

VAPOR EXTRACTION VOLUNTARY CORRECTIVE MEASURE AT THE CHEMICAL WASTE LANDFILL, SANDIA NATIONAL LABORATORIES/NEW MEXICO

James E. Studer, P.E., P.G., Lee Brouillard, and Cynthia Ardito
(Duke Engineering and Services, Albuquerque, New Mexico)

Richard E. Fate (Sandia National Laboratories, Albuquerque, New Mexico)

ABSTRACT

The Chemical Waste Landfill (CWL), located at the Department of Energy's Sandia National Laboratory, Albuquerque, New Mexico (SNL/NM), is an Interim Status Facility undergoing RCRA corrective action. Starting in 1962, bulk liquids, bulk solids, and containerized wastes were placed in unlined pits excavated in permeable sediment to approximately 3.7 meters (m) below ground surface (bgs). Disposal records were kept for the period 1975 through the end of pit disposal operations in 1981. By extrapolation, it is estimated that a total of over 363,000 kilograms (kg) of organic chemical wastes, including approximately 182,000 kg of volatile organic compounds (VOCs) were disposed. Over 100 priority pollutants have been detected in the sediment and soil gas beneath the CWL. Groundwater located at approximately 152-m bgs is impacted by low concentrations of chlorinated solvents, principally trichloroethene (TCE).

In May 1995, SNL/NM determined that the cycle of data collection for the RCRA Facility Investigation could not be adequately managed and opted for a pro-active strategy. It was determined that Voluntary Corrective Measures (VCMs), in the form of vapor extraction (VE) and landfill excavation (LE) VCMs, would serve to efficiently remove important sources of contamination, eliminate exposure pathways, and significantly streamline final corrective actions. The Closure Plan provides for the possibility of one or more VCMs, although specifics were not written into the plan. By December 1995, SNL/NM and the New Mexico Environment Department (NMED) were in general agreement on the value, basic features, and timing of the two VCMs.

The VE VCM design process began with detailed review of the source area and calculation of initial mass to be used as the basis for performance assessment. Multiple pilot tests were performed to provide site-specific data for the design basis. Given the deep-water table aquifer and the large-volume vapor plume, depth-specific performance objectives were established and a two-year performance period proposed. An alternatives identification and engineering evaluation was complete prior to the design. Seven different scenarios were developed and simulated using a three-dimensional airflow model, AIR3D. The final design incorporated 13 wells (eight existing vapor extraction wells or groundwater monitoring wells) installed at three general levels within the system (shallow, intermediate and deep), 7 unique subsystems incorporating one to three wells, 52 in-situ soil gas/pressure monitoring points, a total extraction rate of 58 m³/min, and a total injection rate of 11.3 m³/min.

Vapor extraction started in May 1997 and ended in July 1998. Approximately 2086 kg of VOCs were extracted during approximately nine months of active extraction. In-situ, VOC concentrations dropped dramatically across the site. Initial soil gas concentrations ranged in the

hundreds to low thousands of ppm_v and declined to less than 10 ppm_v in most areas. Except for two areas of limited rebound observed within two months of system shut-down, VCM performance objectives developed for a two-year operational period were met in one year of operation. TCE concentrations in groundwater have been below drinking water standards for three-quarters.

The VE VCM is essentially complete as of September 1998. The outcome after one year of operation was similar to design predictions, which suggests that site conditions are reasonably well characterized from a VOC fate and transport perspective. The time and total cost to obtain closure via a VCM-driven strategy is estimated to be one year and \$1 million dollars less than the typical RFI–CMS–Corrective Measures Implementation process.

INTRODUCTION

The Chemical Waste Landfill (CWL), located at the Department of Energy's Sandia National Laboratory, Albuquerque, New Mexico (SNL/NM), is an Interim Status RCRA Facility undergoing corrective action. This two-acre waste management facility was closed in 1985 after approximately 28 years of being used as the principal chemical waste disposal and temporary storage facility for SNL/NM. The SNL/NM Environmental Restoration (ER) Project is charged with addressing buried waste and contaminated sediment and groundwater beneath the site and obtaining regulatory closure along with a RCRA Post-Closure Care Permit.

In May 1995, the ER Project determined that the conventional RCRA corrective action process was not supporting a timely and cost-effective closure at the CWL. For the purposes of this paper, the conventional RCRA process refers to the step-wise sequence of site characterization followed by remediation activities. These activities are grouped into the RCRA Facility Investigation (RFI), Corrective Measures Study (CMS), and Corrective Measures Implementation (CMI). The ER Project determined that a corrective action process driven by aggressive source removal would support more effective closure efforts. Further, more aggressive action would rapidly reduce risks, break the cycle of data collection, and re-focus stakeholder interests on achieving regulatory closure. The regulatory vehicle employed to accelerate the project is called the Voluntary Corrective Measure (VCM). VCMs are explicitly allowed by the CWL Closure Plan and Post-Closure Care Permit Application and can theoretically be performed at any point during the corrective action process (1).

This paper describes the Vapor Extraction (VE) VCM. This VCM was focused on reducing the magnitude and extent of a relatively large soil gas plume containing volatile organic chemicals (VOCs). The principal means of achieving these reductions was through vacuum-enhanced removal of VOCs in soil gas, volatilization of VOCs from pore water and sediment surfaces to the soil gas. Clean air injection into the soil gas plume was performed to assist in the VOC mass removal. The VE VCM is part of an integrated VCM strategy that also involves a second VCM for removal of waste materials and impacted sediment within 6.1 m of ground surface. The second VCM is referred to as the Landfill Excavation (LE) VCM, and is not the subject of this paper.

The remainder of this paper describes 1) the goals, objectives, and basis for the VE VCM; 2) design, construction, and operation of the vapor extraction and air injection system; and 3) the influence that the VE VCM has had on the extent and magnitude of VOC contamination. Figure 1 shows the site boundary, groundwater and vadose zone wells, and the VE VCM manifold system.

SITE CONDITIONS

The CWL is located in a semi-arid climatic region with an annual average precipitation of approximately 20 centimeters. Most precipitation occurs as thunderstorms during late summer to early autumn. The average daytime summer temperature is approximately 32 °C and the average daily winter temperature 10 °C. Topography in the area of the site consists of a gently sloping surface directed away from granite mountains to the east. The CWL is located in an industrial use area, and the nearest public access is 1.5 mile to the east-southeast.

The sediments underlying the CWL are a heterogeneous sequence of unconsolidated to semi-consolidated cobbles, gravels, very fine-to-fine sands, silts, and clays of alluvial origin, locally cemented by calcium carbonate. In general, the lithologic sequence shows a coarsening-upward sequence, with a higher percentage of clay, clayey sand, and silt layers with depth (2,3). Porosity values for CWL soils range from approximately 18-45 percent. Bulk density values from CWL soil samples range from 1.4 - 2.0 gm/cm³ (3). Weight percent soil moisture in the unsaturated zone ranges from 1.2 to 4.8. Assuming a bulk density of 1.8 gm/cm³ for the sediments at the site, the volumetric moisture ranges from 2.2 to 8.7 percent (4).

The water table occurs at a depth of approximately 149-m bgs. Saturated conductivity ranges from 6.7×10^{-6} to 3.8×10^{-3} cm/sec. The CWL is approximately 6.4 kilometers south of the nearest drinking water supply well.

Starting in 1962, bulk liquids, bulk solids, and containerized wastes were placed in unlined pits excavated to approximately 2.1m to 3.9 m bgs. These unlined pits occupy approximately 50% of the CWL surface area. Wastes were segregated by chemical type and compatibility. Wastes included solvents, oils, metal acids, reactive materials, oxidants, and reducing agents. Relatively detailed disposal records are available for the period 1975 through the end of pit disposal operations in 1981. However, records are incomplete for the years 1962 to 1974. VOCs represent the most significant waste constituent type at the CWL from an environmental mobility and health risk perspective. It is estimated that approximately 200,000 kg of VOC wastes were disposed.

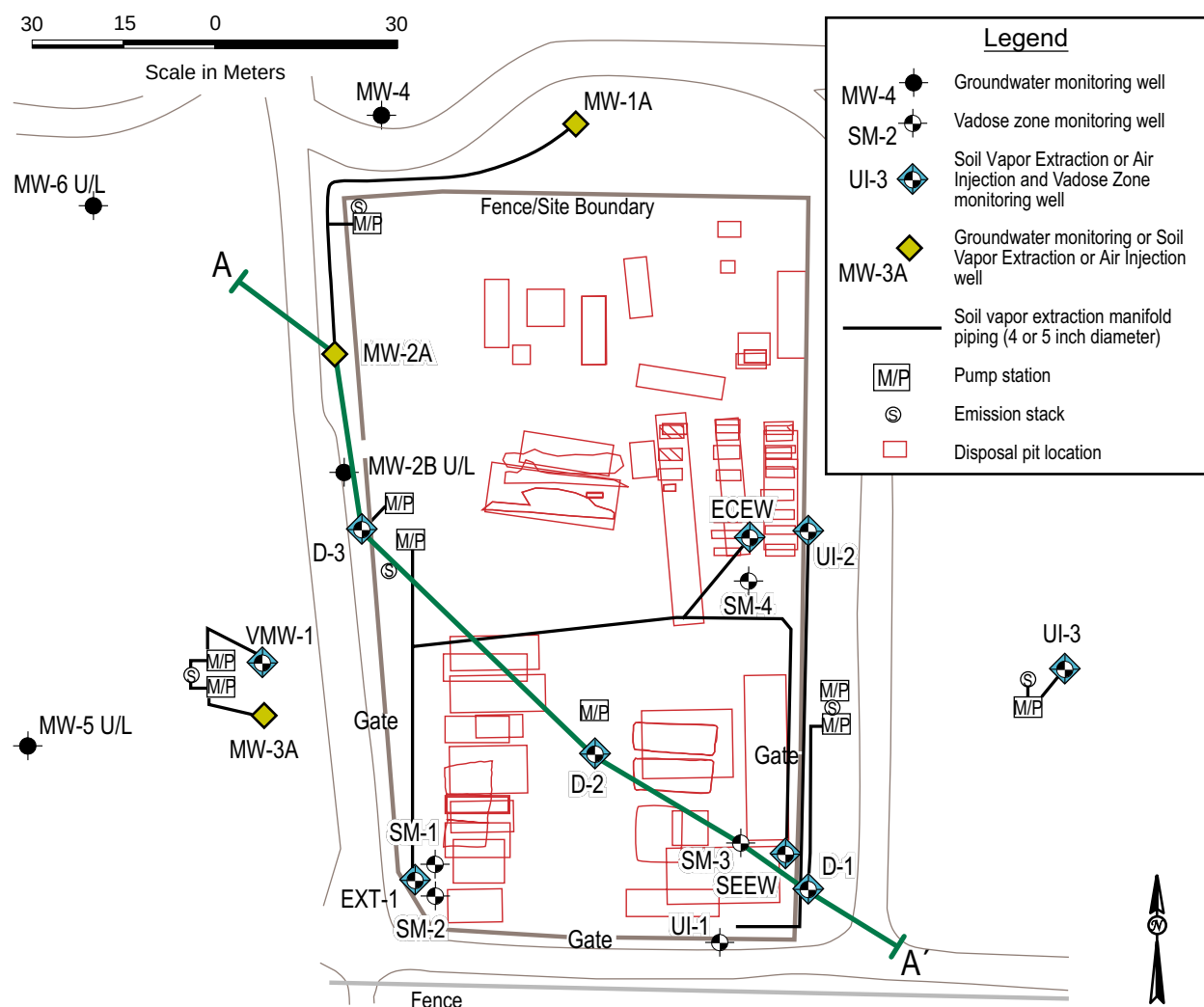


Figure 1. Site Map for the Chemical Waste Landfill

Table 1 summarizes waste volume and mass estimates for the 25 VOC waste constituents disposed at the CWL over the entire 28-year disposal-use period (5). TCE and acetone are the two most prevalent constituents of this group, with estimated disposal volumes of 52,172 Kg and 65,740 Kg, respectively.

Significant waste migration beyond the limits of the disposal pits has been documented (1, 2, 3). Over 100 priority pollutants have been detected in the subsurface sediment and/or soil gas beyond the pits themselves (2,3). Field evidence suggests that a significant volume of spent non-aqueous phase liquid (NAPL) solvents and other organic constituents entered the sediments, beneath certain burial pits, shortly after disposal. These fluids migrated downward approximately 9.1 m in one location and more or less at other locations. In effect, this early penetration of VOCs resulted in isolated volumes of sediment holding VOC mass that slowly volatilized over time, representing, along with the pit contents themselves, persistent VOC sources for a soil gas plume. VOCs have, however, been detected in soil gas and sediment well beyond these isolated zones - at distances exceeding 30.5 m laterally and 146.3 m vertically from suspected source

zones. This more extensive migration of VOCs, through the relatively permeable and dry vadose zone, is due to molecular diffusion and advection.

Since 1990, low concentrations (i.e., typically 5 -10 ppb_v) of the chlorinated solvent TCE have been consistently detected in quarterly groundwater samples from nearly all of the monitoring wells around the site boundary. Analyses of soil gas samples drawn into monitoring wells screened across the capillary fringe/water table demonstrate that gas-

Table 1. Estimates of Volume and Mass of VOCs Disposed at CWL

Volatile Organic Compound	MW (gm/mole)	Estimated Volume of Liquid Disposed (liters)	Liquid Density (gm/liter)	Mass (Kg)
<i>Freons</i>				
trichlorofluoromethane (Freon 11)	137	4465	1487	6639
1,1,2-trichlorotrifluoroethane (Freon 113)	187	8929	1564	13965
<i>Furans</i>				
tetrahydrofuran	72	1066	889	948
<i>Halogenated Aliphatics</i>				
trichloroethene (TCE)	131	35637	1464	52173
carbon tetrachloride	154	333	1595	531
chloroform	119	197	1483	292
1,2-dibromoethane (EDB)	188	197	2169	427
methylene chloride	85	671	1336	896
tetrachloroethene (PCE)	166	234	1623	381
1,1,1-trichloroethane (TCA)	133	7084	1339	9486
1,1,2-trichloroethane	133	197	1440	284
<i>Ketones</i>				
acetone	58	83226	790	65740
methyl ethyl ketone (MEK)	72	9543	805	7686
4-methyl-2-pentanone (MIBK)	100	197	798	157
<i>Aromatics</i>				
benzene	78	10276	877	9007

toluene	92	8361	867	7248
ethylbenzene	106	197	867	171
o-xylene	106	643	880	566
m-xylene	106	643	864	556
p-xylene	106	643	881	567
<i>Substituted Benzenes</i>				
Chlorobenzene	123	197	1106	218
1,2-dichlorobenzene	147	197	1305	257
1,3-dichlorobenzene	147	197	1288	254
1,4-dichlorobenzene	147	197	1248	246
Totals		173,725 liters		178,937 kg

phase TCE concentrations were present at sufficient levels to be the sole source of the groundwater plume (2). This is further supported by three-dimensional diffusion modeling, which was performed to demonstrate through history matching that the soil gas and groundwater plumes could have developed solely by diffusion through the soil gas (5). The diffusion simulations were performed using a modified version of the MODFLOW finite-difference code (6).

The opportunity for groundwater impact is believed to occur at the CWL only where the soil gas plume intersects the capillary fringe and VOCs partition from the gas phase to the aqueous phase. Based on equilibrium partitioning theory, 0.33 ppm_v TCE in soil gas in contact with the capillary fringe can cause 5 ppb_v TCE in the dissolved phase of the capillary fringe. However, due to dilution of the TCE mass flux across the capillary fringe with underlying groundwater, higher TCE concentrations (e.g., 3 to 30 ppm_v) are likely required for consistent detection of TCE at the 5 ppb_v level in groundwater samples (7).

Volumetric/Mass Balance Summary

A volumetric/mass balance analysis on the VOC waste streams was performed to support the VE VCM design. This analysis involved detailed review of waste disposal records, gas-phase and aqueous-phase transport modeling, and assessment of biotic/abiotic transformation and removal processes. Table 2 presents the pre-VCM volumetric and mass balance summary for TCE and total VOCs. The analysis resulted in an estimate of 3720 L of non-NAPL VOCs present in soil gas, pore water, on sediment and in groundwater in 1993. This volume does not approach the total estimated volume disposed (173,720 L). The large volume difference suggests that significant elimination of VOC volume from the subsurface has occurred. Elimination resulted from the following processes acting as early as 1962: initial evaporation; enhanced evaporation and decomposition due to burning waste; volatilization into soil gas followed by release to the atmosphere; and abiotic and biotic decomposition. The remainder, perhaps as much as 50%, is assumed to have been present as liquids containerized within the buried pits or present as NAPL in the sediment. The overall importance of the attenuation mechanisms can not be readily quantified until field estimates of VOC volumes in containers or as NAPL in the upper 6 m have been derived through the excavation work that is underway.

Table 2. Volumetric and Mass Balance Summary for TCE and Total VOCs

Mass Balance Parameter	TCE	Total VOCs
Total Estimated Volume in Vapor Phase (L)	277	1570
Total Estimated Mass in Vapor Phase (kg)	406	1617
Total Estimated Volume in Pore-water and Sorbed to Solid Surfaces (L)	Pore water – 380 Sorbed – 14	Pore water and Sorbed – 2151 ¹
Total Estimated Mass in Pore-water and Sorbed to Solid Surfaces (kg)	Pore water – 556 Sorbed – 21	Pore water and Sorbed – 2215
Total Estimated Volume Removed through Attenuation Processes (L)	15,710	89,254
Total Estimated Mass Removed through Attenuation Processes (kg)	22,999	91,932
Total Estimated Volume as NAPL ² (L)	19,255	80,750
Total Estimated Mass as NAPL ² (kg)	28,189	83,172
Rounded Total	Volume – 35,640 L Mass – 52,180 kg	Volume – 173,720L Mass – 178,930 kg

¹ Based on an average density of 1030 g/L for total VOCs disposed at the CWL.

² Includes containerized NAPL and NAPL trapped in soil pore space.

Non-aqueous Phase Liquids

VOC present as NAPL was believed to exist in the east-central area, southeast quadrant, and the southwest quadrant of the CWL in 1993. Field sampling and a Partitioning Inter-well Tracer Test (PITT), conducted in December 1995 beneath two organic disposal pits located in the southwest corner of the CWL, demonstrated the following in this regard (8). First, that TCE and other VOCs were present as NAPL in the sediment. Second, that NAPL had not migrated more than 9.1-m bgs. Third, that approximately 420 liters of NAPL TCE existed in the swept pore volume of the PITT (approximately 311,480 liters). These disposal pits were used during the last two or three years of CWL operation and accepted a significant quantity of VOC-containing wastes. This relatively detailed understanding of the NAPL distribution beneath the two disposal pits was extended in a general way to the other suspected NAPL source areas. On-going concentration rebound monitoring, post-VE VCM, should more clearly indicate the limits of NAPL-impacted sediment across the site. Further, the volume of containerized NAPL and the magnitude of NAPL migration from disposal pits will be documented through the LE VCM.

DESIGN BASIS FOR THE VE VCM

The relatively permeable, thick, and dry nature of the vadose zone combined with the nature and distribution of the VOCs made vapor extraction technology an obvious choice for addressing the soil gas plume. The basis for the VE VCM design was developed through regulatory, programmatic, and technical interactions. The site conditions and nature of contamination supported streamlined technology selection and design. Laboratory and field pilot tests conducted early in the VCM design phase provided additional information to address the relatively large scale of the plume and the significant hydrogeologic variability present throughout the subsurface occupied by the plume. These tests included six vapor extraction and air injection tests, three in-situ respirometry tests, and one cometabolic bioventing study.

SNL/NM elected at the early planning stage of the VE VCM to propose to the New Mexico Environment Department (NMED) a numerical VCM performance objective. This performance objective was based on total VOC concentration as detected in soil gas using EPA Method TO-14, including the five additional analytes: acetone, MEK, MIBK, Freon 11, and Freon 113 (9). Because potential groundwater impact is partially controlled by transport distance to the capillary fringe/water table as well as the VOC concentration, a set of performance objectives relating total VOC concentration and vertical transport distance was developed and proposed. This function is as follows:

From ground surface to 4.5-m bgs, total VOCs as detected in soil gas of 50 ppm_v or less
From 4.5-61 m bgs, 200 ppm_v or less
From 61-91 m bgs, 100 ppm_v or less
From 91-140 m bgs, 50 ppm_v or less
From 140-149 m bgs (or water table), 2 ppm_v or less

The overall duration of the VE VCM was restricted to two years to ensure that the mandatory CMS and CMI phases would be completed in a timely fashion, supporting a reduced overall time to site closure. It was envisioned that the VE VCM would consist of two stages of approximately one-year duration each. The first stage would focus on overall plume treatment, and the second stage would focus on treating zones of persistent VOC mass. The actual numerical values were selected based on professional judgement as to what could reasonably be achieved over a two-year VE VCM performance period, and that treatment of NAPL zones (i.e., zones with free-phase liquids), if present, would occur during the CMI. The lower concentration objective in the shallow horizon (50-ppm_v) was established to reduce concern over the shallow volatilization pathway as a viable long-term exposure pathway, and to be protective of LE VCM workers. As for the relatively low concentration objective of two ppm_v total VOC, even if TCE were the only VOC present, the possibility that TCE would be detected in groundwater above the Maximum Contaminant Limit (MCL) of 5 ppb_v is remote. Objectives of 100 and 200 ppm_v were selected for the intermediate zone of 4.5-61m bgs in recognition of the relatively large distance of transport to the groundwater and the relatively high initial VOC concentrations in this zone.

DESIGN AND CONSTRUCTION

An alternatives identification and engineering evaluation was completed prior to detailed design. Seven different scenarios referred to as well configuration-operating schemes were developed

and simulated using a three-dimensional airflow model constructed with the AIR3D finite-difference code (10). The number of extraction wells, their locations, depth of screen intervals, and flow rates were varied to create the scenarios. Two of the simulations involved deep air injection in combination with vapor extraction. Only steady-state operation was explicitly considered. The results of the simulations (i.e., individual and total-flow rates and pressure distributions) along with physical attributes of each scenario were combined in a technical-cost ranking exercise that resulted in the selection of a preferred alternative. Ranking and selection criteria included the following: total number of wells involved, total number of new wells, total well footage, total extraction flow rate, total injection flow rate, magnitude of air infiltration from ground surface, and cost.

The preferred alternative included 13 wells, of which eight were pre-existing (Figure 1). The existing wells were generally 5.1 cm in diameter, while the new well diameters were specified at 12.7 cm. Three general levels of well completion depths, or screen intervals, were specified. The shallow extraction wells were to be screened within the upper 30 m of the vadose zone (EXT-1, SEEW, and ECEW on Figure 1). Intermediate level extraction wells were to be screened within the general 30–91 m bgs interval (UI-1, UI-2, UI-3, and VMW-1 (two screen horizons)). Additionally, the deep extraction wells (D-1, MW-1A, MW-2A, and MW-3A) were screened below 134 m bgs. The MW-series wells are screened across the water table and are normally used for groundwater monitoring. Finally, two deep injection wells were included: D-2 and D-3. The design total extraction rate was 58 m³/min and injection rate was 11.3 m³/min. Individual target flow rates ranged from 2.8 m³/min to 7.1 m³/min. An effective radius of influence (EROI), taken as the radial distance from the well where induced vacuum is 5.1 cm water column, was derived for each extraction well from simulation results using the same AIR3D model referenced previously. The range in EROI was 25.6 m at shallow extraction well ECEW to 122 m for all the deep wells.

The combination of well configuration and operating conditions in this design was demonstrated through numerical simulation to offer near-complete hydraulic containment of the soil gas plume. In addition, the degree of atmospheric air infiltration was 70% or less of the total system flux, and this translates to a larger swept pore volume and more extensive pore volume flushes. Further, it was postulated that the injection of atmospheric air immediately over the water table, at relatively high pressure and flow rate, would accomplish two objectives. First, antecedent soil gas containing VOCs would be physically displaced and volatilization of VOCs from the pore water and sediment would be enhanced. Second, some desaturation of the capillary fringe would occur resulting in wicking of groundwater containing VOCs into the vadose zone. This form of “groundwater pumping” would encourage transfer of VOCs back into the soil gas.

It was estimated that this design, if operated at 100% of design for one year, would extract VOCs at an instantaneous rate of approximately 1.4 to 1.8 kg/hour, and a cumulative total of 1,800–2,700 kg. Assuming that a second stage of the VE VCM were designed, installed, and operated to focus on NAPL zones, a cumulative mass removal of approximately 4,500 kg VOCs was estimated. These estimates were predicated on a number of site features and design assumptions. These features and assumptions included the following: waste volumes, fate and transport considerations, the position of well screen intervals, the one-year time period for each stage, and

mass transfer limitations. The relatively wide spacing of the wells, as well as the expected mass transfer limited flux, were the bases for assuming that the VOC production rate would dramatically decline within a couple of months. Based on these estimates, it appeared that adequate management of emissions could consist of frequent sampling and monitoring, condensate removal, and use of a distributed set of engineered emission stacks. To confirm this, SNL/NM performed detailed air emission modeling and determined that worker and public exposure would be below the levels set by OSHA, the local air quality board, and the DOE (5). Local air quality board concurrence was received with the issuance of an air registration.

An integrated performance monitoring system was designed, which included a total of 52 in situ soil gas/pressure sampling ports. A schematic of the 6 new extraction and injection wells and 24 new monitoring ports appears in Figure 2. The design for the twenty-four (24) in situ performance assessment ports was modified from Hubbell (11). The screen intervals for the remediation wells are summarized in Table 3. Supplementing the 24 in situ ports were 28 ports integral to SEAMISTTM membranes lining boreholes SM-1 and SM-2 (10 ports each), SM-3 (5 ports), and SM-4 (three ports) (Figure 1). These boreholes and liners were installed during the early design/pilot-testing phase.

A 100% above-grade manifold, distributed-pump system approach was employed for vacuum and injection pumps, controls, and emission management. The 100% above-grade manifold design was compatible with the site conditions and plans for a large-scale excavation of the CWL. Construction (and dismantlement) was straightforward, and the operation, maintenance, and monitoring were easier. The overall design included seven unique well subsystems consisting of one to three wells, one to two pump stations, connecting piping and, for the extraction subsystems, one exhaust stack (Figure 1). The subsystems were selected based on proximity of wells and/or compatible vacuum requirements. Nine pump stations were specified, and each was specified to meet the pressure-flow-temperature

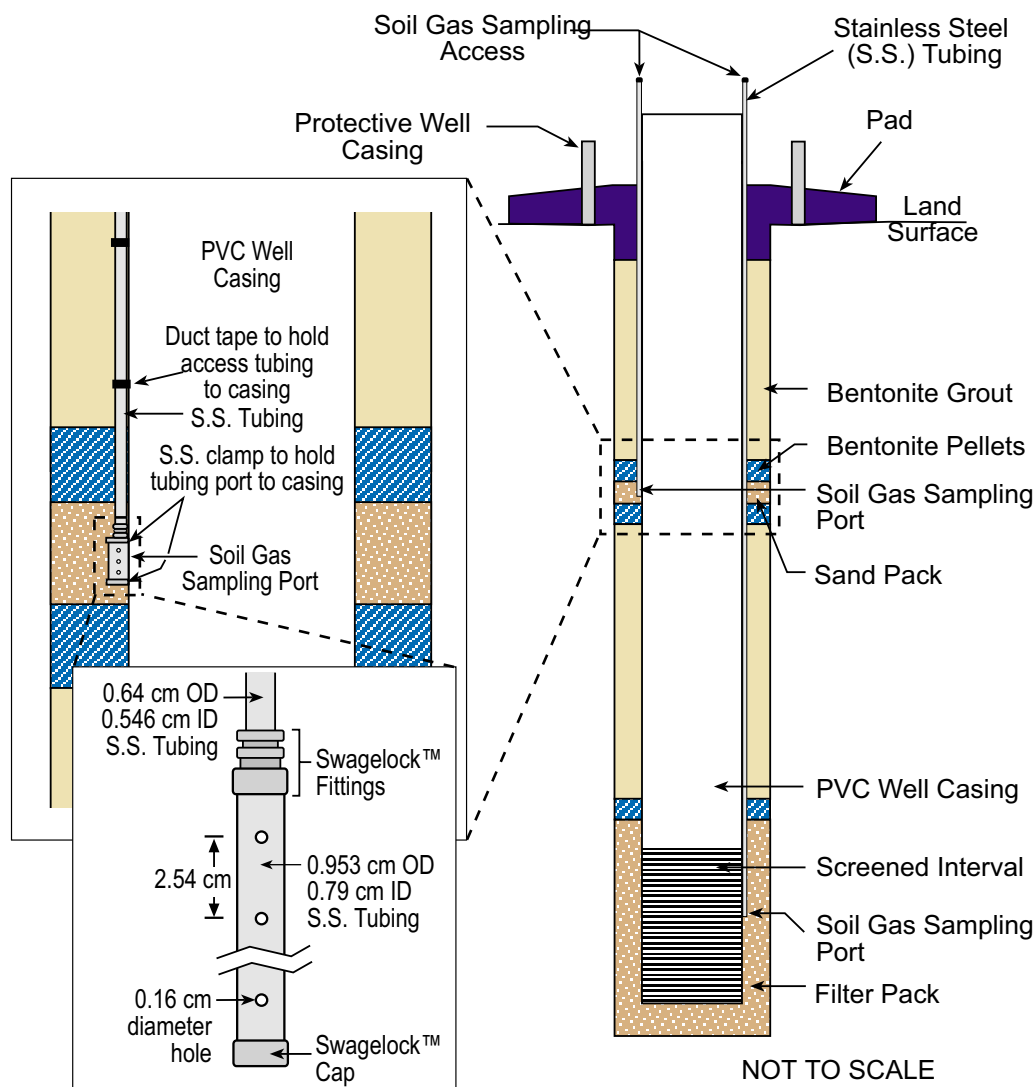


Figure 2. Schematic of Multi-use Vapor Extraction/Air Injection Well. Soil Gas Monitoring Port Construction Specifications Modified After Hubbell and Others (11).

requirements of the corresponding unique well subsystem. These pump stations were skid mounted and weather-proof, and included electric motor, pneumatic pump, inlet and outlet silencers, controls and gages, internal cooling (for two pumps) and dilution, bleed, and pressure relief valves. The motors were manufactured by US Motor, 480Volt, 3 phase, and ranging from 5 to 15 HP. The pumps were specified as multiple-lobe, positive displacement pumps manufactured by Tuthill. Two of the pumps required internal cooling due to high vacuum operation.

A manual operating and monitoring approach was selected over an automated or hybrid approach. Manual operation was technically feasible and cost-effective for this project because the CWL is readily accessible, and most of the O&M requirements could be readily supported by the ER Project field operations office. The design afforded individual well flow rate control via

manual adjustment of manifold control valves (ball valves), dilution, and injection bleed valves. The pump speed could also be adjusted by adjusting the belt drive dimensions. The design included manual monitoring and sampling features in addition to the in situ ports. On the manifold, immediately downstream of each well head, and on each emission stack, tapped ports were specified. One port was specified to house a needle valve and temperature gauge, and the other to house access tubing for a hand-held anemometer (analog gas flow velocity gauge). These ports were also designed to accommodate the tip of an Organic Vapor Analyzed (OVA) and the threaded female port of a SUMMATM canister. A custom pressure monitoring and soil gas purging and sampling system was fabricated to improve the efficiency and quality of data gathering efforts.

Construction of the 6 new wells and 24 new in situ monitoring ports occurred from October 1996 - January 1997. The balance of system construction was completed during March-June 1998. This included minor site grading and foundation preparation, transformer station upgrades and power cable placement, erection of manifold piping and stacks, pump station delivery and placement, and monitoring equipment preparations. Conversion of the three-groundwater monitoring wells could not be completed until July, when approval from NMED was received.

OPERATIONS AND MONITORING

The system described in this paper was operated from May 5, 1997 through July 29, 1998, around the clock with periodic manual checks and system adjustments. Individual well and system downtime periods were scheduled at various times throughout the overall operating period. Scheduled downtime occurred later in operation when instantaneous mass discharge was relatively low. Downtime was scheduled to allow two VOC rebound monitoring periods of one and two months, and for shutdown over week-ends/extended holidays. The percentage of time each well was operated relative to the time scheduled for operation, i.e., Operating Efficiency (OE), ranged from 31% at well D-2 to 84% at UI-3. The typical well and pump station conditions are summarized in Table 3.

Table 3. Summary of Representative Pump Station and Well Conditions for Operations during the Period March 31, 1998, Through June 30, 1998

Stack ID	Well ID	Screen Interval (m-bgs)	Flow Rate By Well (m ³ /min)	Actual EROI (m)	Inlet Pump Pressure or Vacuum (cm. Hg)	Generalized Range in Stack Emission TO14 Values (ppm v/v) High/Low
1	EXT-1	12-24	83 Ext	100	20.3	195/78
	SEEW	14-46	1.8 Ext	105		
	ECEW	14-21	1.8 Ext	84		
2	UI-1	30-46	6.4 Ext	107	6.4	123/7.9
	UI-2	29-45	6.6 Ext	107		
	D-1	139-147	~1.4 Ext	122		
3	UI-3	33-43	~5.7 Ext	46	106.7 cm H ₂ O	29/0.5
4	VMW-1	57-63 and 87-93	4.2 Ext	61	5.1	132/19.9
	MW-3A	143-149	~1.4 Ext	122	44.4	
5	MW-1A	144-150	~0.4 Ext	122	25.4	3.4/0.1
	MW-2A	144-150	~0.7 Ext	122		
NA	D-2	139-148	0.6 Inj	122	0.2 kgf/cm ³	NA
NA	D-3	139-148	3.2 Inj	122	0.4 kgf/cm ³	NA

Notes:

NA = not applicable, Ext = extraction well, Inj = injection well, ppm v/v = parts per million volume per volume

EROI = effective radius of influence taken as vacuum of 5.1 cm water column

Some effort was required to match pump performance to well and manifold hydraulics and subsurface conditions. The operating speed for several of the pump stations had to be reduced to better accommodate lower than expected air permeability conditions and resultant lower soil gas extraction rates and air injection acceptance rates. In other cases, only minor operating adjustments were necessary and adjustment to dilution and bleed valve settings sufficed. Maintenance effort required to maintain the OE achieved was low.

Data collection was performed during site visits that averaged approximately three visits per week. Data collection consisted of atmospheric monitoring, pump and wellhead monitoring, and in situ monitoring. Barometric pressure was obtained from a nearby SNL/NM weather station. Atmospheric monitoring was performed using hand-held OVA photo-ionization detector (PID) instrumentation, and monthly 24-hour weighted soil gas sampling in the breathing zone using SUMMATM canisters. The gas samples were analyzed per a modified method. Pump and wellhead monitoring included periodic measurement of temperature, pressure, flow rate, and VOC concentration. In situ pressure and VOC concentration were the two subsurface monitoring parameters of interest. Occasionally, oxygen and carbon dioxide were measured using hand-held

instruments. Total VOC concentrations were estimated via OVA (calibrated to isobutylene). Individual VOC constituent and total VOC concentrations were quantified via SUMMATM sampling with analysis by EPA Method TO-14. Five separate SUMMATM sampling rounds were completed and included the following events: Well Drilling; Baseline, Startup, Six Month, and One-Year system operation.

The system described in this paper was dismantled in August 1998 to make way for the start of the LE VCM. As of January 1999, all wells inside the original two-acre disposal area, except well D-3, have been plugged and abandoned. With only five months remaining before the planned termination of the VE VCM, and heightened levels of site access restrictions driven by the need to ensure worker and visitor safety during LE VCM operations, a decision was made to not pursue aggressive treatment of suspected NAPL zones within the two-year VE VCM period. Instead, the remaining ten wells were fitted with BaroBallsTM and converted to passive venting operation. Long-term in-situ monitoring using the 24 ports will continue through the VE VCM period and the LE VCM period (expected to conclude in 2000).

RESULTS

VOC concentrations at all the 52 in situ monitoring ports were significantly reduced in a systematic way because of the VE VCM conducted from May 5, 1997 through July 29, 1998. Furthermore, as of October 1998, significant VOC concentration rebound was observed only in the east-central and southeast areas. Persistently high VOC concentrations, potentially including separate-phase VOCs, are believed to be responsible for the rebound. Additionally, in the east-central area, TO-14 and OVA data collected after June 1998 suggest that a subsurface release of acetone from a buried container may have occurred sometime during the latter few months of operation. Significant ground surface settlement over two nearby disposal pits was observed to develop throughout the first six months of 1998, and this suggests waste material collapsed in-situ, perhaps as a result of liquid releases and container crushing. Acetone concentrations rose rapidly during and after the one-year sampling period, with approximately 20,000 ppm_v acetone detected at the lower two SM-4 ports and over 1,000 ppm_v total VOCs (as isobutylene) detected at the shallow port UI-2 P3.

Immediately before the one-year operation was terminated, it was observed through the OVA and SUMMATM sampling that the VCM performance objectives were met at all assessment points except SM4 (at 18.3 m bgs), UI-2 P3 (at 10.9 m bgs), and D-1 P3 (at 73.2 m bgs). OVA screening into October 1998 supported the rebound at UI-2 P3 but did not support the presence of sustained total VOC concentrations at D-1 P3. SM4 was plugged and abandoned in August 1998 and therefore could not be monitored.

The VOC concentrations detected at the in situ ports are one line of evidence in support of widespread treatment of the soil gas plume. Ports located even at significant distance from extraction well screens (i.e., 60-120 m) showed significant VOC reductions. Other evidence includes the instantaneous and cumulative VOC mass discharge history (Figure 3), vacuum and pressure measurements, and groundwater sampling results. As can be seen in Figure 3, VOC mass removal was relatively high early on and declined rapidly towards asymptotic behavior.

After about two months of operation, most of the VOC mass near the well screens had been removed, and VOC concentrations detected in the effluent streams had fallen dramatically. Because synthesis of in-situ pressure measurements, corrected for barometric pressure fluctuations, showed that individual well and system-wide EROI was extensive (refer to Table 3), it was clear that contaminated soil gas at those distances would be migrating towards the wells and would eventually be extracted. The tailing response seen in Figure 3 represents the extraction of this soil gas containing VOC mass originally present near the outer limits of the zone of vacuum influence, and in most cases at lower initial concentrations. The exhaust gas concentrations would have been higher than observed at any point in time, if it were not for the high degree of dilution that occurred from mixing with cleaner soil gas flowing through previously cleaned zones near the well screens.

The relatively lengthy, stable period of low mass removal rates depicted in Figure 3 was observed even after the August 1997 and December – February 1998 shutdown periods. The sustained period of low mass removal rates and the absence of significant observable rebound at most ports suggest that the presence of concentrated VOC mass (e.g., NAPL) was not widespread. These results also suggest a state had been reached that was characterized by relatively low in-situ VOC mass flux caused by relatively small pressure gradients over long-travel distances, dilution with cleaner soil gas, and diffusion-limited mass-transfer of VOCs from lower-permeability (or higher moisture and/or organic carbon) layers or zones to higher permeability (or lower moisture and/or organic carbon) zones.

The cumulative VOC mass removed (approximately 2,100 kg) is also in agreement with design estimates of non-NAPL mass, and this suggests that much of the available VOC mass has been extracted. Finally, results from the May and August 1998 groundwater sampling events indicate that VOC concentrations in groundwater have declined across the site from low ppb_v levels to below the detection limits of 1 ppb_v.

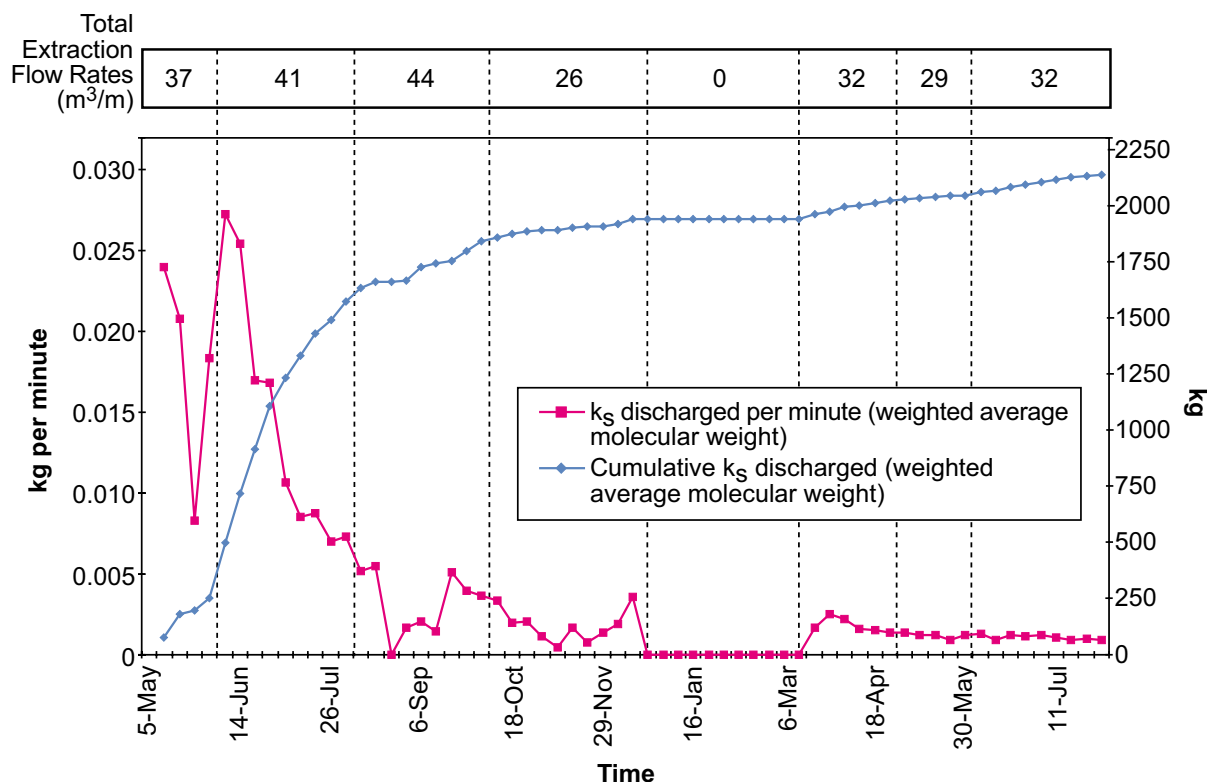


Figure 3. Instantaneous and Cumulative VOC Mass Discharge (based on weighted average molecular weight) from Stacks S1-S5 for Start-Up Through July 29, 1998

Figure 4 presents vertical profile conceptualizations of the soil gas plume, taken along the transect A-A' shown on Figure 1. The profiles are defined using total VOC concentration data, at four different times over the VCM period. Figure 4a (Profile 4a) shows the assumed distribution of the soil plume prior to initiation of the VE-VCM. This soil gas distribution has since been shown incorrect based on the data from the remediation wells and associated in-situ ports installed in the winter of 1996-97. Profile 4b represents the soil gas plume several weeks after the beginning of vapor extraction operations. The plume is shown to dramatically reduce in magnitude and extent as the VE VCM proceeds for 6 months (profile 4c) and one year (profile 4d). The range in total VOC concentrations depicted in profile 4d is approximately 300 ppm_v to the cutoff of 5 ppm_v. In addition to reductions in total VOCs, the soil gas VOC composition changed over the operating period. This change is indicated by both in situ soil gas analytical results and results for the extracted vapor streams. In general, TCE appears to have been removed at a greater rate early in the operation and this caused a general reduction in the proportion of TCE in soil gas compared to the other VOCs. Conversely, the proportion of acetone in the soil gas appears to have increased in some regions of the subsurface with increasing time of operation. This is believed to be the result of on-going leakage of containers holding acetone; the LE VCM, currently in progress, will remove these containers.

Certain regions of suspected NAPL were, it seems, effectively eliminated (e.g., southwest corner pit area) while other regions persist (e.g., acetone in east-central pit area). In the southwest pit

area, approximately 270 kg of VOCs were extracted from well EXT-1. The PITT conducted in December 1995 indicated that NAPL existed in the 3 to 9 m depth interval and that from 218 to 998 kg of NAPL (at a specific gravity equal to TCE of 1.46) was present in what was later a portion of the EROI for well EXT-1. Screening and laboratory data from wells EXT-1, SM-1, and SM-2 demonstrate that most VOC mass originally present beneath the pits has been removed. Thus, based on the PITT and post-vapor extraction soil gas data, it appears that most of the NAPL in the southwest corner pit area was removed.

The in situ changes to the soil gas plume indicate that the approximate one-year VE VCM operation was highly successful. Another year of operation, primarily focused on efforts to treat zones of concentrated VOCs, would have achieved all the VE VCM performance objectives.

From a cost versus benefit perspective, the VE VCM was a success despite being prematurely terminated. The generalized cost of performing the VE VCM was \$1,030,000. This includes Planning, Permitting, Design, Procurement, Well Installation and Construction Management, Well/Port Installation, Equipment, Materials, Supplies Site Utilities, System Construction, O&M Management and Field Labor, Analytical Services, Waste Management and Decommissioning. By conducting the VE VCM, other projected significant costs (e.g., additional data collection, additional groundwater monitoring wells and groundwater sampling) and probable schedule delays were avoided. In effect, the VE VCM represented a minimal incremental cost to the closure project. The incremental cost is estimated to be approximately \$5/liter of VOC removed.

IMPLICATIONS FOR FINAL CORRECTIVE ACTION

The CMS and CMI phases will be completed after the VE and LE VCMs are complete. Because the vast majority of waste, waste constituents, contaminated debris, and highly contaminated sediment will have been removed by the VCMs, the scale of the CMS and CMI are both expected to be streamlined and less complex. The soil gas plume has been dramatically reduced in magnitude and extent. VOC mass persists in several areas. Although some NAPL was volatilized during the VE VCM, separate-phase is indicated to still be present in these areas. Acetone may be the most important chemical from this perspective (perhaps due to on-going subsurface releases from containers). From a risk perspective, however, acetone does not represent a significant health threat compared to TCE. Acetone's toxicity is moderate and attenuation of this chemical was observed to be significant during the VE VCM. Continued attenuation of acetone transport is expected due to acetone's infinite solubility in water and relative biodegradability. A passive venting system is in place and may be successful in removing another 20 kilograms or so of VOCs. More importantly, the passive system is expected to encourage the mass centroid of the plume to continue migrating upward – away from groundwater.

The major technical question that remains has to do with the ultimate fate of the soil gas plume and the impact, if any, on the groundwater system and other exposure pathways. Preliminary diffusion modeling based on TCE as the only contaminant suggests that the 200 ppm_v or greater total VOC concentration zone (see Figure 4d) may represent a source of VOCs that could threaten groundwater quality for a number of years. The risk to groundwater and human health associated with the remaining plume will be more significant if the majority of VOC mass is

TCE as opposed to acetone. These and other issues will be addressed in detail in the CMS and risk assessment that are currently underway.

Based on available information and projections on post-VCM site conditions, it appears that further risk reduction measures, such as extraction of VOC mass from the soil-gas plume, will not be necessary from a purely technical basis. The extent of the groundwater plume is limited; expansion is not expected. Therefore, a monitored natural attenuation program may be appropriate. RCRA and the CWL Closure Plan require that a RCRA final cover be installed. However, an alternative-arid cap technology may be most appropriate for this site. The non-reliance on synthetic liner materials points to the need for low VOC emissions at the ground surface over the long-term.

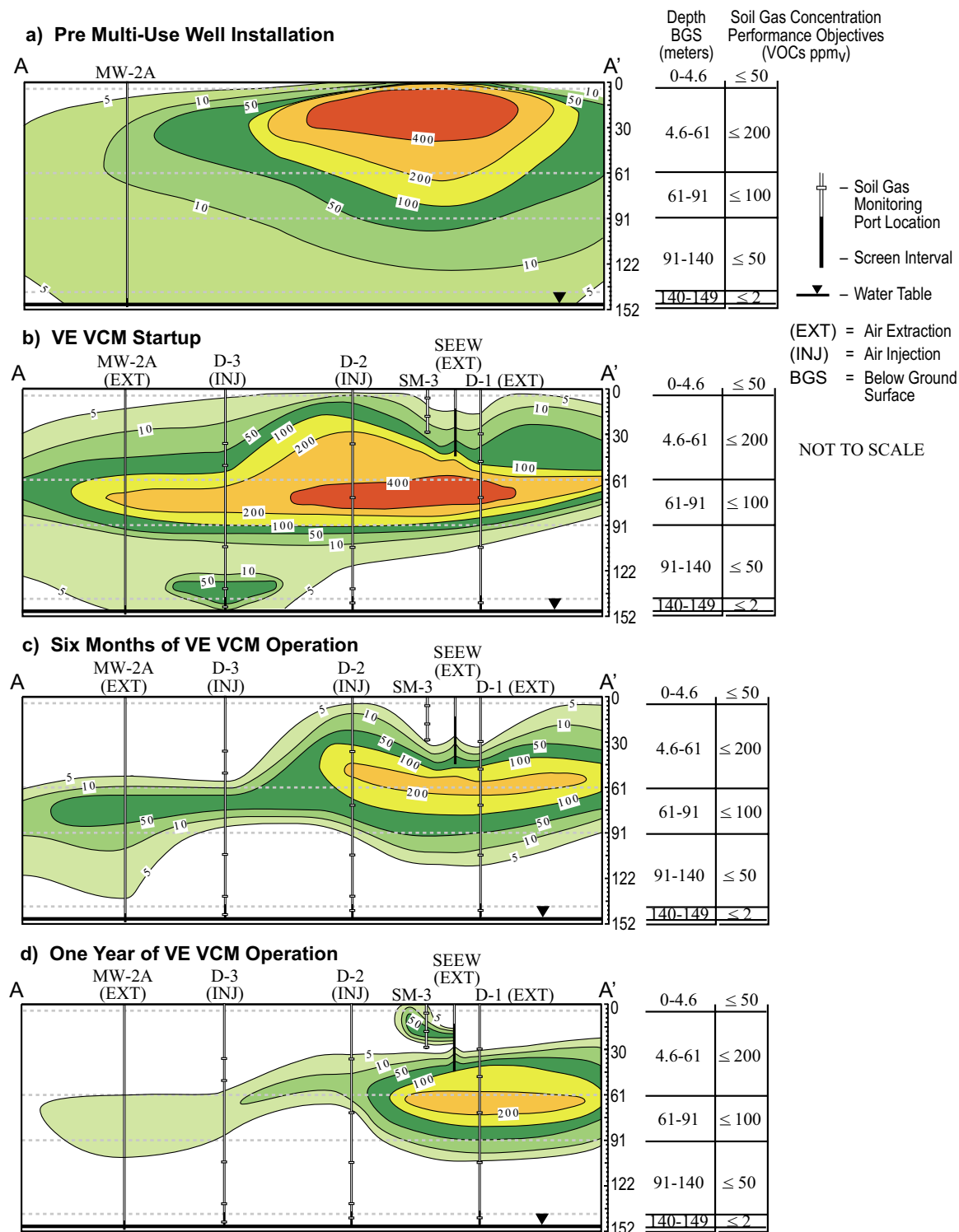


Figure 4. Vertical Profiles of Total VOC Concentration Distribution Along Cross-Section A-A'

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