measured concentrations.

even with several wells in place. The City of Albuquerque is revising its emissions standard to a total mass flow base rather than a concentration base. The change in emissions standard would also allow the passive venting process to be used without an active carbon cartridge at the CWL site.

Data from vendors indicate that a 95% reduction in VOC concentrations can be established with an active carbon cartridge.

If an activated carbon cartridge is used to reduce the VOC emissions from the passive venting process, there would be an additional pressure drop to account for. For 4 x 6 mesh granulated active carbon, the following empirical formula (Khandan, 1993) estimates the pressure drop for flows from 60 to 140 ft/min and bed depths of 5 to 50 in.

$$\Delta P = 0.37\, D\, \left(\frac{V}{100}\right)^{1.56} \qquad (7)$$

where ΔP is bed pressure drop in inches of water

D is the bed depth, in inches

and V is the superficial gas velocity in ft/min.

Table 8 shows the results of a calculation of pressure drop using a flow of 25 ft^3/min and various cartridge diameters and depths. According to the calculation, for pressure drops to be acceptable, the cartridge diameter needs to be 36 in. or greater. It should be emphasized that the range of velocities in passive venting operations is significantly lower than that in soil vapor extraction processes for which this equation was developed. Therefore, actual pressure drops in passive venting should be lower than these calculated values.

Table 8. Pressure Drops for Air Flow through Activated Carbon Beds

Cartridge (inches)	x-sect. (ft^2)	V (ft/min)	Bed Depth (inches)	Press. Drop (inches water)	Press. Drop (mbar)
12	0.79	31.8	5	0.31	0.77
12	0.79	31.8	10	0.62	1.54
12	0.79	31.8	20	1.24	3.08
12	0.79	31.8	40	2.48	6.16
18	1.77	14.2	5	0.09	0.22
18	1.77	14.2	10	0.18	0.43
18	1.77	14.2	20	0.35	0.87
18	1.77	14.2	40	0.70	1.74
24	3.14	8.0	5	0.04	0.09
24	3.14	8.0	10	0.07	0.18
24	3.14	8.0	20	0.14	0.35
24	3.14	8.0	40	0.29	0.71
30	4.91	5.1	5	0.02	0.04
30	4.91	5.1	10	0.04	0.09
30	4.91	5.1	20	0.07	0.18
30	4.91	5.1	40	0.14	0.35
36	7.07	3.5	5	0.01	0.02
36	7.07	3.5	10	0.02	0.05
36	7.07	3.5	20	0.04	0.10
36	7.07	3.5	40	0.08	0.20

6.3 Limitations of Technology

The results indicate that the process may be limited by several factors. These include mass transfer limitations and dilution, which prevent the concentrations of VOCs from attaining concentrations corresponding to equilibrium vapor pressures. Because the concentrations of VOCs emitted from the vent are relatively low, it would take a significantly long time to reduce concentrations in the soil. However, because passive venting is low in equipment and operating cost relative to soil vapor extraction, the technology has potential as a polishing operation subsequent to active soil vapor extraction.

Bioventing has also been considered an option as a polishing operation. Both Khandan (1993) and Hanson (1993) state that below 15 to 50 ppm VOC in the soil gas, the amount of organic material in the soil is not sufficient to sustain microbial life. Passive soil venting does not have this limitation.

6.4 Economics

As a technology, passive venting cannot compare directly with active vapor extraction by vacuum or by pressurized air for a given remediation. However, in the latter stages of remediation, passive venting can be a competitive process. Figure 14 illustrates different stages of remediation. Hanson (1993) mentions that approximately 40 to 60% of the contaminant may be removed in the initial stage of remediation when VOC concentrations in the macropores are high and removal is controlled by advection; the rapid pumping of active systems is therefore preferred in the earlier stage. However, when mass transfer limitations are reached, it is no longer cost effective to use continuous active vapor extraction. As mentioned by Hanson (1993), periodic operation of vacuum pumps or air compressors would reduce operating costs in the mass-transfer limited range. Figure 14 shows gradual decrease in peaks as cyclic pumping continues. When the peaks are reduced to a certain level, cyclic pumping is no longer cost effective. Figure 14 shows passive venting as a feasible option at this stage.

A meaningful economic analysis can be arrived at using a scenario in which active vapor extraction is combined with passive soil venting to reduce the VOC concentration to a specified level. The cost ascribed to passive soil venting can then be compared with the total cost as a percentage. To do this analysis, more data are required, including 1) the change in VOC concentration with active and passive pumping time, most conveniently in terms of pore volumes pumped or vented, 2) level of VOC reduction required for acceptable closure, 3) equipment and operating cost for active venting, 4) cut-off concentration for switching from active to passive venting, and 5) equipment and operating cost for passive venting. In the absence of these data (especially 1, 2, and 4) the analysis cannot be done meaningfully.

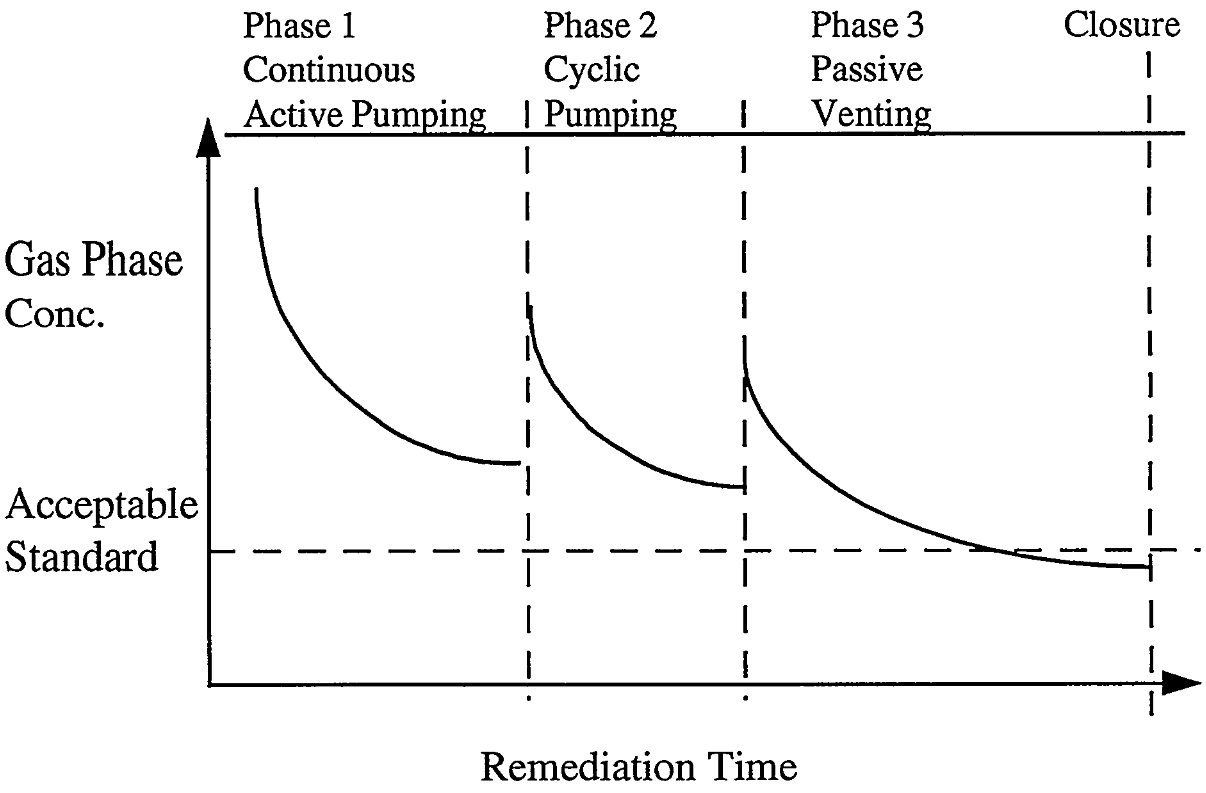


Figure 14. Consideration of passive venting in later stages of remediation (modified from Hanson, 1993).

Standards for VOC levels have been specified for some states but not for New Mexico. Pedersen and Curtis (1991) provide a list of allowed soil residual for each state and the District of Columbia as shown in Appendix H. A reasonable cut-off value for transition from active to passive venting the concentration or mass removal rate of passive venting that is below air emissions treatment requirements.

7.0 SUMMARY

Flow, differential pressure, and ambient pressure data were collected using two wells in the CWL site at Sandia National Laboratories for a period of nearly 30 days. VOC data were collected for two six-hour periods during this time. Differential pressures varied from -0.6 to 0.8 mbar; ambient pressure varied from 822 to 845 mbar. Flows through the 4-in. diameter breathing well with a 3-in. diameter insert varied from -10 to 25 cfm. Total yearly cumulative outflows are estimated at 1.4 million ft^3. Calculated pressure drops due to the screen and piping were significant; at medium flow rates (about 15 cfm), these pressure drops amount to 40% of the available differential pressure. Thus, pipe diameters and screen slot sizes should be significant design considerations.

The average air permeability, over the height of the producing zone, calculated from the flow data is about 10 to 30 darcies, which is in the low range of permeabilities determined from previous studies using other tools.

Maximum total VOC concentrations were in the range of 500 ppm or 100 ppmv. By comparison, equilibrium concentrations of the individual VOCs are in the range of 50,000 to 600,000 ppmv. This result indicates that there may be mass transfer limitations and/or dilution due to flow of air through regions not containing VOC liquid. Total emission of VOC is about 0.1 lb/hr, well below the 3 lb/hr limit of RCRA.

Although a total process evaluation is not possible with the data gathered, the data from the present study are useful in estimating air flows expected from similar soil and barometric conditions. More study is required to evaluate long-term VOC removal using passive venting and to establish total remediation costs when passive venting is used as a polishing process following active soil vapor extraction.

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APPENDIX A:
CALCULATION OF ORDER OF MAGNITUDE FOR VELOCITY HEADS RELATIVE TO TOTAL PRESSURE DIFFERENCE AVAILABLE FOR FLOW

APPENDIX A:
CALCULATION OF ORDER OF MAGNITUDE FOR VELOCITY HEADS RELATIVE TO TOTAL PRESSURE DIFFERENCE AVAILABLE FOR FLOW

- Differential pressure data give maximum pressure drop of about 1 mbar and maximum gas velocity in a 3" pipe was about 500 fpm (2.6 m/s)

- Velocity head is $\frac{1}{2}V_2^2$ or $3.4\,\frac{m^2}{s^2}$

- Gas density at 25 deg. C and 630 mmHg (ave. Albuquerque) is

$$\rho = \frac{n \text{ x MW}}{V} = \frac{P \text{ x MW}}{RT} = \frac{(630/760 \text{ atm})(29 \text{ g/mole})}{0.0821 \text{ L-atm/mole-deg.K}} \text{x} \frac{1}{298 \text{ deg K}} = 0.98 \text{ g/L}$$

- The total pressure difference in head is then:

$$\frac{\Delta P}{\rho} = \frac{1.0 \text{ mbar}}{0.98 \text{ g/L}} \text{x} \frac{\text{bar}}{1000 \text{ mbar}} \text{x} \frac{10^5 \text{ N/m}^2}{\text{bar}} \text{x} \frac{\text{kg-m/s}^2}{\text{N}} \text{x} \frac{1000 \text{ g/kg}}{1000 \text{ L/m}^3} = 100 \frac{m^2}{s^2}$$

- Therefore, the ratio of the maximum velocity head to the average total pressure head is:
  3.4/100 = 3.4 %

APPENDIX B:
DERIVATION OF RELATIONSHIP BETWEEN MEASURED DIFFERENTIAL PRESSURE AND DRIVING FORCE FOR FLOW OF SOIL VAPOR

APPENDIX B:
DERIVATION OF RELATIONSHIP BETWEEN MEASURED DIFFERENTIAL PRESSURE AND DRIVING FORCE FOR FLOW OF SOIL VAPOR

- The mechanical energy balance, neglecting velocity head is:

$$\frac{P_2}{\rho} + Z_2 g = \frac{P_1}{\rho} + Z_1 g + E \qquad \text{or}$$

$$E = \frac{P_2 - P_1}{\rho} + (Z_2 - Z_1)g$$

- With the substitution for P_1,

$$P_1 = P_{atm} + \Delta P_{transd} + \rho g \Delta Z$$

the energy balance becomes

$$E = \frac{P_2}{\rho} - \frac{1}{\rho}[P_{atm} + \Delta P_{transd} + \rho g(Z_2 - Z_1)] + (Z_2 - Z_1)g$$

- Since P_2 is P_{atm}, the energy balance reduces to

$$E = -\frac{\Delta P_{transd}}{\rho}$$

E is then the energy available as pressure drop for flow through the porous soil, the well inlet and the piping, as well as the velocity head at the exit of the pipe.

APPENDIX C:
SAMPLE PRESSURE DROP CALCULATIONS

APPENDIX C:
SAMPLE PRESSURE DROP CALCULATIONS

- At the Screen of the Collector Well
- At the Constriction from the 4-inch Pipe to the 3-inch Pipe
- Through Lengths of 4" and 3" Pipes

Pressure Drop at the Screen of the Collector Well

- The data for the calculation are as follows:
  1. Four inch schedule 40 pipe
  2. screen section is 80 ft. in height (53 ft. to 133 ft. depth)
  3. slots are 0.020 inch, flush threaded
  4. opening is 7% of screen area
  5. air flow rate is 25 ft^3/min at 0.6 mbar pressure differential
  6. Data available from Johnson Screen are 0.5 ft. of water pressure drop across the screen and gravel packing for air flows of 50 cfm/ft. of screen

- Conversion:

$$\frac{1.01\ \text{bar}}{\text{atm}} \text{x} \frac{1000\ \text{mbar}}{\text{bar}} \text{x} \frac{\text{atm}}{34\ \text{ft.}\ H_2O} = 29.7\ \text{mbar / ft.}\ H_2O$$

$$\frac{1}{2} \text{ft}\ H_2O\ \text{x}\ \frac{29.7\ \text{mbar}}{\text{ft}\ H_2O} = 14.9\ \text{mbar}$$

- For 25 cfm collected with 80 ft. of screen, the flow density is

25 cfm/80 ft = 0.31 cfm/ft

- If the pressure drop is assumed to be linear with the flow density, then the pressure drop across the screen and gravel packing would be

$$4.9\ \text{mbar x}\ \frac{0.31\ \text{cfm / ft}}{50\ \text{cfm / ft}} = 0.093\ \text{mbar}\ \text{or 15.5 \% of the available pressure drop}$$

Pressure Drops Due to Constrictions from the 4" Pipe Down to a 3" or 2" Pipe

- The same relation applies for constriction as for the screen

$$\frac{\Delta P}{\rho} = 0.4\left(1 - \frac{S_b}{S_a}\right)\left(\frac{1}{2}V_2^2\right)$$

For a constriction from 4" to 3" pipe, $S_b/S_a = 9/16$ or 0.563. For the varying velocities measured the pressure drops are then:

V (fpm)	V (m/s)	$\Delta P/\rho$ (m^2/s^2)
50	0.254	0.0056
100	0.508	0.023
200	1.016	0.09
300	1.52	0.20
400	2.03	0.36
500	2.54	0.56

- For a constriction from 4" pipe to 2" pipe, $S_b/S_a = 0.25$ and the following pressure drops result:

V (fpm)	V (m/s)	$\Delta P/\rho$ (m^2/s^2)	% of avail. ΔP
50	0.254	0.0097	0.019
100	0.508	0.039	0.076
200	1.016	0.155	0.304
500	2.54	0.968	1.90

Pressure Drops in Straight Pipes

For 4" Pipe

- Basis:
  Flow is 25 cfm
  80 ft of 4" pipe
  total pressure difference is 0.6 mbar so that $\Delta P/\rho$ is 60 m^2/s^2

- for skin friction, the relation is $-\frac{\Delta P}{\rho} = 4f\frac{\Delta L}{D}\frac{V^2}{2}$

where f is the friction factor which is a function of Reynold's number
ΔL is the length of the pipe
D is the diameter of the pipe
and V is the velocity of the gas

- for flow in 4" pipe, the velocity is

$$V=\frac{Q}{A}=\frac{25\ \text{ft}^3/\text{min}}{\pi(4/12\ \text{ft})^2/4}\text{x}\frac{\text{min}}{60\ \text{s}}\text{x}\frac{0.3048\ \text{m}}{\text{ft}}=1.46\ \text{m/s}$$

and the Reynolds number is:

$$\text{Re}=\frac{\rho VD}{\mu}=\frac{(1\ \text{kg/m}^3)(1.5\ \text{m/s})(4\ \text{in})(\text{ft}/12\ \text{in})(0.3048\ \text{m/ft})}{1.75\ \text{x}\ 10^{-5}\ \text{kg/m-s}}=8710$$

- from a friction factor chart, Figure A-1 (McCabe and Smith, Unit Operations in Chemical Engineering, 3rd ed., 1976, p.101), f is 0.008.

- the pressure drop for the length of 4" pipe is then:

$$-\frac{\Delta P}{\rho}=4(0.008)(\frac{80\ \text{ft}}{4/12\ \text{ft}})\frac{(1.46\ \text{m/s})^2}{2}=8.19\ \frac{\text{m}^2}{\text{s}^2}$$

which is 8.19/60 or 13.6% of the total pressure drop

For 3" Pipe

- Basis:
  Flow is 25 cfm
  50 ft of 3" pipe
  total pressure difference is 0.6 mbar so that $\Delta P/\rho$ is 60 m^2/s^2

- velocity in the pipe is

$$V=\frac{Q}{A}=\frac{25\ \text{ft}^3/\text{min}}{\pi(3/12\ \text{ft})^2/4}\text{x}\frac{\text{min}}{60\ \text{s}}\text{x}\frac{0.3048\ \text{m}}{\text{ft}}=2.6\ \text{m/s}$$

- Reynolds number is

$$\text{Re}=\frac{\rho VD}{\mu}=\frac{(1\ \text{kg/m}^3)(2.6\text{m/s})(3\ \text{in})(\text{ft}/12\ \text{in})(0.3048\ \text{m/ft})}{1.75\ \text{x}10^{-5}\ \text{kg/m-s}}=11{,}320$$

- From the friction factor chart, McCabe and Smith (1976), f is 0.0075

- The pressure drop due to flow in the 3” pipe is then

$$-\frac{\Delta P}{\rho} = 4f(\frac{\Delta L}{D})\frac{V^2}{2} = 4(0.0075)(\frac{50\ \text{ft}}{0.25\ \text{ft}})\frac{(2.6\ \text{m}/\text{s})^2}{2} = 20.3\ \text{m}^2/\text{s}^2$$

or 20.3/60 = 33.8 % of the differential pressure drop

APPENDIX D:
ESTIMATION OF PERMEABILITY FROM DIFFERENTIAL PRESSURE AND FLOW DATA IN TEVES1/TEVES2 USING RADIAL AND CYLINDRICAL FLOW MODELS

APPENDIX D:
ESTIMATION OF PERMEABILITY FROM DIFFERENTIAL PRESSURE AND FLOW DATA IN TEVES1/TEVES2 USING RADIAL AND CYLINDRICAL FLOW MODELS

Radial Model

The pressure to flow relationship for the radial model is:

$$k = \frac{Q\mu P_2}{2\pi(P_2^2 - P_1^2)r_2}$$

where k is air permeability
r_2 is the borehole radius
P_1 is pressure at the source location
P_2 is pressure at the sink location
μ is air viscosity
and Q is flow

The parameters are:

μ = gas viscosity = 1750 x 10^{-7} poise = 1.75 x 10^{-4} g/cm-s
r^2 = 4 inch = 10.16 cm

$P_1 = P_{atm} + \Delta P_{transd} + \rho gz$
$= 630$ mmHg +0.4 mbar + ρg(100ft)

$$630 \text{ mmHg} \times \frac{\text{atm}}{760 \text{ mmHg}} \times \frac{1.01\times10^6 \frac{g}{cm-s^2}}{\text{atm}} = 8.37 \times 10^5 \frac{g}{cm-s^2}$$

$$0.4 \text{ mbar} \times \frac{\text{bar}}{1000 \text{ mbar}} \times \frac{10^6 \frac{g}{cm-s^2}}{\text{bar}} = 400 \frac{g}{cm-s^2}$$

$$\rho gz = 1\frac{kg}{m^3} \times \frac{1000\ g}{kg} \times \frac{m}{100\ cm} \times 9.8\ \frac{m}{s^2} \times 100\ ft \times \frac{0.3048\ m}{ft} = 2987 \frac{g}{cm-s^2}$$

$P_1 = 8.37\times10^5 + 400 + 2987 = 8.404 \times 10^5$ g/cm-s^2

$$P_1^2 = 7.063 \times 10^{11} \frac{g^2}{cm^2 - s^4}$$

$P_2 = P_{atm} + \rho gz$
$= 8.37 \times 10^5 + 2987$

$$= 8.4 \times 10^5 \text{ g/cm-s}^2$$

$$P_2^2 = 7.056 \times 10^{11} \frac{g^2}{cm^2 - s^4}$$

$$P_1^2 - P_2^2 = 6.72 \times 10^8 \frac{g^2}{cm^2 - s^4}$$

$$Q = 10 \frac{ft^3}{min} \times (\frac{0.3048 \text{ m}}{ft^3})^3 \times (\frac{100 \text{ cm}}{m})^3 \times \frac{min}{60 \text{ s}} = 4.72 \times 10^3 \frac{cm^3}{s}$$

$$k = \frac{(4.72 \times 10^3 \frac{cm^3}{s})(1.75 \times 10^{-4} \frac{g}{cm - s})(8.4 \times 10^5 \frac{g}{cm - s^2})}{2\pi(10.16 \text{ cm})(6.72 \times 10^8 \frac{g^2}{cm^2 - s^4})}$$

$$= 1651 \text{ darcies}$$

In Figure 9 in the text, the slope of the differential pressure versus flow plot has a larger slope at the higher flows and a smaller slope at the lower flows. If darcy's law applies, then the permeability should be proportional to these slopes. Therefore, the permeability at the low flow range should be

$$651 \text{ darcies} \times \frac{11.6 \text{ cfm / mbar}}{43.8 \text{ cfm / mbar}} = 438 \text{ darcies}$$

Cylindrical Model

The pressure to flow relationship for the cylindrical model is:

$$k = \frac{QP_2\mu \ln(r_w / r_i)}{\pi L(P_2^2 - P_1^2)}$$

where L is the length of the withdrawal zone
r_i is the radius of influence
r_w is the radius of the collector well
P_2 is the pressure at the collector well
P_1 is the pressure at the source
and Q is the flow

The following tables summarize the calculations

Table D-1
Calculation of Permeabilities

Cylindrical Model is:
$K = \dfrac{QP_2\mu\ln(r_w/ri)}{\pi L\,(P_2^2 - P_1^2)}$
Q = 20 cfm = 9438 cm^3/sec
L = 80 ft = 2438.4 cm
visc = 1.80E-04 g/cm-sec
r_w = 4 inch = 10.16 cm
r_i = 1 m = 100 cm
P_2 = 630 mmHg = 837236.8 g/cm-s^2
dP = 0.5 mbar = 500 g/cm-s^2
P_1 = 837736.8 g/cm-s^2
K = 1.31E-07 cm^2 = 13.37 darcies

Table D-2 Variation of K with Radius of Influence and Available Differential Pressure (which may be diminished by friction losses)

Variation of K with r_i **Variation of K with ΔP due to losses**

r_i (cm)	K (cm^2)	K (darcies)		ΔP (mbar)	ΔP (g/cm-s^2)	P_1 (g/cm-s^2)	K (cm^2)	K (darcies)
50	9.13E-08	9.32		0.2	200	837437	3.28E-07	33.44
100	1.31E-07	13.37		0.3	300	837537	2.18E-07	22.29
200	1.71E-07	17.43		0.4	400	837637	1.64E-07	16.72
400	2.1E-07	21.48		0.5	500	837737	1.31E-07	13.37

APPENDIX E:

CALCULATION OF HEAT REQUIREMENT AND HEAT AVAILABLE FOR VAPORIZING VOLATILE ORGANIC COMPOUNDS IN THE SOIL

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CALCULATION OF HEAT REQUIREMENT AND HEAT AVAILABLE FOR VAPORIZING VOLATILE ORGANIC COMPOUNDS IN THE SOIL

- Day to night temperature difference in Albuquerque is about 30 ^{0}F
- Average air flow in and out of TEVES1 is about 8 ft^3/min or
- $$\frac{8\text{ft}^3}{\text{min}} \text{x} \frac{28.3\text{ L}}{\text{ft}^3} \text{x} \frac{\text{mole}}{28.6\text{ L}} = 7.92 \text{ mole / min}$$
- Heat capacity of air is about 0.25 cal/g-^{0}C
- Heat available is then:

$$\frac{7.92\text{ mole}}{\text{min}} \text{x} \frac{29\text{ g}}{\text{mole}} \text{x} \frac{0.25\text{ cal}}{\text{g-}^0\text{C}} \text{x} \frac{^0\text{C}}{1.8\ ^0\text{F}} \text{x } 30^0\text{F} = 957 \text{ cal / min}$$

Note: With the passing of air into or out of the soil, the soil will be heated up or cooled down. Therefore, not all of this heat will be available for evaporating liquid VOCs.

Latent heats of vaporization for some of the compounds found in the analyses are:

Compound	**Latent Heat of Vaporization, cal/mole**
Chloroform	7500
Chloromethane	5375
Dichlorodifluoromethane	8363
1,1-dichloroethene	7211
Tetrachloroethene	9240
1,1,1 Trichloroethane	8012
Trichlorofluoromethane	6424

Calculation of maximum VOC Volatilization and Concentration in Gas Phase

- For a chosen heat of vaporization of 7300 cal/mole, the maximum rate of VOC evaporation is:

$$\frac{957\frac{\text{cal}}{\text{min}}}{7300\frac{\text{cal}}{\text{mole}}} = 0.131 \text{ mole / min}$$

- Total VOC concentration in the soil gas would then be

$$\frac{0.131 \text{ mole / min}}{7.92 \text{ mole / min}} = 0.0165 \text{ or } 1.65\% \text{ of the air flow, or } 16{,}500 \text{ ppmv}$$

Note: Since Table 4 in the text shows equilibrium concentrations of the VOCs of interest at 100's of thousands of ppmv's, one would conclude that the heat available is not sufficient for VOCs to obtain their equilibrium concentrations.

- The actual concentrations of VOCs measured totaled to about 100 ppmv. This would be 100 ppmv/16,500 ppmv or only 0.6% of the total air heat content available. This would lead to the conclusion that factors other than the heat available are involved. One possibility is dilution of soil gas in contact with VOC liquid with soil gas that is not in contact with VOC liquid.

APPENDIX F:
ESTIMATION OF PARAMETERS REQUIRED FOR REMEDIATION OF A CARBON TETRACHLORIDE CONTAMINATED SITE AT HANFORD, WASHINGTON

APPENDIX F:
ESTIMATION OF PARAMETERS REQUIRED FOR REMEDIATION OF A CARBON TETRACHLORIDE CONTAMINATED SITE AT HANFORD, WASHINGTON

Basis: Data from Rohay, Rossabi, Cameron, September 1993, WHC-SA-2064-FP

- Annual air flow through each well is 3.5×10^7 L
- Spill is 470,000 L of CCl_4
- VOC concentration is 10,000 ppm by volume observed in one area. Use 5000 ppm for calculation, although concentrations will go down substantially with time.

Data:

- $\rho(CCl_4, \text{liquid}) = 1.6$ g/c m^3
- MW (CCl_4)= 154 g/mole

Calculation:

- $470{,}000 \text{ L} \times \frac{1.6 \text{ kg}}{\text{L}} \times \frac{1000\text{g}}{\text{kg}} \times \frac{\text{mole}}{154 \text{ g}} = 4.9 \times 10^6 \text{ mole } CCl_4$
- 5000 ppmv $CCl_4 = 5 \times 10^{-3}$ moles CCl_4/mole air
- $4.9 \times 10^6 \text{ mole } CCl_4 \times \frac{\text{mole air}}{5 \times 10^{-3} \text{ mole } CCl_4} = 9.8 \times 10^8 \text{ mole air}$
- $\text{Specif. Vol.} = V = \frac{nRT}{P} = \frac{(1 \text{ mole air})(0.0821 \text{ L-atm/mole-K})(298 \text{ K})}{(1 \text{ atm})} = 24.5 \text{ L/mole}$
- 9.8×10^8 moles air x 24.5 L/mole = 2.4×10^{10} L of air
- $\frac{2.4 \times 10^{10} \text{ L}}{3.5 \times 10^7 \text{ L/yr-well}} = 682 \text{ yr-well}$
- Allowing 10 years for remediation and assuming the concentration of VOC in the exiting gas remains constant, we would need

  682 yr-well/10 yr = 68 wells

- The area of the spill is 120 x 520 m or 62,400 m^2

We would then need one well every 62,400/68 = 920 m^2 or one well for each 17 m radius land coverage

APPENDIX G:
CALCULATION OF MEAN FREE DIAMETER

APPENDIX G:
CALCULATION OF MEAN FREE DIAMETER

For low density gases, the viscosity is related to the mean free path and molecular velocity by the relation:

$$\mu = 1/3\ \rho\ v\ \lambda$$

where μ is viscosity
ρ is density
v is velocity
λ is mean free path

(Bird, Steward, Lightfoot. *Transport Phenomena.* 1960 John Wiley and Sons, Inc. p. 21)

Kinetic theory relates velocity to temperature and the mass of the molecule:

$$v = \sqrt{\frac{8kT}{\pi m}}$$ (Bird, Steward, Lightfoot, p. 20)

where m is the mass of a molecule
k is Boltzman's constant
T is temperature

Substitution of v into the relation for mean free path gives:

$$\lambda = \frac{3\mu}{\rho}\sqrt{\frac{\pi m}{8kT}}$$

Values for the parameters are:

$\mu = 1.8 \times 10^{-5}$ kg/m-s
$\rho = 1.8$ kg/m^3
k = 1.38×10^{-6} erg/molec.-K × (g-cm^2/s^2)/erg = 1.38×10^{-6} g-cm^2/(s^2-molec-K)
T = 283 K

Substitution into the equation and appropriate unit conversions gave $\lambda = 3.3 \times 10^{-6}$ μm.

APPENDIX H:
STATE STANDARDS FOR SOIL REMEDIATION

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STATE STANDARDS FOR SOIL REMEDIATION

(After Pedersen - EPA Survey of State Programs Pertaining to Contaminated Soils,1988)

State	Office	Contact	Telephone	Allowed Residual
Alabama	Dept. of Envir. Mgmt., Groundwater Sect.	Susan Chamlies	205-271-7832	Site Specific ... < 1 ppm TPH
Alaska	Air & Solid Waste Mgmt.	Jeff Mach	907-465-2653	No State Regulations
Arizona	Underground Storage Tank Compliance	Kim Macafee	602-257-2300	TPH - 100 ppm Benzene -0.13 ppm Toluene - 200 ppm Ethyl Benzene - 68 ppm
Arkansas	Underground Storage Tanks	Linda Greschen	501-562-7444	No State Regulations
California	State Water Resources - Underground Storage Tanks	Betty Morano	916-739-4436	Based on Models ... HIGHEST .. Benzene 1 ppm, Each TEX 50 ppm, TPH 1000 ppm LOWEST .. TPH 10 ppm
Colorado	Dept. of Envir. Health	Scott Winters	303-320-8333	No State Regulations
Connecticut	Oil and Chemical Spills	James Sanpacroce	203-566-4633	No minimums; Cleanup to limits of property line; groundwater limits
Delaware	Underground storage tanks	Emil Onuschak	302-323-4588	Site by site, BTEX 1 ppm
District of Columbia	EPA Guidance	Angelo Tomprose	202-783-3194	100 ppm TPH
Florida	Bureau of Waste Cleanup	Todd Allen	904-487-3299	No Formal Regulations.. >500 ppm TPH-check groundwater impact <10 ppm No cleanup required < 500 ppm THC <100 ppb Total Aromatics
Georgia	Environ. Protection Dept...Industrial Waste Mgmt. Program	Cliff Trussell	404-669-3297	Gasoline.. should clean to 10 ppm BTEX, if BTEX > 10 ppm, clean to background (general practice, not law)
Hawaii	Underground Storage Tanks	Liz Albaz	808-548-8837	Visibility, odor, some soil sampling
Idaho	Dept. of Environment - Water Qual. Bureau		208-334-5839	RCRA rules (hazardous) to background if feasible (non-hazardous)

State	Office	Contact	Telephone	Allowed Residual
Illinois	EPA- Div. of Land Pollution Control	Kelly Dunbar	217-782-6761	Benzene - 5µg/kg Toluene - 2 mg/kg EthylBenzene - 680 mg/kg Xylenes - 1.4 mg/kg
Indiana	Dept. of Environ. Mmgt.	Manuella Johnson	317-243-5060	Site by Site TPH Test for Determ. >100 ppm cleanup reqd. background if possible
Iowa	Dept. of Natural Resources	Jim Horn	515-281-8964	No State Regulations
Kansas	Dept. of Health and Environment	Mary Jane Stell	913-296-1500	TPH-100 mg/kg Benzene - 1.4 mg/kg 1,2 DCE - 8 mg/kg
Kentucky	Div. of Waste Mgmt.	Doug Bonk	502-564-3382	No State Regulations
Louisiana	Office of Solid and Haz. Waste Mgmt.	George Gullet	504-342-7808	Site by Site - BTEX 50 -100 ppm
Maine	Dept. of Environ. Mgmt. Waste Mgmt.	Ron Severence	207-289-2651	No State Regulations
Maryland	Dept. of Environ.	Herb Nead	301-631-3442	TPH < 100 ppm, if low flash pt., Mix with clean soil
Massachusetts	Dept. of Environ. Protection	Charlie Tuttle	617-292-5903	Site Specific, Developing new policy as of 10/4/89
Michigan	Land and Mgmt. Development	Don Parsons	517-373-1170	10 mg/kg Total VOC with <15% above 1 mg/kg
Minnesota	Pollution Control Agency	Shiela Grow	612-297-2316	Guidelines .. <10 ppm TPH with organic vapor analyzer, OK; 10 to 100 ppm Cleanup necessary, Fuel oil clean to 1 ppm over background
Mississippi	Bureau of Pollution Control	Jack McCord	601-961-5062	1 Composite Sample/ Tank Action .. 100 ppm (mg/kg) <10% LEL
Missouri	Dept. of Natural Resources	Fred Hutson	314-751-7326	Site Specific -- Generally<10 ppm TPH, < 1 ppm BTEX
Montana	Solid and Haz. Waste Bureau	Doug Rogness	406-444-3454	Site Specific
Nebraska	Dept. of Environ. Control	Jim Borovich	402-471-4230	TPH - 2 ppm Benzene - 0.005 ppm Toluene - 2.42 ppm Ethylbenzene - 1.4 ppm Xylene - 0.4 ppm
Nevada	Div. of Underground Storage Tanks	Alan Biaggi	702-885-5872	100 ppm TPH -- RCRA ignitability and Pb content
New Hampshire	Dept. of Environ. Services	Tim Drew	603-271-3306	Total Volatiles, Pb

State	Office	Contact	Telephone	Allowed Residual
New Jersey	Div. of Water Resources	Analab, Inc.	609-984-3156	Benzene - 0.07 mg/l Toluene - 14.4 mg/l DCE - 0.1 mg/l
New Mexico	Dept. of Health and Environ., Environ. Impact Division		505-827-2894	Visual & Olfactory -- Observe after aeration
New York	Dept. of Underground Storage Tanks	Frank Pedudo	518-457-2462	Site Specific - Generally Drinking Water Standards, with toxicity characteristics of leachate potential test, i.e. if <DW STDS, OK
North Carolina	Dept. of Health and Human Services	Bill Jeeter	919-733-5083	>100 ppm TPH, remediate 10 to 100 ppm, monitor <10 ppm considered clean THC < 100 ppm
North Dakota	Health Department	Gary Berreth	701-224-2366	Site Specific
Ohio	EPA Office of Solid and Hazardous Waste Mgmt.	Tom Forbes	614-752-7938	BTEX 2 ppb TPH 1 ppm
Oklahoma	Corporation Commission	Tana Walker	405-521-3107	Action Levels TPH - 500 ppm BTEX - 10 ppm
Oregon	Dept. of Environ. Quality	Mike Anderson	503-229-5731	Site Specific Models: Level 1 - TPH 40 ppm Level 2 - TPH 80 ppm Level 3 - TPH 130 ppm
Pennsylvania	Non-Point Sources and Storage Tanks	John Borland	717-787-2666	No State Regulations
Rhode Island		David Sheldon	401-277-2808	Visual Observance - Shipped to state approved facility
South Carolina	Dept. of Health and Environ. Control	Preston Campbell	803-734-5331	THC - 100 ppm
South Dakota	Dept. of Water and Natural Resources	Dick Piefer	605-773-3351	TPH - 10 ppm
Tennessee	Dept. of Groundwater Protection	Don Gilmore	615-741-4094	10 ppm BTEX (gasoline), 100 ppm TPH
Texas	Water Commission and Dept. of Health Corrective Action	Dan Airey	512-463-7972	<500 ppm BTX; ignitability
Utah	Bureau of Solid and Hazardous Waste	Bob Ford	801-538-6121	Site Specific, 100 mg/l THC in soil
Vermont	Agency of Natural Resources	Paul Van Holibeke	802-244-5674	Site Specific - Soil may be placed on site if <20 ppm as Benzene
Virginia	State Water Control Board	Steve Williams	804-367-0970	Site Specific through risk assessment - 100 ppm generally

State	Office	Contact	Telephone	Allowed Residual
Washington	Ecology Dept.	Joe Hickey	206-867-7000	TPH - 200 ppm Benzene - 660 ppb Toluene - 143 ppm Ethylbenzene - 14 ppm Xylene - 900 ppm
West Virginia	Underground Storage Tanks	Pat Boyd	304-348-5935	Background levels
Wisconsin	Bureau of Solid and Haz. Waste Mgmt.		608-266-1327	Site Specific - 10 to 50 ppm THC or lower dep. on groundwater levels
Wyoming	Dept. of Environ. Quality	Dave Montague	307-777-7781	No State Regulations - Olfactory Levels

Legend:

BTEX - Benzene, Toluene, Ethylbenzene, Xylene
DCE - Dichloroethylene
DW STDS - Drinking Water Standards
GW - Groundwater
LEL - Lower Explosive Limit
RCRA - Resource Conservation and Recovery Act
TEX - Toluene, Ethylbenzene, Xylene
THC - Total Hydrocarbon
TPH - Total Petroleum Hydrocarbons
VOC - Volatile Organic Compound

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