

Miscellaneous Chemical Basin Treatability Study: An Analysis of Passive Soil Vapor Extraction Wells (PSVE)

by

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Executive Summary

A passive soil vapor extraction (PSVE) treatability study at the Miscellaneous Chemical Basin (MCB) of the Savannah River Site (SRS) has been progressing since September 1996. During this time more than 100 pounds of chlorinated organic contaminants have been removed by natural barometric pumping of wells fitted with BaroBall™ valves (low pressure check valves). In addition, contour maps of the vadose zone contaminant gas plume made before the study and after 1.1 years of operation show a significant decrease in the extent of the gas plume and identify the source location. From extrapolations of the exponentially declining contaminant concentrations measured in the wells, all of the wells except those in the source zone will be below 1 ppmv in approximately three years simply using PSVE. The source zone wells will be below 1 ppmv in approximately 10 years using no additional remediation method.

Mass removal during this time frame is attributed to residual contamination in the coarse grained material and some contaminant mass transfer from the finer grained zones to coarse zones where the majority of the PSVE flow is achieved. Removal from the fine grained sediments will be limited by the mass transfer from these zones to the coarse grained zones.

PSVE requires minimal operation and maintenance costs during its lifetime of operation (more than 10 years). Monthly well vapor sampling and analysis requires approximately 8 hours per month. For this study, characterization and well installations at 25 locations using cone penetrometer technology (CPT) were performed in three weeks for approximately \$60K. The characterization included continuous geologic profiles through the entire vadose zone, depth-discrete gas sampling for volatile organic contaminants, and sediment samples.

To remediate the source zones more quickly, passive heat injection is proposed as an extension to the treatability study. From previous testing and theoretical calculations, the subsurface can be heated using a passive solar collector and passive soil vapor injection. If the subsurface temperature can be raised by 10° C, contaminant removal rate will approximately double.

The PSVE system is performing well in a cost-effective manner. It is recommended that this system be allowed to continue operating for at least another year to verify the anticipated contaminant removal rates using passive heat injection and to evaluate removal effectiveness in the lower permeability zones.

Background

Site Description

The Miscellaneous Chemical Basin waste unit is located in the northwest portion of SRS, approximately 1.5 miles south of the 3/700 Area operations and 3 miles east of the SRS boundary. Little information is available on the historical operations of the basin. It is thought to have received liquid wastes from the 3/700 Area operations, consisting of waste solvent and used oil. It is also believed that partially full drums were emptied at this site.

The basin boundaries have been estimated based on site photographs. The MCB was approximately 20 by 20 feet in length and width, and approximately 1 foot deep. Photographs indicate that the basin received liquid chemical wastes from about 1956 to 1974 and was located in a shallow borrow pit covering a small portion of the waste unit. In 1974 the basin was re-graded and the original near-surface basin sediments were distributed in a field at the site with approximate dimensions of 350 by 350 feet. The site is currently covered by weeds, grasses and small pine trees. The surface of the waste unit exhibits a slight slope of approximately 3 percent to the east-southeast.

Previous Characterization Efforts

Previous screening activities conducted at the MCB include continuous geologic profiles, soil gas surveys, soil confirmation sampling, and groundwater monitoring as discussed below.

Geology

The Savannah River Site is underlain by a thick wedge (approximately 1000 ft) of unconsolidated Tertiary and Cretaceous sediments consisting primarily of sands, clayey sands, and sandy clays. Two significant fine grain layers in the vadose zone at the Miscellaneous Chemical Basin are located at approximately 0-15 ft (330 ft msl) and 75-85 ft (260 ft msl) below ground surface. The water table at the site is at approximately 120 ft (220 ft msl) below the ground surface.

The CPT friction ratio logs collected in 1996 indicate a significant fine grained sediment layer which occurs approximately 5 to 15 below the surface. Below this layer is a coarse grained (sandy) layer approximately 50 ft thick with a few narrow silty layers. Below this interval is an interbedded clayey/silty/sandy zone ranging in thickness from 5 ft on the northwest to 15 ft on the southeast of the investigated area. The sediment layering dips to the southeast and tends to follow the surface contour. The boundaries of the area investigated is shown in Figure 1.

Soil Gas

Two phases of shallow soil vapor sampling were conducted in 1986 with 120 samples collected from a depth of 1.5 to 2 ft on approximately 20 ft centers. Sampling results indicated the presence of trichloroethylene (TCE) and perchloroethylene (PCE) in

concentrations up to 5.5 ppmv and 44.8 ppmv, respectively. Trichloromethane and cis-1,2 dichloroethylene (cis-1,2 DCE) were also detected at concentrations up to 0.02 ppmv and 0.30 ppmv, respectively. The highest concentrations were detected north of the basin and vadose zone contaminant migration appeared to be in a north-northeasterly direction.

During September and October of 1996, in support of the treatability study, a total of 128 soil gas samples were collected at varying depths between 15 and 110 ft at 25 locations using a CPT soil gas method described in the characterization report (Riha et al., 1996). Sampling depths were chosen during the CPT push by analyzing the friction ratio logs and determining permeable locations near the clayey zones. Contaminants are expected to be located in the fined grained sediments but it is difficult to obtain sufficient soil gas flows for sampling in these zones. Soil gas samples were also taken near the center of the 50 ft thick sandy zone to determine the vertical distribution of soil gas concentrations. A site map showing soil gas and well locations is presented in Figure 1.

The results from the initial soil gas analysis are presented in the characterization report (Riha et al., 1996). These results were used to locate the PSVE wells for the treatability study. Concentrations ranged from 28.7 ppmv carbon tetrachloride (CCL_4), 140 ppmv TCE and 99.5 ppmv PCE in the vicinity of CPT-MCB-4 to non-detect levels at the outer perimeter of the basin. Soil gas concentrations are generally highest in the vicinity of the 15-20 ft depth interval at the MCB. Concentrations are highest for TCE and the center of the plume is located around CPT-MCB-4, 13, and 22. Soil gas concentrations decrease and spread laterally with depth. The lateral soil gas migration tends toward the southeast away from CPT-MCB-4.

Sediment Sampling Results

In 1987 and 1989, soil samples collected from soil borings, monitoring wells, and test pits were analyzed and found to contain VOCs (e.g. TCE, PCE, chlorobenzene, chloroform, and trans-1,2-DCE) from just below surface (0-2 feet) to depths of approximately 225 feet. However, the highest concentrations appear to occur within the upper 120 feet (vadose zone). Analysis of the groundwater since 1985 show TCE and PCE levels in excess of the EPA Maximum Contaminant Levels (MCLs) for drinking water standards in 9 of the 13 monitoring wells which surround the basin. Depth to the water table in the vicinity of the MCB is approximately 120 feet below surface; therefore removal of the VOCs within the vadose zone is considered a priority.

Five locations at the MCB were sampled for sediment analyses in 1996. Continuous 2 foot long core samples were collected at CPT-MCB-S1 from 2 ft to a depth of 82 ft to determine the vertical extent of the sediment contamination. This location corresponds to the highest soil gas concentrations during the current characterization effort. Well CPT-MCB-4 was installed in this borehole. The core was also inspected visually and compared to the CPT logs which provided a good correlation for lithology determination with CPT logs at the site.

Contaminants in the sediment samples appear primarily in the two zones of fine grained sediments. The highest concentrations for two of the sampling locations were measured in

the lower layer (74-80 ft) which has a higher clay content than the upper zone at 5-15 ft. Lower concentrations of TCE were measured in the sandy/silty layers.

Sediment VOC concentrations at CPT-MCB-S2 were high in the upper clay layer in the 4-8 ft depth (231 - 10,735 $\mu\text{g}/\text{kg}$ PCE). Duplicate samples in this range did not correlate well which may be attributed to the heterogeneous nature of the sediments. The concentration in the lower clay zone (74-80 ft) was 123 $\mu\text{g}/\text{kg}$ (TCE) indicating the contaminants are still trapped in the upper clay layer (5- 15 ft). Sediment concentrations in CPT-MCB-S3 follow a similar trend with higher concentrations in the shallow clay zone (5-15 ft) and lower concentrations in the deeper clay zone (74-80 ft).

Sediment concentrations at CPT-MCB-S4 and S5 are higher in the deeper clay zone (74-80 ft). The highest VOC sediment concentration in CPT-MCB-S4 was 5,325 $\mu\text{g}/\text{kg}$ PCE at 69 ft. However, VOC contaminants in the duplicate sample were not detected. This discrepancy may be attributed to the heterogeneity of the sand/silt/clay layers in this region.

The results from the sediment samples suggest a contaminant source was released in the area near CPT-MCB-S2 and CPT-MCB-4. Sediment VOC contamination is consistent with releases of PCE and TCE to the subsurface over an 18 year period. The contaminants have migrated down through the upper clay layer and to the southeast into the lower clay layer.

PSVE Well Installation

Twenty five vadose zone wells were installed at the MCB in the same push hole as the CPT geophysical and soil gas pushes. The wells were installed by threading a steel push tip onto the PVC screen and pushing the tip with the steel CPT rods in the center of the PVC, effectively pulling the PVC well down with the push tip. The 6 inch long steel push tip remained in the ground.

The wells were installed so the formation was compressed against the outer surface of the casing and screen, leaving no annular space. The potential for vertical migration is minimal because the well material provides no channels to transport liquids. The compression of the formation against the walls of the well reduces gravity flow along the casing in contrast with the flow processes occurring in the natural materials of the formation. All vadose zone wells were installed to a depth that did not breach the water table; the maximum termination depth of the vadose zone wells was greater than 10 feet above the water table. Concrete pads were installed around the wells at the surface.

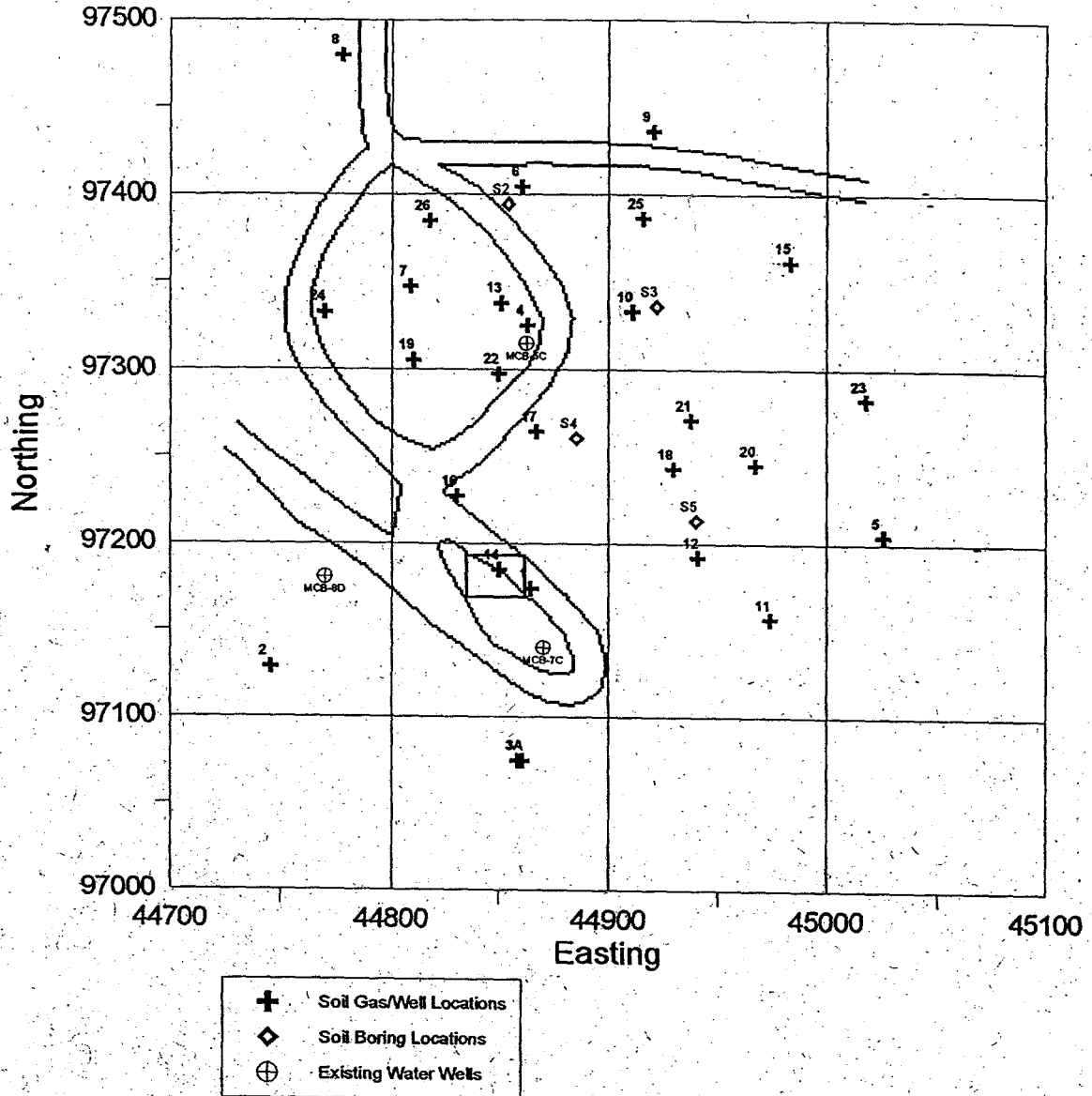


Figure 1 - Miscellaneous Chemical Basin Vadose Zone Well and Soil Boring Locations

Technology Description - Barometric Pumping

Natural atmospheric pressure fluctuations are transmitted through the unsaturated subsurface, however, these pressure waves are damped and delayed in phase to degrees dependent on the effective vertical permeability of the formation. As a result of the attenuation and delay of the transmitted pressure wave, at a given time the atmospheric pressure at the surface and the soil gas pressure in the subsurface will be different. If these two zones are directly connected (by a vadose zone well), the pressure differential will result in a flow either into or out of the well. If the subsurface contains VOCs in the gas phase, flow out of the well will result in removal of the contaminants from the subsurface without mechanical pumping. This phenomena has been observed for more than a century, (the first reference in the literature is an article in Science, 1897 by Fairbanks) but has only recently been proposed for

environmental remediation. The technology is also known as barometric pumping. The duration of flow events (either flow into the well or flow out of the well) can be as long as three days continuously but, as expected by mass balance considerations, the average time of flow in is equal to the average time of flow out. The flow rates for a typical well are generally low (.1 to 10 scfm) but if the concentration of the contaminant in the gas phase is high, mass removal by this process can be significant. Rates as high as 1 to 2 kg/day/well have been observed near sources in the A/M Area of SRS. Mass removal can be enhanced using low cost or natural techniques. Enhancements to PSVE include the addition of wind powered turbine vacuum pumps, installation of one way mechanical valves to prevent dilution of the contaminated soil gas by clean air from the surface, and solar heat injection to raise vapor pressures and the partitioning of the VOCs from the liquid or aqueous phases to the gas phase.

The BaroBall is a device developed and patented by WSRC specifically for barometric pumping applications. It uses a light weight ball in a conical seat to permit gas flow in one direction with a minimal pressure requirement (approximately 1 millibar) but effectively prevents gas flow in the reverse direction. Depending on the configuration, the BaroBall can be used to allow contaminated soil gas out of a well and prevent clean air from diluting the soil gas in the subsurface (standard mode of operation), to inject air and/or nutrients into the subsurface to enhance bioremediation, to control or confine the movement of a subsurface gas phase plume in the vadose zone, or to passively transfer solar heated, water-saturated air into the subsurface to enhance volatilization in the subsurface. The BaroBall device is attached directly to the top of the well casing at the surface.

Application of this technology is directed to any site where volatile substances (chlorinated solvents, petroleum products, etc.) have contaminated the vadose zone. Natural pressure fluctuations and their damped and delayed transmission through the subsurface occur in all environments but are particularly well-suited to sites with large vadose zones or substantial low permeability layers that increase the damping and delay of the atmospheric pressure signal.

Field scale studies have been ongoing at SRS, the Hanford site and the Idaho National Engineering Lab for approximately five years, and a field scale implementation of the technology for control of subsurface methane migration using a combination of passive injection and extraction was recently installed at a landfill in Richmond County, Georgia. The MCB treatability study is the first implementation to directly target the removal of the vadose zone source term.

Methods

Sediment Sampling and Analysis Methods

At each soil sampling depth, the cone penetrometer truck using a MOSTAP® soil sampler collected a core sample of approximately 1" in diameter and 24" long. Once the sample was brought to the surface, a 2 cc plug sample was collected using a modified plastic syringe.

The plug was transferred to a 22 ml vial containing 5 ml of nano-pure water and the vial was sealed with a crimped septum top for later head space analysis. Duplicate samples were collected at each depth and all samples were stored at 4°C until analysis.

Each sample was weighed and then analyzed on the HP 5890 Series gas chromatograph using an automated head space sampler for equivalent water concentrations. Mass soil concentrations (ppb, $\mu\text{g}/\text{kg}$) were calculated based on an equal head space volume from 7 ml of water standards and 7 ml of water/soil matrix and were corrected for the mass difference between the soil and water. The gas chromatograph was calibrated using stock solutions of neat (pure) solvents diluted to specific concentrations. The standard concentrations used for each head space sample run were 3, 5, 10, 50, 100, 500, and 1,000 ppb ($\mu\text{g}/\text{ml}$). The samples were analyzed for Vinyl Chloride, Freon-11, Freon-113, 1,1-DCE, Trans-DCE, Cis-DCE, CHCl_3 , TCA, CCl_4 , TCE, and PCE. The record of the brand name and lot number of the standards was logged in the GC log book along with the amount used, date and person making the stock solutions.

Well Vapor Sampling and Analysis Methods

Concentration measurements were made on the vadose zone wells approximately monthly during barometric pumping outflow events. Well vapor was sampled and analyzed using a Bruel and Kjaer Model 1302 photo acoustic infrared gas analyzer. The instrument was calibrated to measure TCE, PCE, CCl_4 , and CO_2 and periodic samples were obtained in Tedlar sample bags and analyzed on an HP 5890 series GC for instrument verification.

Pressure and Flow Measurement

Pressure and flow measurements were recorded using either a Campbell Scientific® CR10 or Z-World® data logger. Barometric pressure was measured with a Vaisala® PTA 427 pressure transmitter with a range of 800-1060 mbar. Differential pressure was measured with an Omega® PX163 low pressure transducer with a range of ± 5 inches of water. Gas flow was measured with a Cambridge Accusense®, Inc. AVS 1000 Series air velocity sensor with a range of 1000 fpm. For all parameters, point measurements were made at 15 minute intervals.

Results and Discussion

Well Flow Rates and Vapor Concentration

Well vapor flow and concentration measurements show mass removal from the vadose zone at the Miscellaneous Chemical Basin. Pressure and flow rates were measured on several wells at the site with CPT-MCB-3 having the longest history of measurements. A typical pressure and flow response during 4 days of measurements is shown in Figure 2. Wells CPT-MCB-3 and 3A are 3 ft apart and have screen lengths at 57-72 ft and 80-95 ft respectively. The flow measurements were made on the deeper well and pressure measurements were made on the shallower well. These data were used to create a

pressure/flow correlation for long term flow estimation. Pressure measurements were made on these wells for 61 days and the estimated flow rates for this period are shown in Figure 3. The cumulative volume of soil gas removed during periods of venting from the vadose zone was 100,356 ft³ and is shown by the cumulative curve on the chart. This removal is based on the assumption that air flow is not allowed to enter the well by using a Baroball. Statistics from this period are presented in Table 1.

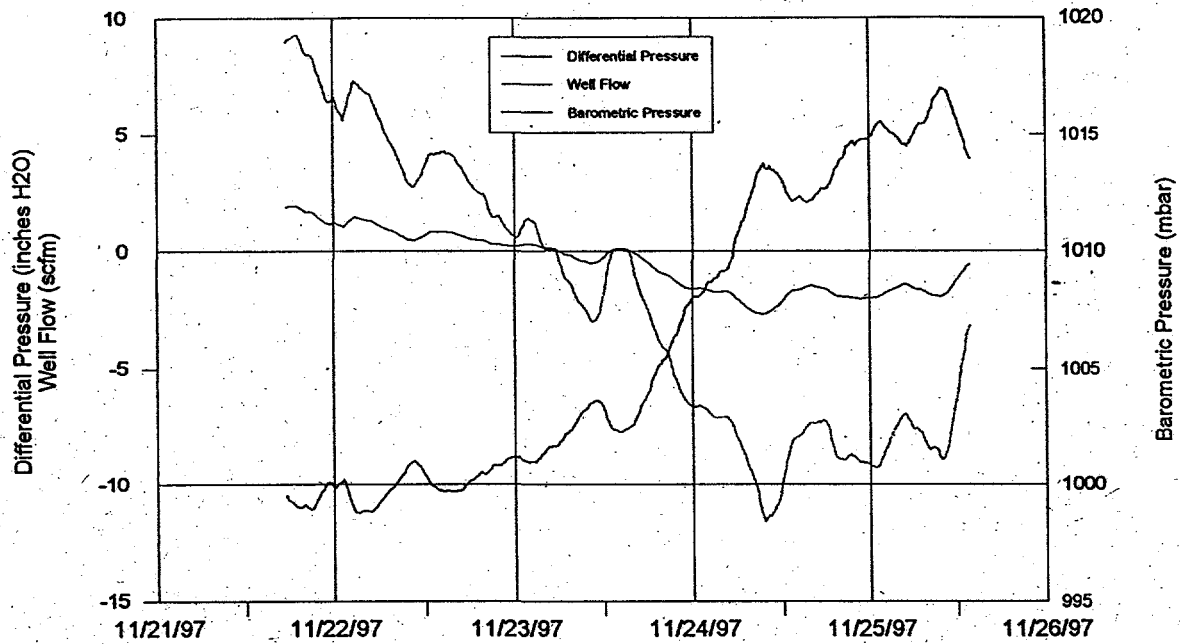


Figure 2 - Typical Pressure and Flow Response for Well CPT-MCB-3

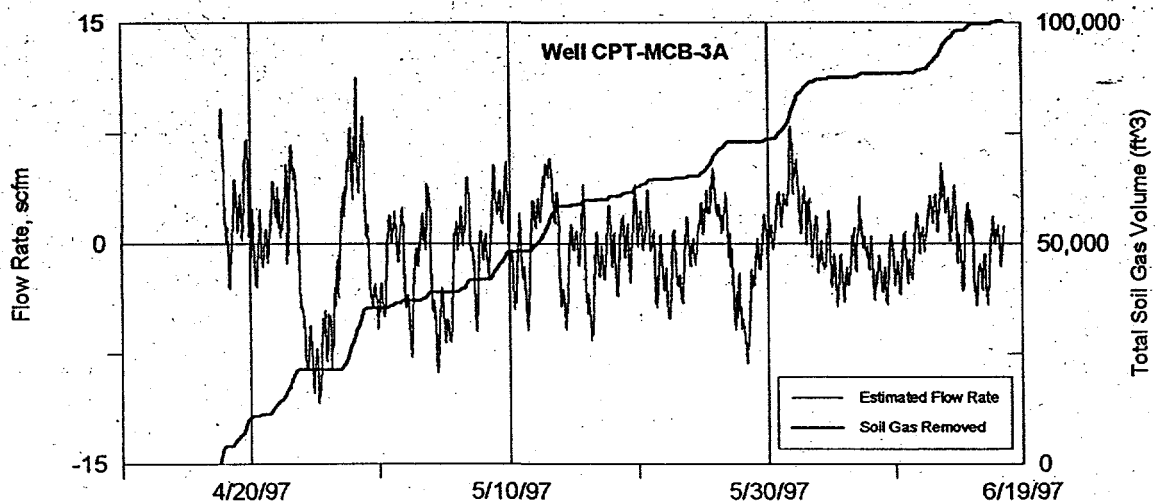


Figure 3 - Estimated Flow Rate and Volume Removed with Flow Enhancement

Table 1 – Statistics from Pressure and Flow Measurements at CPT-MCB-3A

Duration 4/17/97 – 6/17/97	61 days
Barometric Pressure Range	983.8 to 1015.3 mbar
Differential Pressure Range	-3.24 to +3.39 in H ₂ O
Outflow Events	30.4 days (49.8%)
Total Outflow	100,356 ft ³
Total Inflow (if Baroball not installed)	125,717 ft ³
Average Outflow	2.28 cfm
Average Outflow Event Duration	0.50 days
Maximum Outflow Event Duration	3.36 days

Well vapor concentrations were measured approximately monthly to determine the soil gas concentration trends at the MCB. Well head measurements were made during outflow events with a Bruel and Kjaer infrared photo-acoustic analyzer calibrated for PCE, TCE, CCl₄, and CO₂. The contaminant concentrations were normalized with the CO₂ concentrations to the average soil gas CO₂ levels of 12,000 ppmv. This normalization was required to provide more accurate contaminant concentration levels at the unit. The Baroballs leak slightly during inflow periods which dilutes the soil gas and produces low readings during the beginning of outflow events. The normalized concentration values are provided in Appendix A.

Soil gas concentrations measured over this 1.1 year time period show an exponentially declining concentration as is expected based on a conceptual model of mass transfer from fine grain zones in the liquid or aqueous phase to the coarse grain sediments in the gas phase. Once in the gas phase, the contaminants can be swept out of the subsurface system. The rate constants calculated from these plots show that the wells outside of the source zone will be below 1 ppmv in approximately three years simply using PSVE. The source zone wells will be below 1 ppmv in approximately 10 years using no additional remediation method. The parameters for the exponential concentration decline equations are provided in Table 6. Concentration trends from four wells along with the exponential fits are shown in Figure 4 as an example.

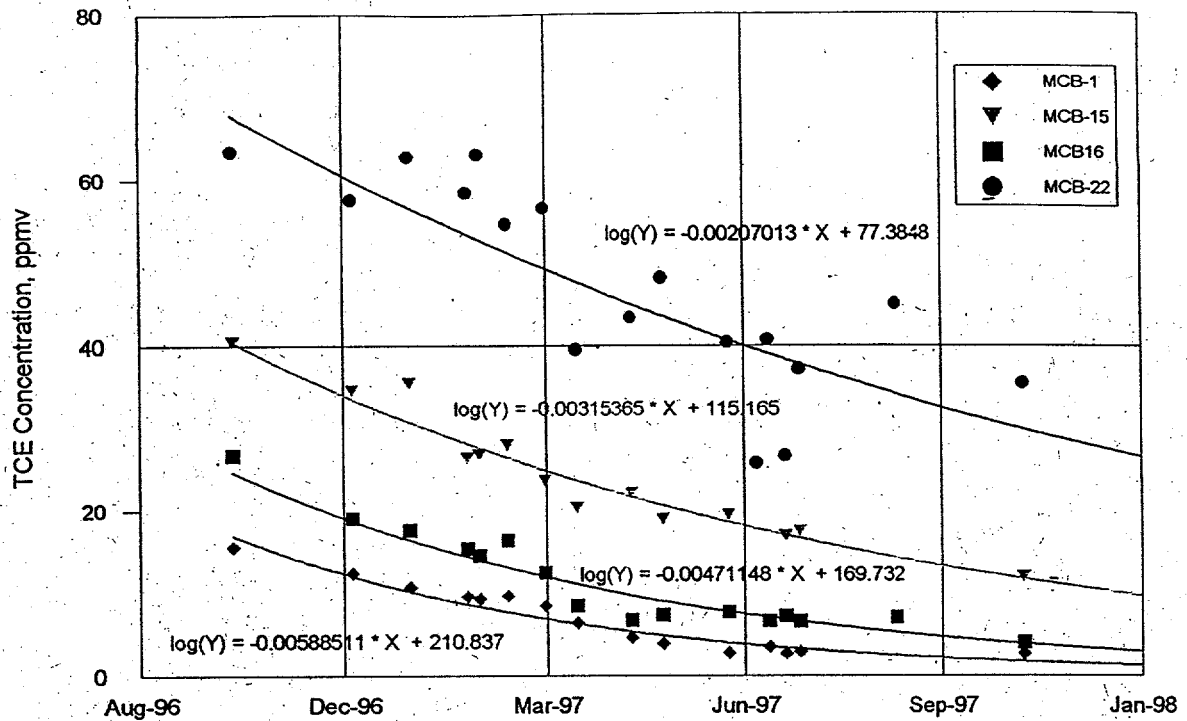
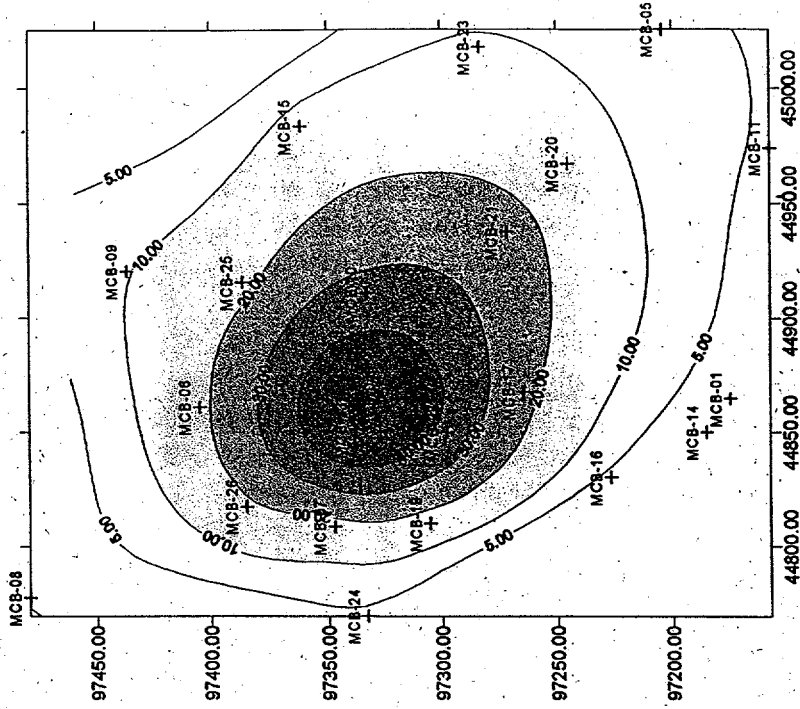


Figure 4 - Well Vapor Concentration Trends and Exponential Fits

Contour plots of well TCE concentrations at 10/7/96 and 11/7/97 are provided in Figure 5. The 25 wells are screened at different levels so these plots show a general representation of the soil gas plume at the unit. Over the 13 months of PSVE with Baroball flow enhancement, the soil gas plume has decreased in concentration and size. The plume suggests that the source term is isolated around CPT-MCB-4.

11/7/97



10/7/96

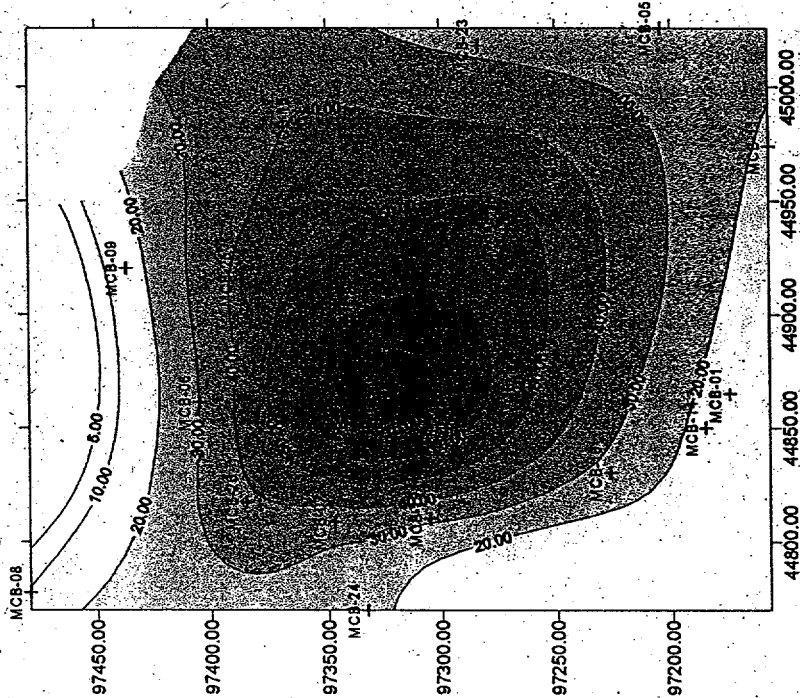


Figure 5 - Pre and Post-Study Soil Gas Plumes

Pre and Post Study Sediment Concentration

Post-study sediment samples were collected at 5 locations within 3 ft of the pre-study CPT sediment sample locations. Pre-study samples were collected September 1996 and post study samples were collected November 1997. The depths of samples targeted fine grain zones and depths with detectable contaminant levels from the original sampling. The methods for sampling and analysis are discussed in the methods section above. The post-study sediment samples were all taken within the fine grain zones.(low permeability zones).

Pre and post-study TCE concentration plots are shown in Figure 6 and 7 and the data are presented in Table 2. The locations correspond to the soil boring locations in Figure 1. The pre and post-study concentrations vary significantly; some locations show an increase and some a decrease. Observed decreases during the short treatability study were expected to be small, especially from the fine grained sediments, due to mass transfer limitations. Differences between the pre and post-study concentrations may be attributed to PSVE impacts and several other factors including the heterogeneous disposition of the contaminants corresponding to sediment properties, migration of the sorbed contaminants and the difficulty in obtaining soil samples from identical locations in the interbedded geology. Quality checks on the field and laboratory work indicate the pre and post-test data sets are equivalent in terms of sampling and analysis.

Despite the short operating period and observed variability, the composite results from the sediment sampling suggest a 13% decrease in TCE mass from the fine grain sediments in the source area of the unit during 13 months of PSVE. This value was calculated using the difference in estimated total contaminant mass from pre- and post-study core samples. Although supported by the observation of diminished soil gas concentration, the sediment values may not be precisely representative of the true remediation rate because of the inherent variability in point sampling and the heterogeneity of contaminant distribution.

Mass removal during this time frame is primarily attributed to residual contamination in the coarse grained material and contaminant mass transfer from the finer grained zones to coarse zones where the majority of the PSVE flow is achieved. Removal from the fine grained sediments will be limited by the mass transfer from these zones to the coarse grained zones.

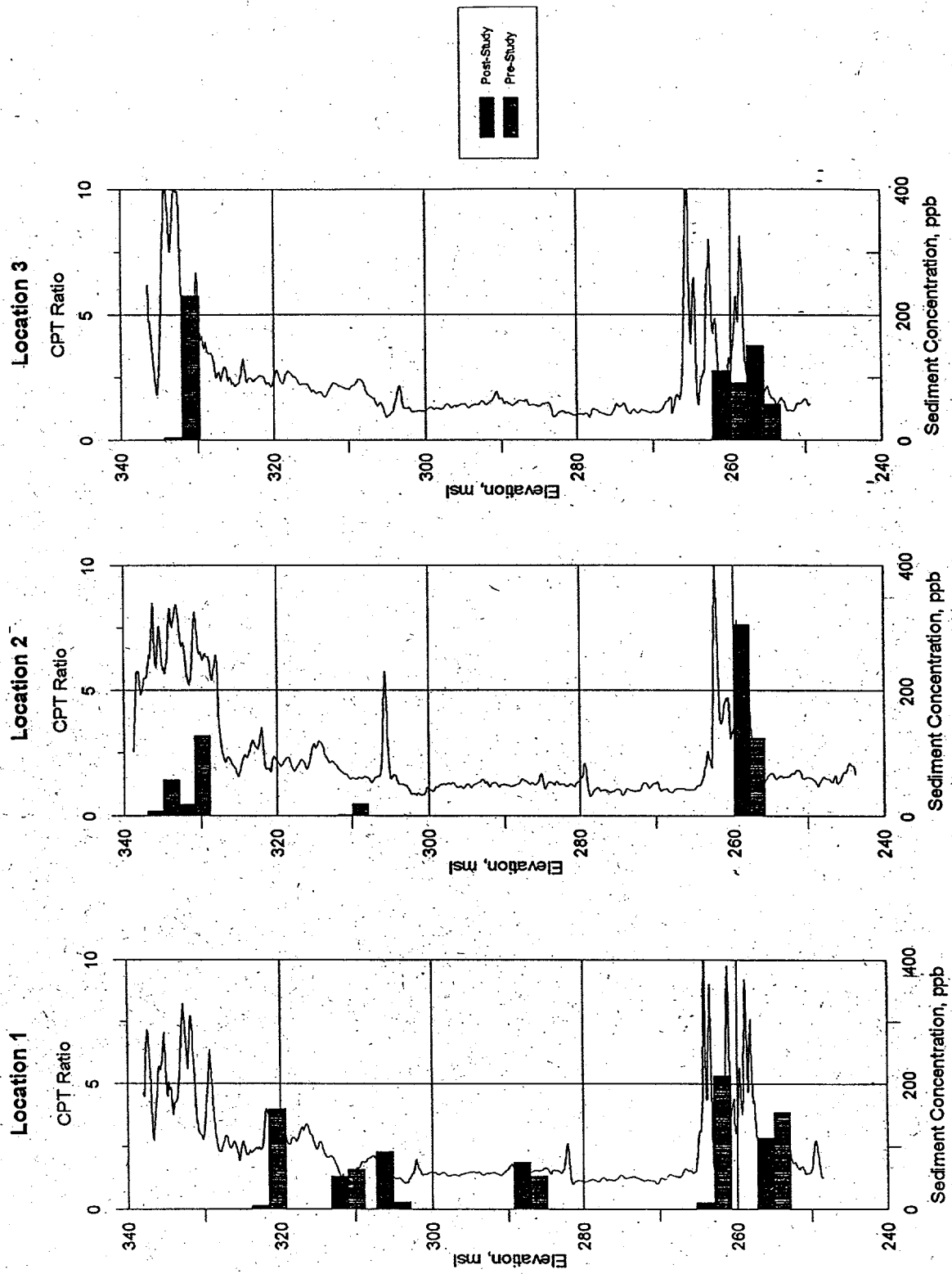


Figure 6 - Pre and Post-Study TCE Sediment Concentration Profiles (Locations 1-3)

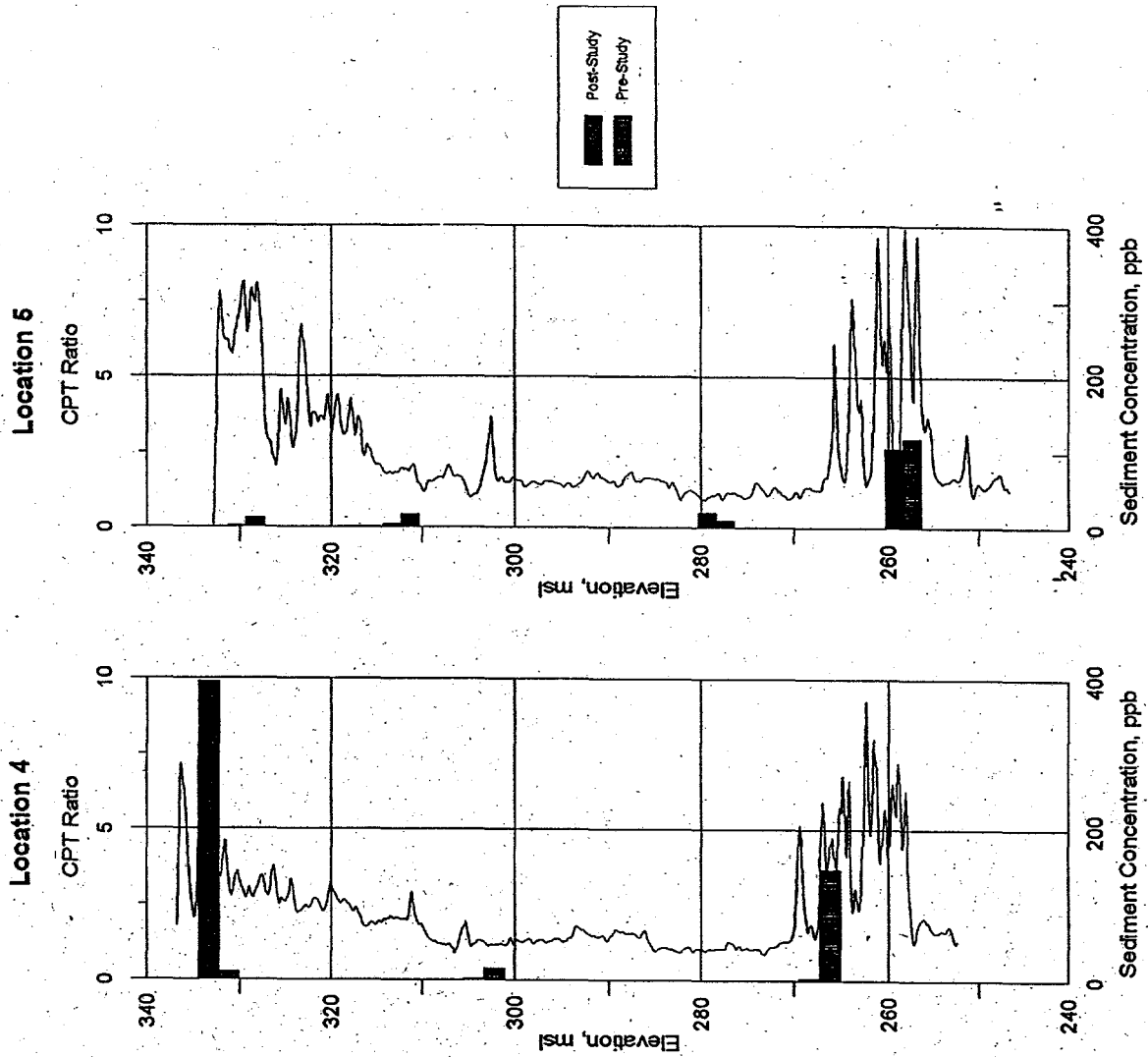


Figure 7 - Pre and Post-Study TCE Sediment Concentration Profiles (Locations 4-5)

Table 2- Pre and Post Study Sediment Concentrations ($\mu\text{g}/\text{kg}$)

Location	Depth, ft	pre-CCl ₄	post-CCl ₄	pre-TCE	post-TCE	pre-PCE	post-PCE
S1	16	<6.6	<6.6	159.98	<6.6	39.87	<6.6
S1	26	<6.6	<6.6	63.97	52.37	9.94	8.16
S1	32	<6.6	<6.6	11.19	92.65	<6.6	8.61
S1	50	<6.6	<6.6	52.42	74.46	8.76	8.51
S1	74	<6.6	<6.6	213.16	10.62	35.87	<6.6
S1	82	<6.6	<6.6	154.66	114.03	18.70	11.98
S2	4	10.86	<6.6	56.53	6.96	6023.62	<6.6
S2	8	6.82	<6.6	126.25	17.06	231.42	<6.6
S2	29	<6.6	<6.6	18.53	<6.6	10.29	<6.6
S2	81	<6.6	10.96	123.11	305.06	33.03	114.87
S3	4	<6.6	<6.6	229.86	<6.6	25.17	<6.6
S3	75	<6.6	<6.6	90.86	110.01	14.94	19.47
S3	80	<6.6	<6.6	57.13	150.78	8.72	24.94
S4	4	<6.6	<6.6	9.80	395.17	<6.6	15.77
S4	33	<6.6	<6.6	14.75	<6.6	<6.6	<6.6
S4	69	24.70	<6.6	146.51	<6.6	5324.95	<6.6
S5	4	<6.6	<6.6	12.14	<6.6	<6.6	<6.6
S5	21	<6.6	<6.6	17.15	<6.6	<6.6	<6.6
S5	55	<6.6	<6.6	9.32	19.76	<6.6	<6.6
S5	74	<6.6	<6.6	118.14	105.52	13.73	8.33

Flow Control Enhancement of Mass Removal

Flow control enhancement has been proven to increase mass removal by at least a factor of 2 (May et al., 1994). Theoretically, without any engineering controls, the volume of soil gas outflow is approximately equal to the volume inflow in an open vadose zone well. Under these conditions, air entering the vadose zone will dilute the soil gas and force the soil gas plume away from the well. The soil gas removed after an inflow event will thus be a mixture of surface air and soil gas, effectively reducing the mass of contaminants removed.

With flow control which only allows outflow, the soil gas is not diluted and a step process is created which brings contaminants from further distances from the well screen with each successive outflow event. Also, when wells are not flowing out (checked inflow event), contaminants will move into the coarse grained sediments by mass transfer and will be removed during the next outflow event(s). The Baroball check valve does leak slightly during inflow events and will produce some subsurface dilution dependent on the length of the inflow event.

Solar Heat Enhancement of Mass Removal

PSVE has been successfully removing chlorinated organic contaminants from the vadose zone at the Miscellaneous Chemical Basin for more than one year. This process has been steady but slow (approximately 100 lbs. of chlorinated solvents in the first year). The rate of removal is dependent on both the rate of PSVE (i.e., the gas flow rate out of the wells) and

the mass transfer rate of the contaminants from within the fine grain zones to the coarse grain zones. The majority of the advective flow of PSVE occurs in the coarse grain zones (i.e., zones of higher permeability) in the vadose zone. An active vapor extraction system (e.g., vacuum blower) can increase the flow rate out of the wells and the contaminant removal rate. This strategy is effective until the contaminant mass transfer limitations are dominant. At this point, the active vapor extraction reaches a point of diminishing returns in its removal effectiveness. Once installed, a PSVE system never reaches a removal effectiveness point of diminishing returns because it has a negligible operation and maintenance cost.

An alternative method to increase contaminant removal rate is by increasing the mass transfer processes in the system. Heating the subsurface system is an effective way to accomplish this. Heating exploits the physical properties of the volatile contaminants by increasing the vapor pressure of the contaminant in the system. For PCE and TCE, a temperature rise of 10° C results in a nearly two fold increase of the vapor pressure. By doubling the vapor pressure, twice the mass of contaminants will be in the vapor phase and available for removal by soil vapor extraction. Increased temperature also increases diffusion coefficients and related mass transfer processes. Using a set of simple assumptions we can approximate the energy required for a temperature increase of 10° C in the subsurface system a priori. Table 3 below lists the assumptions and energy calculations.

Table 3 - Energy Required for Heating Subsurface in PSVE Volume of Influence

Radius of Influence	3 m		
Well Screen Length	2 m	Volume of Influence	56.5 m ³
Porosity	0.4		
Volumetric soil moisture (S _w)	0.6		
Sediment Density	2,650 kg/m ³	Mass of Sediments	89,912 kg
Water Density	1,000 kg/m ³	Mass of Water	13,572 kg
Sediment heat capacity (C _{vs})	0.79 BTU/kg/°C	Energy for 10° C rise (sediments)	713,602 BTU
Water heat capacity (C _{vw})	3.97 BTU/kg/°C	Energy for 10° C rise (water)	538,568 BTU
		Total Energy Required	1,252,170 BTU

Given this energy target, cost-effective strategies can be selected to heat the subsurface and double the contaminant removal rate.

In the southeastern United States, solar energy can be used to create a large amount of heat cost-effectively. By using innovative passive solar collection devices developed as a result of a SRS Cooperative Research and Development Agreement (CRADA) with a local company, it has been demonstrated that solar energy can be efficiently converted to heat energy to warm surface sediments near the M Area Basin. By joining the two passive technologies (passive solar collector and passive soil vapor extraction/injection) it should be possible to heat the subsurface using only natural energy sources. Data were collected on available solar

energy at SRS using a pyrometer and data logger as part of the CRADA. The data are summarized in Table 4 below and compared to theoretical solar energy availability.

Table 4 - Energy Available from the Sun at SRS

Average sun/day	6 hours	Area of collector	5.9 m ²
Theoretical		Measured	
Average Energy from Sun (approx.)	0.95 BTU/sec/m ²	Average Energy from Sun	0.70 BTU/sec/m ²
Energy to collector	121,734 BTU/day	Energy to collector	89,600 BTU/day

Using the measured value of energy available at SRS and assuming 100% efficiency of solar energy collection and complete transfer of that energy to the subsurface, a 10° C rise in temperature can be achieved in 14 days.

Passive subsurface injection is the transmission of surface air into the subsurface using the same pressure gradients that enabled passive soil vapor extraction, only in this instance, surface pressure is higher than subsurface pressure. Air is not an efficient heat transfer fluid so to transfer heat developed in the solar collector air saturated with water (i.e., steam) would be used. The steam will condense on contact with the lower temperature sediments, which are at a nominal temperature of 19° C. The low temperature steam injection is an effective method for rapidly transferring energy because the latent energy of the steam is immediately transferred to the subsurface sediments when the steam condenses. To create the water-saturated air, we maintain a reservoir of water in the sealed solar collector and allow surface air in through baffles only when steam injection is occurring. In Table 5 below, the physical parameters of the passive solar collector and estimated heat capacity and flux are provided for creating and transferring steam at different temperatures. A time history of the temperature in the solar heat collector is shown in Figure 8.

Table 5 - Passive Steam Injection Rates

Temperature (°C)	Approximate BTU/day	Number of days to raise sediments 10°C
130	74810	17
120	57600	22
110	40000	31
100	26830	47
80	14740	85
60	5790	216
40	2020	618

Volume of collector = 3.63 m³, Average flow rate = 40.8m³/day (2scfm), Flow into well 50% of time

From the table above it is clear that the higher the temperatures achieved, the more effective the heat transfer. An added benefit of higher temperature steam not accounted for above is the increase in pressure created in the solar collector and subsequent increase potential flow to the subsurface. The increase in pressure also may create difficulties in maintaining the airtight seal in the solar collector. The experiments scheduled for this fiscal year should provide the performance parameters for this system.

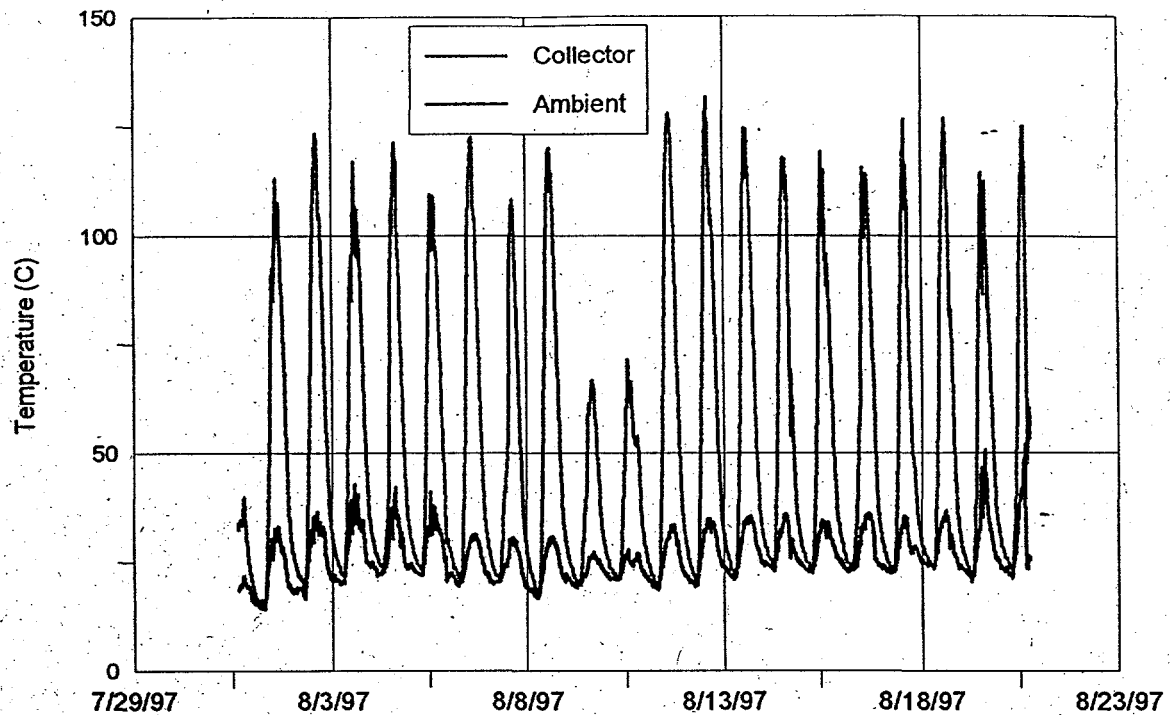


Figure 8 - Time History of Solar Heat Collector Temperatures

Cost Analysis

Based on the exponentially declining concentration curves for 19 of the wells installed at the Miscellaneous Chemical Basin, life-cycle costs can be developed for removal of the chlorinated contaminants using a PSVE system. The assumptions include a uniform average flow rate out of all of the wells based on measured flow from the wells, initial concentrations measured 10/7/96 and final concentration projected using the rate constants from more than a year of monitoring.

Operating and maintenance costs are assumed negligible for this cost analysis so that the total cost of the project was incurred during installation in the summer of 1996. Costs are calculated in terms of dollars per pound of contaminant removal in 1996 dollars. The installation cost includes the entire cost of the cone penetrometer characterization and 25 well installations performed in three weeks during August, 1996. In general, characterization costs should not be included in remediation system cost analyses. Without concurrent characterization, the costs will be lower.

The cost per pound of removal is calculated for two average flow rates (2 scfm and 4 scfm). Soil gas is removed 50% of the time (50% of the time atmospheric air is blowing into well). The area under the removal curves is calculated and multiplied by the flow rate to obtain the mass of contaminant removed. The total mass removed at the Miscellaneous Chemical Basin

for a given time period is the sum of the mass removed from the individual wells. The cost of installation is then divided by the mass removed resulting in the cost per pound of contaminant removed. The cost per pound of removal is quoted for two time periods (and two flow rates): cost per pound for 1.1 year, and cost per pound for 10 years. The calculations show that contaminant concentrations in all wells will be approximately 1 ppmv within 10 years. The calculated mass removal and costs are presented in Tables 6 and 7. Cost estimates for a solar heat enhanced system will be developed after tests are concluded in FY98.

Table 6 - Mass Removed by PSVE from 10/7/96 to 11/7/97 and Projected Mass Removed in 10 Years

Well # MCB-	TCE Concentration Decay Constants		TCE Conc (ppmv) @ date:			Mass (kg) Removed by date			
	A	B	10/7/96	11/7/97	10/7/06	November 7, 1997 For Avg. Flow Rate:		October 7, 2006 For Avg. Flow Rate:	
						2.00 scfm	4.00 scfm	2.00 scfm	4.00 scfm
13	1.00E+20	-0.0012	38.00	23.63	0.47	2.67 kg	5.34 kg	6.97 kg	13.94 kg
10	1.00E+23	-0.0014	32.34	18.58	0.19	2.19 kg	4.38 kg	5.12 kg	10.23 kg
9	3.00E+40	-0.0025	126.41	46.97	0.01	7.08 kg	14.16 kg	11.27 kg	22.53 kg
11	2.00E+62	-0.004	7.95	1.63	0.00	0.35 kg	0.70 kg	0.44 kg	0.89 kg
8	3.00E+28	-0.0018	7.03	3.45	0.01	0.44 kg	0.89 kg	0.87 kg	1.74 kg
4	2.00E+21	-0.0013	22.17	13.25	0.19	1.53 kg	3.06 kg	3.77 kg	7.54 kg
7	9.00E+49	-0.0031	233.78	68.50	0.00	11.88 kg	23.76 kg	16.81 kg	33.61 kg
6	4.00E+44	-0.0028	41.85	13.81	0.00	2.23 kg	4.46 kg	3.33 kg	6.66 kg
1	4.00E+91	-0.0059	10.87	1.05	0.00	0.37 kg	0.74 kg	0.41 kg	0.82 kg
5	1.00E+58	-0.0037	16.01	3.70	0.00	0.74 kg	1.48 kg	0.96 kg	1.93 kg
17	3.00E+44	-0.0028	31.39	10.36	0.00	1.67 kg	3.35 kg	2.50 kg	5.00 kg
15	1.00E+50	-0.0032	7.58	2.13	0.00	0.38 kg	0.76 kg	0.53 kg	1.06 kg
16	5.00E+73	-0.0047	35.75	5.56	0.00	1.43 kg	2.86 kg	1.70 kg	3.39 kg
14	5.00E+86	-0.0056	5.47	0.60	0.00	0.19 kg	0.39 kg	0.22 kg	0.44 kg
22	4.00E+33	-0.0021	23.27	10.13	0.01	1.39 kg	2.79 kg	2.47 kg	4.94 kg
26	2.00E+22	-0.0014	6.47	3.72	0.04	0.44 kg	0.88 kg	1.02 kg	2.05 kg
24	4.00E+74	-0.0048	8.34	1.25	0.00	0.33 kg	0.66 kg	0.39 kg	0.77 kg
25	4.00E+33	-0.0021	23.27	10.13	0.01	1.39 kg	2.79 kg	2.47 kg	4.94 kg
23	9.00E+42	-0.0027	32.28	11.08	0.00	1.75 kg	3.50 kg	2.66 kg	5.33 kg

Conc = Ae^{Bt} . Assumes average flow rate when wells are blowing. Wells blowing out 50% of time

Table 7 - Total TCE Mass Removed and Estimated Cost for Removal

Flow Rate	After 1.1 years		After 10 years	
	2 scfm	4 scfm	2 scfm	4 scfm
Total Mass Removed	38.48 kg	76.94 kg	63.9 kg	127.8 kg
Removal Cost	\$1,559 / kg	\$780 / kg	\$939 / kg	\$470 / kg
	\$709 / lb	\$354 / lb	\$427 / lb	\$213 / lb

Installation Cost = \$60,000

Conclusions

The results to date on the treatability study of the PSVE system at the Miscellaneous Chemical Basin of the Savannah River Site indicate that the technology is performing well. In just over one year more than 100 pounds of chlorinated organic contaminants have been removed by natural barometric pumping of wells fitted with BaroBall valves (low pressure check valves). Contour maps of the vadose zone contaminant gas plume made before the study and after 1.1 years show a significant decrease in the extent of the soil gas plume and identify the source location. From extrapolations of the exponentially declining contaminant concentrations measured in the wells, all of the wells except those in the source zone are estimated to be below 1 ppmv in approximately three years simply using PSVE. The source zone wells are estimated to be below 1 ppmv in approximately 10 years using no additional remediation method.

Mass removal during this time frame is primarily attributed to residual contamination in the coarse grained material and some contaminant mass transfer from the finer grained zones to coarse zones where the majority of the PSVE flow is achieved. Removal from the fine grained sediments will be limited by the mass transfer from these zones to the coarse grained zones.

The PSVE system has required minimal operating and maintenance costs and can be expected to operate continuously for at least 10 years with no intervention. The cost for the initial installation of the system (including continuous geologic and chemical characterization, and the installation of 25 wells with screens lengths and positions selected based on depth-discrete soil gas analyses all performed in three weeks) was approximately \$60K.

To remediate the source zones more quickly, passive heat injection is proposed as an extension to the treatability study. From previous testing and theoretical calculations, the subsurface can be heated using a passive solar collector and passive soil vapor injection. If the subsurface temperature can be raised by 10 C, contaminant removal rate can be doubled.

All of the vadose zone extraction wells installed can also be used with an active vapor extraction system. This system would be most useful on wells near the source zone. An active extraction system will remove contaminants much faster than a PSVE system. An evaluation of the cost for installing and operating the active system should be compared with the current status quo (i.e., PSVE alone).

The PSVE system is performing well in a cost-effective manner. It is recommended that this system be allowed to continue operating for at least another year to verify the anticipated contaminant removal rates and to further evaluate removal effectiveness in the lower permeability zones.

References

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Riha, B.D., B.E. Pemberton, and J. Rossabi. 1996. "Miscellaneous Chemical Basin Expedited Site Characterization Report (U)". WSRC-TR-96-0407. Westinghouse Savannah River Company, Aiken, SC.

APPENDIX A - Well Vapor Concentrations

Date	MCB-1			MCB-4			MCB-5			MCB-6		
	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2
10/07/96	1.94	15.53	10200	19.90	75.90	12300	4.29	22.58	11800	12.16	28.45	4640
12/05/96	1.32	12.32	11200	19.94	76.33	13300	3.32	19.51	10700	9.55	19.48	1860
01/02/97	1.53	10.67	11700	20.29	76.86	12600	3.35	19.20	11000	17.11	36.98	6620
01/30/97	1.19	9.60	11400	18.12	75.65	10200	3.10	17.27	10700	14.45	31.01	3580
02/05/97	0.94	9.28	10800	17.59	74.78	9800	1.78	16.19	9030	12.33	30.54	5230
02/19/97	1.08	9.67	10800	14.65	69.66	11000	2.07	13.81	8620	10.74	25.16	3050
03/10/97	0.76	8.44	10900	17.95	78.61	10000	1.79	13.71	9440	10.56	25.13	3980
03/26/97	0.52	6.34	10200	17.07	72.94	9260	1.59	10.57	7740	6.56	14.34	1820
04/23/97	0.23	4.58	12000	18.38	75.94	10600	1.40	11.88	10900	8.26	21.96	7940
05/09/97	0.18	3.83	10600	17.40	75.33	10200	1.19	10.96	10100	8.83	22.60	5450
06/11/97	0.30	2.71	7710	16.38	68.81	9650	1.21	8.25	7930	5.01	8.96	2260
06/25/97										1.29	2.57	1810
07/01/97	0.60	3.47	14000	17.30	64.65	12900	1.60	9.59	12500	9.05	20.09	8540
07/09/97	0.55	2.59	10500	15.98	60.05	12200	1.35	7.50	9530	6.03	12.71	4720
07/16/97	0.54	2.84	11600	16.32	62.78	12500	1.46	8.44	11100	6.21	11.83	5700
09/03/97			0	9.96	43.72	5110			0	9.56	23.30	6720
11/07/97	0.59	2.57	15300	13.94	51.16	13100	1.32	6.18	9920	7.77	17.00	9210

All concentrations in ppmv and normalized by CO₂ levels

MCB-2: not completed as a well

MCB-3: not measured due to low concentrations and access problems

Date	MCB-7				MCB-8				MCB-9				MCB-10			
	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2	PCE	TCE	CO2	
10/07/96	12.04	34.73	6530	6530	4.64	11.00	4780	4780			0	13.52	57.38	6400		
12/05/96	14.69	39.56	8250	8250	4.92	11.27	7240	7240	9.77	26.25	9190	6.91	32.55	1980		
01/02/97	14.62	39.47	9030	9030	5.87	10.43	7320	7320	10.34	27.19	9400	12.76	51.65	4740		
01/30/97	15.76	43.05	9060	9060	2.94	7.57	4280	4280	9.06	24.38	8910			0		
02/05/97	12.59	38.40	8510	8510	3.00	7.99	5500	5500	7.82	22.42	8150	8.14	38.62	3460		
02/19/97	14.85	42.29	9480	9480	3.60	8.42	7140	7140	7.25	20.43	8790	8.98	43.59	4000		
03/10/97	10.84	32.57	8430	8430	3.21	7.59	5940	5940	6.30	18.45	7920			0		
03/26/97	9.28	27.29	7880	7880	2.77	7.53	5570	5570	5.05	13.73	6120	7.43	33.19	3460		
04/23/97	6.64	18.35	8930	8930	3.30	7.37	6430	6430	5.04	15.08	9210	12.69	52.33	8280		
05/09/97	8.10	22.43	8470	8470	3.00	7.04	6450	6450	4.93	15.58	8310					
06/11/97	6.35	18.32	8090	8090	1.88	4.49	4880	4880	5.73	15.79	8730	5.68	26.90	4037		
06/25/97												5.64	17.02	2700		
07/01/97	7.23	18.41	11600	11600	2.57	5.45	8390	8390	5.11	13.89	11400	9.96	39.42	8980		
07/09/97	5.90	16.34	10500	10500	2.06	4.46	6650	6650	8.78	23.94	6290	6.37	23.94	6290		
07/16/97	5.30	14.14	11200	11200	5.86	21.49	592	592	5.25	14.23	11300	9.22	32.09	7890		
09/03/97	6.26	19.53	9570	9570	2.30	6.07	7190	7190			0	8.31	39.86	7020		
11/07/97	8.16	17.42	16000	16000	2.21	4.76	9720	9720	3.96	10.09	11900	9.02	34.11	10100		

All concentrations in ppmv and normalized by CO₂ levels

Date	MCB-11			MCB-13			MCB-14			MCB-15		
	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2
10/07/96	2.54	18.50	12000	24.30	70.71	12100	2.32	16.62	10900	10.85	40.44	8130
12/05/96	2.00	15.00	11600	28.04	76.58	11000	1.85	11.57	11200	8.57	34.58	9370
01/02/97	2.30	15.20	12000	28.92	79.49	11700	1.66	10.61	12100	8.54	35.43	9720
01/30/97	1.87	13.31	11900	25.59	68.69	8770	1.08	8.63	12200	6.98	26.37	8420
02/05/97	1.46	13.37	11400	28.85	82.23	10500	0.92	8.79	11400	6.20	26.76	3980
02/19/97	1.45	10.89	11700	20.99	63.94	8360	1.34	10.54	10900	6.19	27.97	9480
03/10/97	0.99	10.70	12100	25.77	74.55	8430	0.69	7.50	11200	5.16	23.65	8080
03/26/97	0.98	8.52	12200	23.38	65.52	7330	0.51	5.62	10300	4.45	20.33	7650
04/23/97				32.17	84.93	10400	0.26	3.58	12900	4.59	22.14	8960
05/09/97	0.48	7.64	13000	20.24	58.99	6300	0.24	4.23	12000	3.69	18.95	7990
06/11/97	0.76	7.45	12900	16.79	47.48	7960	0.42	4.22	11000	3.82	19.41	8820
06/25/97				15.72	40.36	9010						
07/01/97	0.94	6.53	16000	27.71	66.73	12300	0.57	3.48	15400			
07/09/97	0.93	6.26	15700	22.71	57.22	12100	0.71	3.95	13800	4.06	16.90	10650
07/16/97	0.93	6.22	15800	24.94	61.22	12800	0.63	3.32	14800	4.05	17.50	10900
09/03/97			0	23.50	65.31	9160			0			0
11/07/97	0.70	4.33	17200	20.49	49.64	11000	0.49	2.09	16500	3.01	11.88	9580

All concentrations in ppmv and normalized by CO₂ levels
 MCB-12: no flow - well clogged

Date	MCB-16			MCB-17			MCB-19			MCB-20		
	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2	PCE	TCE	CO2
10/07/96	4.35	26.65	10400	8.38	51.61	10300	7.56	30.93	7760	6.73	40.07	11800
12/05/96	3.01	19.03	11100	9.10	54.00	10000	5.21	22.75	5960			
01/02/97	2.48	17.59	11800	9.09	53.94	10300	9.73	25.55	1320			
01/30/97	2.34	15.33	11900	6.84	49.07	8510	3.69	20.12	6500			
02/05/97	2.72	14.48	11100	6.19	47.49	8860	5.40	20.49	5350			
02/19/97	2.30	16.38	10900	5.37	43.53	7770	2.79	11.93	8180			
03/10/97	1.56	12.44	11500			0	5.20	19.94	7590			
03/26/97	1.05	8.45	11200	5.51	43.68	8390	4.07	16.51	6640			
04/23/97	0.83	6.65	11500	4.53	35.70	10000	6.92	24.07	9630			
05/09/97	0.94	7.27	11600	4.32	36.09	9140	6.09	21.75	8830			
06/11/97	1.01	7.65	12100				3.82	11.00	684			
06/25/97				3.91	28.19	10600				1.19	5.18	844
07/01/97	1.10	6.57	15100	4.60	29.66	12300				2.72	15.96	5520
07/09/97	1.32	7.14	15000	3.77	22.12	10200	5.21	17.55	12000	0.36	17.55	12000
07/16/97	1.18	6.52	15600	3.20	22.27	11100	6.74	16.09	977	2.84	12.67	2510
09/03/97	0.86	6.99	12400	3.61	30.60	10100	5.38	21.35	11200	2.89	18.83	4200
11/07/97	0.88	3.96	15900	3.27	21.74	13400	4.85	15.31	14800	2.39	13.40	5350

All concentrations in ppmv and normalized by CO₂ levels

MCB-18: no flow - well clogged

MCB-20: sealed for pressure measurements until 6/25/97

Date	MCB-21				MCB-22				MCB-23				MCB-24			
	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2
10/07/96	10.14	52.43	10300	13.97	63.34	12200	12200	6.00	27.45	10100	10100	7.94	24.60	9950	9950	
12/05/96	0.02	17.52	781	12.05	57.51	9160	9160	5.57	28.58	11000	11000	5.24	16.32	8160	8160	
01/02/97	6.79	24.64	2050	13.89	62.67	10800	10800	5.66	27.57	11100	11100	5.68	16.71	9840	9840	
01/30/97	0.01	17.14	910	11.39	58.40	9020	9020	5.48	24.00	11100	11100	4.33	14.50	9680	9680	
02/05/97	1.85	4.61	706	12.12	62.99	9680	9680	4.31	24.80	9600	9600	3.69	12.14	9030	9030	
02/19/97	4.96	4.09	424	9.29	54.56	8840	8840	3.99	22.68	9530	9530	4.12	13.55	9480	9480	
03/10/97	0.91	3.92	560	10.24	56.47	8560	8560	3.79	22.91	10300	10300			0	0	
03/26/97	3.43	17.97	2260	6.67	39.47	6560	6560	3.28	19.29	10500	10500	2.48	9.13	9240	9240	
04/23/97				7.55	43.30	10200	10200	2.87	18.24	10300	10300	1.78	6.98	9190	9190	
05/09/97	3.64	21.10	3760	7.78	48.05	9930	9930	2.82	18.39	10500	10500	1.85	7.30	9580	9580	
06/11/97				6.61	40.34	8980	8980	2.81	16.99	10200	10200	1.92	6.43	8280	8280	
06/25/97	3.26	19.62	5480	4.45	25.71	7840	7840									
07/01/97	4.60	25.23	7150	7.89	40.67	12600	12600	2.98	15.53	12900	12900	1.95	5.84	12200	12200	
07/09/97	3.21	17.82	5800	5.34	26.60	10600	10600	3.03	14.95	12800	12800	1.90	5.80	11500	11500	
07/16/97	4.86	28.15	8270	6.52	37.12	11800	11800	2.88	15.14	13000	13000	1.68	4.68	11700	11700	
09/03/97			0	7.08	44.96	8870	8870			0	0	1.45	5.76	10300	10300	
11/07/97	3.81	22.74	8770	6.65	35.42	14000	14000	2.27	10.60	13200	13200	1.77	4.19	12800	12800	

All concentrations in ppmv and normalized by CO₂ levels
 MCB-21: open venting (no Baroball) until 3/16/97

Date	MCB-25				MCB-26			
	PCE	TCE	CO2	CO2	PCE	TCE	CO2	CO2
10/07/96	14.00	42.39	7870	7870	15.35	37.15	7170	7170
12/05/96	13.77	43.08	6240	6240	12.68	25.30	4790	4790
01/02/97	13.69	45.17	6960	6960	15.63	32.12	7510	7510
01/30/97	10.59	35.87	5520	5520	10.43	22.49	4370	4370
02/05/97	9.90	38.48	6050	6050	12.15	25.38	5800	5800
02/19/97	9.85	37.92	6360	6360	11.82	23.56	6160	6160
03/10/97	9.51	37.61	6190	6190	11.54	22.19	5880	5880
03/26/97	7.99	31.58	5620	5620	8.80	18.17	5230	5230
04/23/97					11.00	21.17	8630	8630
05/09/97	8.59	36.90	6790	6790	10.51	19.89	6930	6930
06/11/97	5.43	23.38	5180	5180	8.57	18.50	5260	5260
06/25/97								
07/01/97	8.65	32.85	9060	9060	12.68	21.62	10600	10600
07/09/97	7.58	29.41	8140	8140	10.83	18.47	8610	8610
07/16/97	8.93	30.54	8880	8880	14.89	22.95	3530	3530
09/03/97			0	0	12.49	25.09	8820	8820
11/07/97	5.45	17.81	4870	4870	10.01	17.10	10500	10500

All concentrations in ppmv and normalized by CO₂ levels