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Effects of Natural Environmental Changes on Soil-Vapor Extraction Rates

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Effects of Natural Environmental Changes on Soil-Vapor Extraction Rates

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ABSTRACT: Remediation by soil-vapor extraction has been used for over a decade at Lawrence Livermore National Laboratory (LLNL). We have found that natural changes in environmental conditions affect the rate of soil-vapor extraction. Data on flow rate observations collected over this time are compared to in-situ measurements of several different environmental parameters (soil-gas pressure, soil-temperature, soil-moisture, Electrical Resistance Tomography (ERT), rainfall and barometric pressure). Environmental changes that lead to increased soil-moisture are associated with reduced soil-vapor extraction flow rates. We have found that the use of higher extraction vacuums combined with dual-phase extraction can help to increase pneumatic conductivity when vadose zone saturation is a problem. Daily changes in barometric pressure and soil-gas temperature were found to change flow rate measurements by as much as 10% over the course of a day.

INTRODUCTION

Vapor Treatment Facility 518 (VTF-518) was established in 1995 to treat Chlorinated Volatile Organic Compounds (CVOCs) in the vadose zone by soil-vapor extraction. Design criteria that lead to the establishment of the facility are described by Berg et al (1994). Soil-vapor was successfully removed from extraction well SVB-518-201 at VTF-518 at rates of up to 34 m^3/hour of soil-gas at vacuums up to 127 mm Hg until 1997. CVOC vapor in this soil-gas was removed with Granular Activated Carbon (GAC).

In the first two years of operation, the facility performed well and operational data were used by Nitao et al (2000) to verify and calibrate the NUFT numerical model of soil vapor extraction. In March of 1997, well SVB-518-303 was added to the soil vapor extraction system (VES). In early April of that year, flow from the primary extraction well SVB-518-201 began to decline. By early 1999 soil-gas could not be extracted under normal process conditions from the primary extraction well, nor from two secondary wells (SVB-518-204 and SEA-518-301), although soil-gas was still successfully extracted from SVB-518-303. The facility was shut down in 1999 due to low flow rates, and lack of CVOCs in SVB-518-303. Evaluation of existing and new data at that time suggested that the reduction in soil-gas extraction flow rate was due to reduced pneumatic conductivity. Heavy rainfall from the 1995-98 El Niño events were thought to have increased vadose zone saturation, with the possible return of a perched aquifer observed in 1989. The addition of well SVB-518-303 may have hastened the decline of flow rates in SVB-518-201 because of its extremely long screen (it was screened to 2 m below the surface) and was added just as the heavy El Niño rains commenced. Well SVB-518-303 potentially acted as a conduit to allow perched water from shallower zones to reach the deeper zones where the primary extraction wells were completed.

In an effort to resume our remediation efforts, new wells were drilled to monitor conditions in the vadose zone and to provide alternate points for soil-vapor extraction. Several new and existing wells were instrumented in the vadose zone to monitor soil conditions. Well SVB-518-303 was destroyed due its poor completion and replaced by SVB-518-1915 in 2003 (Figure 1). Data collected from these monitoring wells while the facility was down revealed additional episodic and cyclic changes in soil-temperature, soil-gas pressure and soil-moisture that had the potential to impair extraction efficiency.

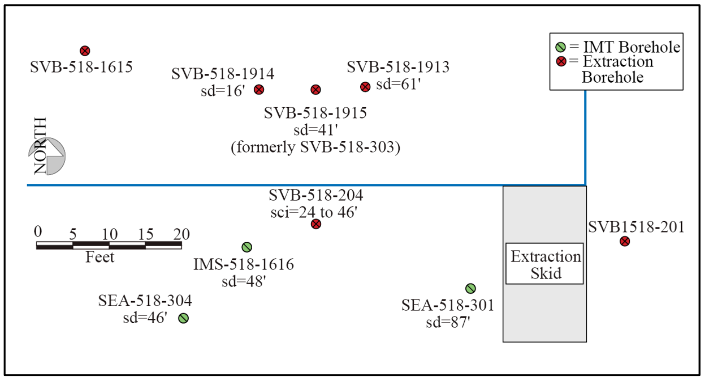


FIGURE 1: Borehole layout at VTF-518.

In 2004, a vapor extraction system capable of sustained vacuums greater than 710 mm Hg was installed. When the flow rates from six individual extraction wells were optimized for maximum vapor removal, the new system generated soil-gas flow rates up to 15 m^3/hour. Before rains from El Niño events impacted this site in 1998, flow rates greater than 34 m^3/hour were extracted from a single well. Because this new system generated such high vacuums, considerable up-coning of water into the screened section of these wells occurred. The use of dual-phase (gas and water) extraction in response to this problem has allowed us to sustaining maximum flow rates over time, helped to de-water the vadose zone, has increase the rate of soil-gas extraction in these wells, and is shortening the time to cleanup.

MATERIALS AND METHODS

Prior to 2004, a Sutorbilt positive displacement blower driven by Baldor 5 hp Blower Motor was used for vapor extraction at VTF-518. Because the GAC canisters used in this system were under vacuum, our maximum extraction vacuum was limited to 127 mm of Hg.

In 2003, five new extraction/monitoring wells were drilled (Figure 1) for use by VTF-518. Three of these wells (-1913, -1914, and -1915) were equipped with Electro Resistive Tomography (ERT) sensors spaced at 46 cm intervals. The primary purpose for all of these wells is to provide additional soil-vapor extraction points for our new vapor extraction system.

As mentioned, various parameters, such as soil-gas pressures, soil-moisture, and soil-temperatures were measured at discrete depths in several boreholes in the VTF-518 area. All these data were collected with sensors deployed in uncased boreholes using Instrumented Membrane Technology (IMT) borehole liners, Keller (1993), currently provided by Flexible Liner Underground Technologies (FLUTe), Santa Fe, NM. Two of these instrumented liners were in use since 1994 in boreholes SEA-518-301 and SEA-518-304. In 2003, a third liner was installed into borehole IMS-518-1616. Soil-gas pressures are logged from the instrumented wells SEA-518-301, SEA-518-304 and IMS-518-1616 (Figure 1) with a Campbell Scientific CR10 data logger. Pressure ports from these wells are multiplexed to Setra Model 264 pressure transducers as described by Martins (2000). Soil-temperatures and soil-moisture content are also logged onto this data logger. Prior to the year 2000, soil-moisture was measured with model GB-1 (Delmhorst, Towaco, NJ) agricultural gypsum blocks. Because gypsum blocks degrade quickly, soil-moisture is presently monitored with sorbent-pads pressed between the soil and two conductivity electrodes, Martins (2000) and Keller (1993). Soil temperatures are logged with Campbell Scientific Model 107 thermistors.

In 2004, a model 2BL1041 Airtech, Inc. (Englewood, NJ) liquid-ring vacuum pump replaced the old blower. This new system was able to create a vacuum greater than 700 mm Hg. Flow rates up to 15 m^3/hour from the combined influent of six extraction wells are routinely achieved with the new system. Flow rate data are now measured with venturi flow meters (Gerand Engineering Co., Minnetonka, MN). The differential pressure across each venturi is monitored with series 2000 indicating Magnahelic dial-manometers (Dwyer Instruments, Inc., Michigan City, IN). Both the venturis and the Magnahelic are sized appropriately for each well. Figure 2 shows the soil-gas flow rate monitoring manifold. The flow signal from each of these pressure transducers is logged electronically with an LLNL-modified and programmed TFX-11 single board computer (Onset Computers, Bourne, MA). Soil-gas temperature at each venturi and barometric pressure used in flow calculations are also logged. Each Venturis-Magnahelic combination has been calibrated for the well with which it is used. The resulting differential pressure signal is used, along with line vacuum data, flow sensor temperature and atmospheric barometric pressure to calculate flow rates in Standard Cubic Feet per Minute (SCFM) for each well according to the methods of ISO 5167-1 (1991) and ASME (1971).

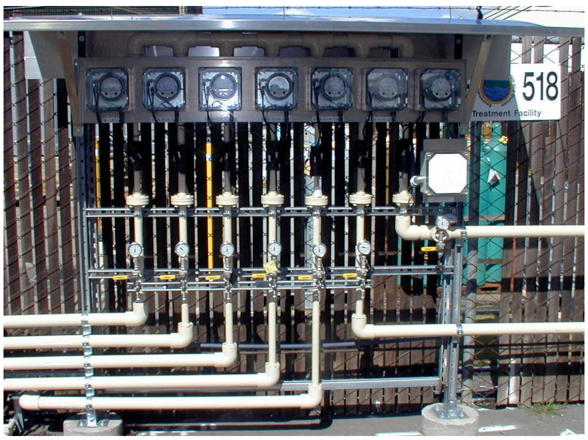


FIGURE 2: VTF-518 soil-gas flow monitoring manifold.

Soil-moisture content is inferred from electrical conductivity measurements made either in the gypsum blocks or with sorbent pads. While conductivity measurements are both temperature and solute depended, the temperature component is easily corrected.

ERT is used to monitor changes in subsurface soil-moisture over time. Using the ERT electrodes deployed in boreholes -1913, -1914, and -1915, electrical resistance baseline measurements were made between all of the individual electrodes in each of these boreholes from October 17 to 24, 2003. Measurements made over the next year were compared to this baseline. The ERT transmitters, multiplexers, receivers and power supplies were provided by Zonge Engineering and Research Organization, Inc. of Tucson, AZ. When ERT data are acquired, an electrode pair in the soil is excited with alternating current and the resulting signal is measured with two other electrodes. This signal is logged as intensity (labeled “absolute” in the tomographs) with a phase-shift component. After measurements are made between the first set of electrode pairs, additional measurements are made between other sets of electrode pairs until the entire volume of soil has been described. Raw data from these ERT measurements were processed into two dimensional tomographs using the methods described by Daily et al (2005 and 2004).

RESULTS AND DISCUSSION

As can be seen in Table 1 and Figure 3a, soil-gas flow rates started dropping at VTF-518 in early April of 1997. Around this time, unusually heavy rains associate with the 95-98 El Niño condition occurred at this site. Table 1 data indicate that rainfall between

1995 and 1998 were far heavier than normal, either in total rainfall for the year or in the amount of rain received prior to February 1 in each of these years. Figure 3a clearly shows soil-moisture at 2 m increased through the end of 1997. While rainfall between 1999 and 2001 were about normal or below normal, subsequent extraction attempts in 2000 and 2001 was unsuccessful using the old VES system operated at a vacuum of 127 mm Hg.

Table 1: Precipitation at LLNL from 1995 through 2001, Laguna et al (1998) associated with soil-gas flow rates from SEA-518-201.

Rain Season [a]	Precipitation as Percent of Normal Rainfall [c]	Precipitation as Percent of Normal Rainfall [c] on Feb. 1	Annual Average Flow rate (m^3/hour) on Feb. 1
95-96[b]	**167.9%**[d]	**176.9%**	34
96-97	82.3%	**140.3%**	34
97-98	**173.5%**[d]	**142.5%**	15
98-99	88.0%	87.4%	1
99-00	113.2%	65.5%	-
00-01	70.7%	54.2%	-

a. The rain season starts on July 1 and ends on June 30.
b. Data from 1995 were obtained from a different rain gauge at the LLNL meteorological site.
c. Average precipitation at LLNL between 1995 and 2005 was 13.13 Inches (33.3 cm). Normal rainfall on February 1 is 7.26 Inches (18.4 cm).
d. Precipitation between July 1, 1995 and June 30, 1998 were unusually high, either because of total precipitation for the year or because a high rate of precipitation was experienced prior to February 1.

Figure 3b details the first 15 months of operation using the new VTF-518 SVE system. After an initial drop during the rainy season of 2004-05, flow rates generally increased through early 2006. The soil-moisture at 2 m in well SEA-518-301 followed seasonal changes in precipitation when soil-gas extraction was underway. During the

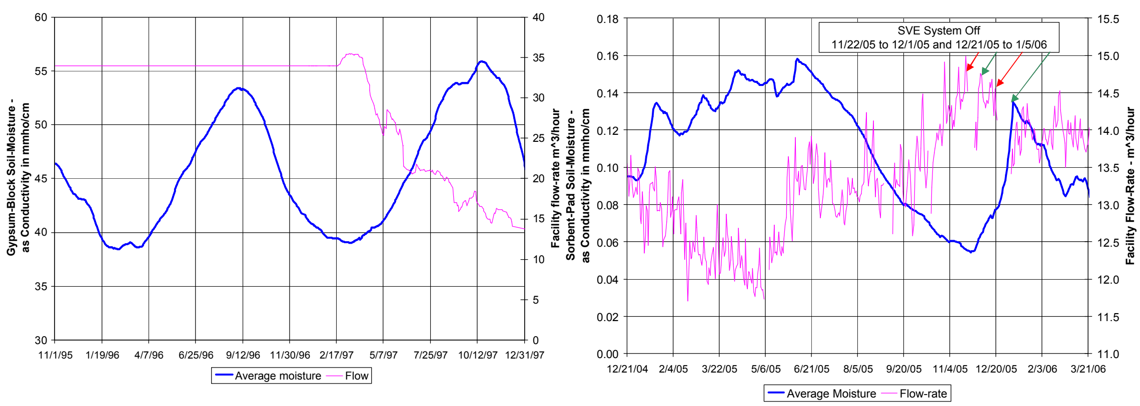


FIGURE 3: a) Soil-moisture in SEA-518-301 at 2 m from 11/1/1995 to 12/31/1997 versus SVE soil-gas flow rate from one well (on the right), and b) soil-moisture in SEA-518-301 at 2 m from 12/21/2004 to 3/21/2006 versus SVE soil-gas flow rate from six wells (on the left). Soil-moisture decreases as the values expressed as millimhos per cm (mmho/cm) decrease.

time when soil-gas was not extracted (e.g. between 12/21/2005 and 1/5/2006), soil-moisture increased (Figure 3b). The annual soil-moisture averages (year-to-date) decreased by about 20% between 12/22/2004 and 12/21/2005 when 700 mm Hg of vacuum was used. From Figures 3a and 3b one may infer that higher soil-moisture content seems to be associated with lower flow rates at VTF-518.

Differences in environmental and operating conditions can account for the different trends observed in Figures 3a and 3b. In Figure 3a, the facility flow rate drops dramatically and continues to decrease even after surface soils show some drying. After an initial drop in flow rate during the 2004-05 rainy season in Figure 3b, the flow rate increases with time and the shallow soils are seen to become dryer. As mentioned previously, soil-gas was extracted from a single well at about 120 mm Hg vacuum during the time span shown in Figure 3a. Soil-gas was extracted from 5 or 6 wells at ~700 mm Hg vacuum during the time span shown in Figure 3b. Using multiple extraction wells under higher vacuums along with dual phase extraction (gas and water) was effective in drying the formation and increasing the pneumatic conductivity. This change in condition resulted in an increase in soil-gas flow rates.

During the VTF-518 feasibility study performed in 1994, “pump curves” were generated where soil-gas extraction rates were measured at several different extraction vacuums, Berg et al. (1994). On the first day of the test, soil-gas was extracted with a vacuum of 127 mm Hg from well SVB-518-201 at a rate of ~20 m^3/hour. The next day, a series of tests were run using vacuums ranging from 127 mm Hg to 700 mm Hg. On the third day, soil-gas was again extracted at 127 mm Hg, but the flow rate had increased to 34 m^3/hour. When the facility was brought online in 1995, the flow rate remained at 34 m^3/hour until 1997. This experience demonstrates that the pneumatic conductivity can be improved with higher soil-gas extraction vacuums. The increase in soil-gas flow rates, shown in Figure 3b, suggests higher SVE vacuums have improved pneumatic conductivity as they did during the tests in 1994.

Figures 4a and 4b show that the vacuum around vadose zone monitoring wells at VTF-518 has increased since the facility was restarted in 2004. This indicates that the zone of influence around the extraction wells is increasing with time and may be related to vadose zone de-saturation described above. This trend is seen at depths of 1.8 m to 26.5 m in wells SEA-518-301, IMS-518-1616 and SEA-518-304 (not shown in the figure).

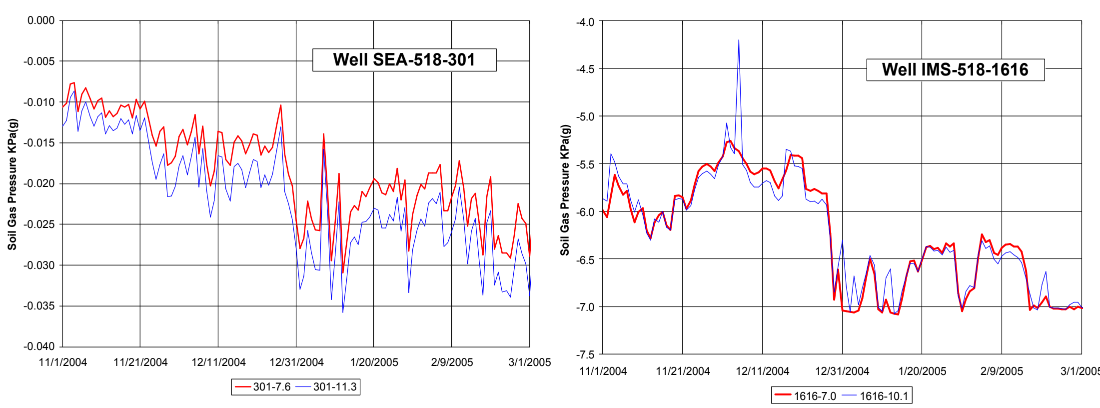
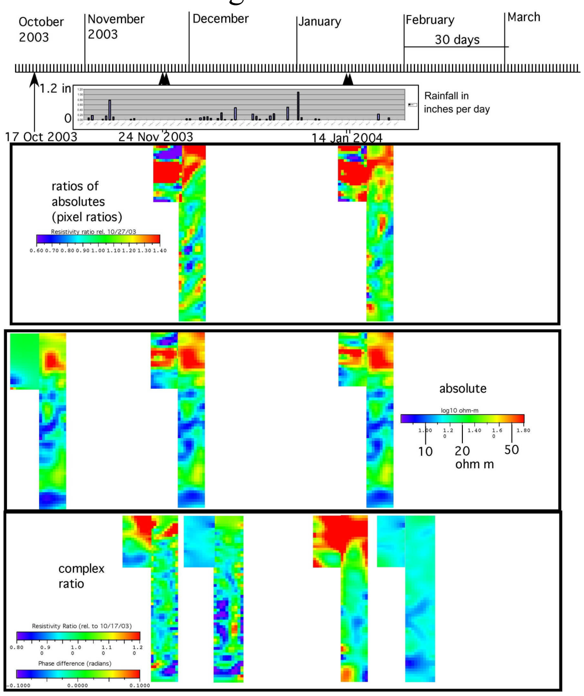


FIGURE 4: a) Soil gas pressure measured at wells SEA-518-301 (left), and b) IMS-518-1616 (right) decreased with time after the onset of soil vapor extraction at all depths as vapor-capture zone of influence increases.

Figures 5a and 5b are tomographs representing ERT data obtained at VTF-518 just prior to startup and after the first year of operation. Because electrical resistivity is a function of pore water content, water chemistry, temperature and surface electrochemistry (e.g., clay content and type) all of these data are compared to baseline measurements made in 2003. Our interpretation of these data assumes that all conditions are constant except water content and that a resistivity ratio greater than one means that moisture content is decreasing relative to the baseline.

With this assumption, it can be inferred that 1) spatial trends in wetting and drying have continued over the 2 year period shown in Figure 3b, and that areas where drying began during the first year continue to dry. An exception to this observation can be found in the soil column between the two boreholes at 12 m depth that showed drying only during the second year. 2) The region from the surface to about 5 m depth is drying slightly over time. 3) The region showing the most prominent wetting is the area adjacent to the screened region around borehole -1915.



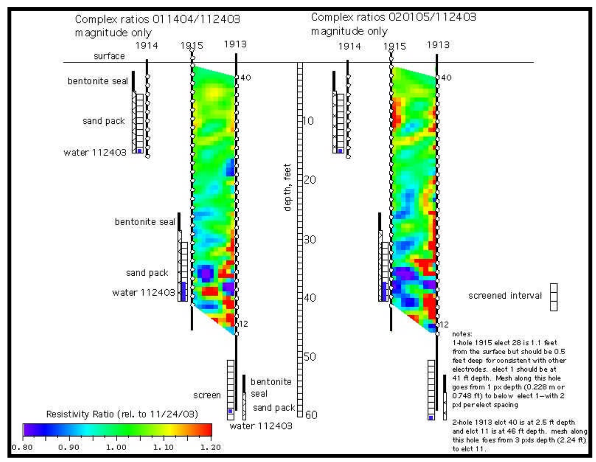


FIGURE 5: a) Time-line of ERT results (to the left) and b) changes over the first year of extraction (above). Charts are expressed as absolute values, and complex and absolute ratios using baseline data from 10/17 and 10/27/2003.

Figure 5a displays the absolute resistivity measurements made during baseline observations, ratios of resistivity to the baseline during this period and complex ratios of both resistivity and phase data over time.

Figures 6a and 6b demonstrate how changes caused by short term weather fronts and diurnal changes can influence soil-gas extraction rates. Figure 6a correlates changes in atmospheric barometric pressure to changes in soil-gas flow rates, which occur over a period of about four days. Figure 6b shows that daily changes in measured flow rate are associated with changes in influent soil-gas temperatures. Both soil-gas temperature and barometric pressure are measured and used with differential pressure measurements across venturi sensors to calculate flow rate. Figure 6b shows that daily changes in soil-gas flow rates vary as much as 8% each day. Figure 6a shows that changes in soil-gas flow rate over a four day period can be as high as 10%. Accurate flow rate measurements are required for accurate mass-removal calculations. It is therefore wise to electronically log flow rate data for these calculations rather than use the "snapshot" approach where flow rates are manually recorded at intervals as great as a month.

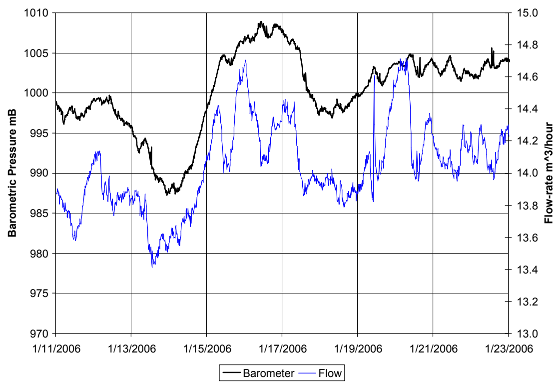


FIGURE 6a: Influent soil-gas flow-rate appears to follow barometric pressure changes.

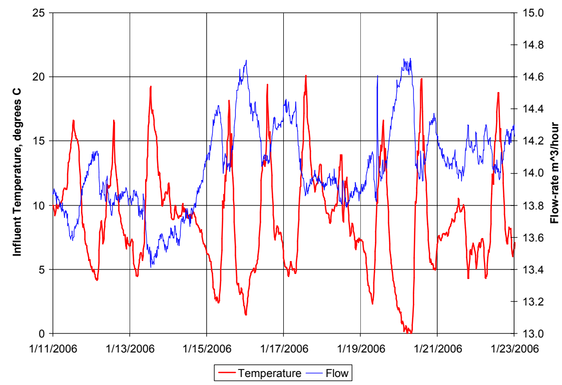


FIGURE 6b: Influent soil-gas flow rate appears be inversely related to temperature changes.

CONCLUSIONS

Changes in natural environmental conditions can impact soil-vapor extraction rates. We have seen that water saturation in the vadose zone caused by the 1995-98 El Niño events resulted in the reduction of soil-gas flow rate from 35 m^3/hour to 0.

Higher extraction vacuums can partially overcome reduced pneumatic conductivity caused by vadose zone water saturation, but often require the use of de-watering to manage the up-coning of water in extraction wells. Results from this site, both during the feasibility study performed in 1994 and from the results obtained after the installation of the new VES system indicate that sustained higher extraction vacuums over time can cause pneumatic conductivity to increase through vadose zone de-watering and through the expansion of preferential pathways. Data presented from ERT observations, soil-moisture sensors and soil-gas flow rate observations agree with this assertion.

Data from the wide variety of vadose zone instrumentation at this site helped us to understand the soil-vapor extraction problems we encountered.

One should not underestimate the effect short term changes in environmental conditions can have on soil-gas extraction rates. We routinely see daily changes in flow rates of 8% and weekly changes in flow rate of 10% that are associated with changes in temperature and barometric pressure.

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