Chapter 9
Soil Gas Surveys

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9.1 Introduction

Soil gas sampling is a screening tool that can be used to identify and evaluate the extent of VOCs in the subsurface. Contamination by volatile organic compounds (VOCs) can result from the spillage and improper disposal of chemicals from a wide variety of commercial and industrial processes. A common technique applied to the investigation and delineation of VOCs are the use of soil borings and monitoring wells. Samples from these types of investigations provide an effective method of detecting volatile organics both qualitatively and quantitatively. An alternative is soil gas sampling which is a screening tool that can also be used to identify and evaluate the extent of VOCs in the subsurface. Soil gas sampling involves the collection of gas samples at shallow depths (typically 1-3 feet) across a site. Volatile organic compounds that have become soil or ground water contaminants are present to varying degrees in the soil as a vapor due to their high vapor pressure and low aqueous solubility. The measurement of the vapors in the soil pore space can aid in assessing the presence, composition, source, and type of release and distribution of contaminants in the subsurface. A soil gas survey may provide rapid analytical results and a more thorough assessment of the site at a reduced cost. Soil gas sampling, when applied appropriately, is an acceptable screening procedure for aiding in the decision-making process of locating monitor wells and soil sampling locations.

It should be noted that a soil gas survey is not intended to be a substitute for certified analytical methodology, but instead, as a screening tool to enable conventional methods to be used more effectively.

There are two basic types of soil gas surveys performed during site assessments. The first type is an active soil gas survey where a volume of soil gas is collected from the vadose zone[1] and into a sample container or directly into an analyzer. The second type is the passive soil gas survey where a sorbent material is placed within the vadose zone so that contaminant vapors can be absorbed over time using the ambient flow of vapors through the subsurface.

This chapter will give guidance to the theory, applications and some of the common methodologies employed for performing soil gas investigations.

The NJDEP maintains a library of guidance manuals on its website at https://www.nj.gov/dep/srp/guidance/. It is recommended the reader access the website and review the guidance manuals pertinent to the respective task. Additional guidance may also be found at websites of the EPA and the American Society for Testing and Materials (ASTM). Examples of some of the relevant guidance manuals and websites pertaining to this chapter are:

Soil Investigation Technical Guidance https://www.nj.gov/dep/srp/guidance/#si_ri_ra_soils;

Ground Water Technical Guidance: https://www.nj.gov/dep/srp/guidance/#pa_si_ri_gw;

Ecological Evaluation Technical Guidance https://www.nj.gov/dep/srp/guidance/#eco_eval;

Quality Assurance Project Plan Technical Guidance https://www.nj.gov/dep/srp/guidance/#analytic_methods;

Vapor Intrusion Technical Guidance https://www.nj.gov/dep/srp/guidance/#vi;

Soil Gas Sampling https://www.epa.gov/sites/default/files/2015-06/documents/Soil-Gas-Sampling.pdf; and

OSHA https://www.osha.gov.

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[1] The vadose zone is the variably saturated zone between the ground surface and the permanent water table of the groundwater.

9.2 Vapor Transport Theory

Subsurface contamination by volatile contaminants may produce a concentration gradient in soil gas that decreases in a direction away from the major source or body of contamination. Typically, volatile organic contamination is detected in the unsaturated (vadose) zone when it moves upward from the saturated zone, through the capillary fringe, (a transition zone between the ground water table and the vadose zone) and into the unsaturated zone area where the gas samples are obtained. Additionally, source material may be present in the vadose zone which may result in a similar migration of volatile organic compounds within soil gas. The concentrations of volatile organics in soil gas are a function of their concentration in the ground water, aqueous solubility, soil and subsurface characteristics, degradation, and vapor pressures.

Ideally, when an upward vertically decreasing volatile organic concentration gradient is found in the soil gas, it is caused by the vertical migration of volatiles from contaminated ground water or soil to the ground surface. A horizontal concentration gradient will also be present with decreasing concentrations of volatile organic vapors in the soil gas from the source of contamination. In some cases, the concentration gradient between the water table and ground surface in soil gas may be distorted by hydrologic and geologic variables such as perched water or impermeable layers. Movement of vapors will generally occur around geologic and hydrologic barriers unless they are of great lateral extent as compared to the area of the plume.

A summary of the applications of soil gas surveys is as follows:

- Assess the presence or absence of contamination.
- Provide a 3-dimensional profile of contaminant distribution.
- Delineate the extent of contamination in soil and ground water.
- Obtain a chemical characterization of the contamination.
- Identify and differentiate between sources of contaminants.
- Assess migration patterns of contamination in ground water.
- Monitor byproducts from the chemical or biological breakdown of contaminants.
- Differentiate between one-time releases and ongoing releases of contaminants.
- Collect data for the design of Soil Vapor Extraction (SVE) systems.
- Monitor remedial activities (SVE systems, bioremediation).
- Monitor the subsurface for leaks from underground storage tanks (USTs) or containment systems.
- Monitor the subsurface for the movement of landfill gases to structures or off-site properties and need for control of gas movement.
- Assist in the decision for placement of soil borings and monitor wells.

9.3 Soil Gas Generation and Movement

Soil gas may be generated by biological, chemical, and physical decomposition of spilled or dumped wastes. Waste characteristics such as type, source, quantities, and the geologic and geographic location of entry into the subsurface can affect the rate of decomposition and gas production.

9.3.1 Biological Decomposition

Biological decomposition is important in most active and closed landfills containing organic wastes, which decompose due to anaerobic microbial degradation. Generally, the amount of gas generated in a landfill is directly related to the amount of organic matter present. Waste type and in-situ characteristics and conditions can affect biological decomposition. Landfill gas production will vary spatially within a landfill unit as a result of pockets of higher microbial activity. Under anaerobic conditions, organic wastes are primarily converted by microbial action into carbon dioxide and methane. Also, trace amounts of hydrogen, ammonia, aromatic hydrocarbons, halogenated organics, and hydrogen sulfide may be present.

Biological activity is also an important factor in the detection of many VOC contaminants. It can have a negative effect on their detection. Oxidation can convert volatile organics into nonvolatile or water-soluble compounds that are not amenable to soil gas sampling and analysis. Hydrocarbons are easily oxidized under aerobic conditions in the upper unsaturated zone. Halocarbon compounds are generally more resistant to aerobic degradation but can undergo anaerobic degradation. The original contaminant can be biologically degraded into various byproducts of the original compound.

9.3.2 Chemical Reactions

Gas production from chemical reactions results from the mixing of incompatible materials. Reactive or ignitable wastes can cause explosions or heat producing reactions (exothermic) resulting in a rapid production of gases and increased temperatures. A strong oxidizing agent may react with organic wastes to produce ammonia and carbon dioxide under acidic conditions.

9.3.3 Physical Decomposition

Volatile organic compounds can undergo a variety of equilibrium and transport processes in the subsurface. The most important physical process affecting the production of vapors is the solution/ vapor equilibrium. Due to the high vapor pressures and low aqueous solubility, volatile organic compounds have an affinity to partition into the vapor phase. The physical law that quantitatively describes this process is Henry's Law (also known as the air-water partition coefficient). Volatile organic compounds with high Henry's law constants will favor to partition from the aqueous to the vapor phase.

9.3.4 Transport Mechanisms

Several physical mechanisms describe the movement of vapors through the subsurface. They are molecular effusion, molecular diffusion, and convection.

9.3.4.1 Molecular Effusion

Molecular effusion occurs at the surface boundary of the soil and atmosphere. It is the process by which vapors are released from the soil surface to the atmosphere. Any VOCs, which are in the soil surface, are released to the atmosphere based upon the vapor pressure of the VOC. One of the physical effects on the release rate of VOCs from the surface is wind speed. Atmospheric conditions (wind velocity, temperature, pressure), allow the VOC to escape to the atmosphere while the soil contamination allows the effusion to continue.

9.3.4.2 Molecular Diffusion

Molecular diffusion occurs when there is a concentration difference between two different locations. Diffusive flow is in the direction of lower concentration. The vapor density affects molecular diffusion, but the concentration will tend to overcome small differences in density. Specific compounds will exhibit different diffusion coefficients. Due to tortuosity within soils, the diffusion coefficients are only relative indicators of soil gas transport.

9.3.4.3 Convection

Convection flow occurs when a pressure or temperature gradient exists between two locations. Gas will flow from an area of higher pressure to an area of lower pressure. Where it occurs, convection flow of gas will overcome the influence of molecular effusion and molecular diffusion. This type of flow is usually associated with landfills. Biodegradation processes, chemical reactions within the landfill, compaction effects or methane generation in the lower regions of the landfill which will all drive vapors vertically and horizontally. Changes in barometric pressure will have an effect on convection flow. The rate of gas movement is generally orders of magnitude greater by convection than for diffusion.

9.4 Site Specific Characteristics

The site conditions and the type of contaminant release must be evaluated prior to performing a soil gas survey. The type of contaminant spilled and its components, along with any breakdown products must be evaluated to determine the best compounds for detection in the vadose zone that will represent the contaminant source and plume. An assessment of site geologic conditions will help determine any potential contaminant sources and migration routes. Natural or anthropogenic structures at a site may produce areas of preferred pathways for soil gas migration or conversely, restrict and impede gas flow.

During the planning and preparation for conducting a soil gas survey, site specific parameter characteristics should be evaluated. Unique characteristics for the area should also be considered (i.e., soil composition, tidal impacts, and groundwater fluctuations). This will aid in the recognition of the variability of the site-specific parameters so accurate interpretations of the results, can be made. The degree of preparation will have a direct bearing on the success or failure of an investigation. The following are some of the site conditions and contaminant properties that should be considered to determine if a soil gas survey will be successful and aid in the interpretation of the data.

9.4.1 Chemical and Physical Properties of the Contaminant

9.4.1.1 Concentration

The known or estimated concentration of the ground water contaminant will dictate the vertical concentration gradient of soil gas established in the vadose zone. The diffusion of vapors from areas of high concentrations to lower concentrations is the mechanism of great importance for gas transport in the unsaturated zone. Therefore, if the known or suspected concentrations of contaminants in ground water are low, the compound may be difficult to detect in the vadose zone. Therefore, to address this, samples can be obtained from multiple depths at several locations to establish a concentration gradient and aid in selecting the optimal sample depth for contaminant detection.

Monitoring impacts from landfill gas migration to surrounding properties and buildings is vital due to the history of fires and explosions caused from the migration of methane gas into structures. Landfill gas monitoring is also important due to the presence of toxic and carcinogenic compounds in the trace composition of landfill gas. Concentrations of these compounds will vary between landfills. A

Table 9.1 Typical Landfill Gas Components[2]

Compound	Percent by Volume
Methane	45-60
Carbon Dioxide	40–60
Nitrogen	2-5
Oxygen	0.1-1
Ammonia	0.1-1
Sulfides	0-1
Hydrogen	0-0.2
Carbon Monoxide	0-0.2
Trace Compounds Toluene, Dichloromethane, Ethyl Benzene, Acetone, Vinyl Acetate, Methyl Ethyl Ketone, Xylenes, 1,1-Dichloroethane, PFAS, Trichloroethylene, Benzene, 1,4-Dioxane	0.01-0.6

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[2] Tchobanoglous, Theisen, and Vigil 1993; EPA 1995

correlation does not exist between the major gas concentrations and the occurrence of trace compounds. Some typical compounds and concentrations found in landfill gas are included in Table 9.1.

9.4.1.2 Partitioning

Partitioning represents a group of processes that control the movement of contaminants between physical phases. The phases include the liquid, vapor, and solid (i.e., soil). The product phase must be included if free product is present in the subsurface. The relationship between the phases is represented in Figure 9.1.

Henry's law constant (K_H) is commonly expressed as the ratio of an organic compound's vapor partial pressure to its aqueous concentration at equilibrium. It represents the partitioning of volatile contaminants between the solute phase and the gas phase in dilute solutions. This constant can be reported in both dimensional (K_H) and dimensionless ($K_{H'}$) forms. Henry's law constants should not be used for determining contaminant vapor pressures due to the unknowns related to the concentration of contaminants and additional partitioning process of the solution. Those compounds with Henry's law constants greater than 0.05 atm M^3/mole or, 1 microgram per liter soil gas/micrograms per liter water ratio would be good candidates for soil gas detection.

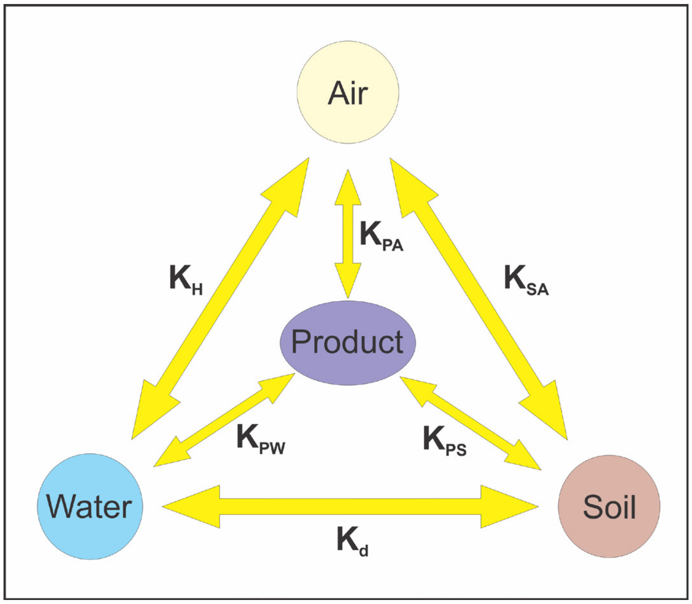

Figure 9.1 Phase Relationships for VOCs

The soil-water partition coefficient (K_d) represents the equilibrium concentration of a contaminant on solid surfaces and in solution with larger K_d values representing a greater contaminant affinity for the solid phase. Soil-water partitioning is strongly influenced by the available surface area of soils, with larger K_d values typically associated with organic carbon- and clay mineral-rich soils. Chemical-specific properties (i.e., size, hydrophobicity, functional groups) can also influence the extent of contaminant sorption. Some of the important parameters for soil gas surveys are the sorbed contaminant concentration in the soil, soil makeup including the quantity, type and distribution of clay and organic material, vadose zone pore water content, and soil porosity.

K_d values are often normalized to soil organic carbon content via the equation $K_{oc} = K_d/f_{oc}$ where f_{oc} is the fraction of organic carbon in the soil. The use of the soil-organic carbon partitioning coefficient (K_{oc}) to estimate soil-water partitioning assumes that that the extent of partitioning to the solid phase is directly correlated to the soil organic carbon content. This assumption is most appropriate for neutral organic compounds. Generally, the organic carbon content in the vadose zone decreases with depth, so the greatest influence will be at or near the surface.

Soil-air partitioning (K_{SA}) is the process by which VOCs move between the sorbed phase and the vapor phase. The pore water content, the amount, type, and distribution of clay and organic materials, and contaminant chemical properties largely control this process. Compounds with a high affinity for the soil phase are unlikely to be available for soil gas sampling techniques.

The partitioning of free product to air, water, and soil in a dynamic system is also represented in Figure 9.1. Product to soil partitioning (K_{PS}) describes the movement of a contaminant between the free product and soil phases. As discussed in detail in the soil-water partitioning section above, the extent of partitioning to the soil phase can be influenced by both soil and chemical properties. Contaminants with a high affinity for the soil phase will have a greater tendency to be immobilized in the subsurface environment.

Product-air partitioning (K_{PA}) is the process by which a contaminant moves between the free product and air phases. The major process influencing the movement of VOCs from the product phase to the vapor phase is volatilization. Depending upon the contaminant mixture and vapor pressures, a significant number of compounds can be present in the soil atmosphere by volatilization. The soil atmosphere will have a composition similar to the free product, except for the compounds with the lowest vapor pressures. The quantity of contaminant volatilized into the vapor phase is strongly dependent upon the temperature. The rate of volatilization is also controlled by the rate of transport of VOCs from the product/air interface and is the highest when there are pathways (i.e. macropores) or driving forces (i.e. concentration gradients).

Product to water partitioning (K_{PW}) describes the movement of a contaminant from the free product to aqueous phase. Product-water partitioning is limited by the solubility of a contaminant. The solubility of a compound is the saturated concentration of a compound in water at a given temperature and pressure. Other factors that can influence solubility include salinity and the presence of co-solvents. Solubility is also an important parameter in determining the fate and transport of a compound in ground water. Compounds with high water solubility tend to desorb from soil and sediments (low K_{oc}) and move into the ground water. They will also have a short residence time in the unsaturated soils decreasing the amount of time for the product to volatilize and establish a vapor concentration gradient. Once in the ground water, highly soluble compounds are less likely to partition to the vapor phase. VOCs that are highly water soluble such as ketones and alcohols are not good candidates for soil gas surveys since they do not readily move into the vapor phase.

9.4.1.3 Vapor Pressure

Vapor pressure is the pressure exerted by a vapor that is in equilibrium with its liquid phase and is a measure of the relative volatility of a contaminant. Ground water contaminants with high vapor pressures will diffuse readily into the soil horizons and are therefore excellent targets for soil gas analysis. Those compounds with vapor pressures of 1mm Hg at 20°C or higher are the best target analytes for soil gas analysis.

9.4.1.4 Microbial Degradation

Biodegradation of contaminants refers to the conversion of a contaminant to mineralized end products (CO_2, H_2O, and salts) through the metabolism of living organisms. The resistance of a compound to biodegradation can be a limiting factor to the applicability of a soil gas survey at a site. If conditions permit, microbial degradation of contaminants can lead to significant degradation of organic compounds. The amount of degradation will depend upon the number of species available and the degree of difficulty in breaking down the compounds. Degradation can reduce the amount of contaminant, especially non-halogenated hydrocarbons, particularly C5 and higher. These compounds will degrade readily in an oxygenated soil if they are present at low concentrations. This limits the effectiveness of a soil gas survey in cases where the ground water is deeper than 25 feet or shallower than 5 feet. When the ground water is deeper than 25 feet, the limitation is the ability, time, and expense to drive a soil gas probe to an adequate depth for contaminant detection. In most geologic settings, the soil gas probe must be driven within 5 feet of the ground water table to obtain a reliable soil gas signal. In some cases, biodegradation rates can exceed the rate at which vapors move into the vadose zone. In these cases, contaminants are not detectable for soil gas sampling techniques.

In areas of high concentrations of contaminant vapors, such as around leaking underground fuel tanks, the degradation of VOCs is inhibited. The concentration of VOCs in these areas is high enough to destroy the soil bacteria.

The stability of halogenated compounds is generally related to the number and type of halogens. Solvents having three or four chlorines will degrade to some extent in the environment, but will degrade slowly, so there is little impact on their detectability in the soil gas. Dichloro compounds (DCE, DCA) are produced in the subsurface as the first breakdown products of primary chlorinated compounds. These products tend to degrade in the soil faster than the primary solvents. As a result, soil gas data for the dichloro compounds is less representative of their concentrations in the ground water than the primary chlorinated solvents. Vinyl chloride, a mono chlorinated compound and a second stage degradation product, is the least stable chlorinated solvent in soil gas. Therefore, vinyl chloride is seldom detected in soil gas over a contaminated ground water plume, and is an unreliable indicator of ground water contamination. Several examples of biodegradation products of chlorinated compounds are included in Figure 9.2.

Sampling the gases produced by biodegradation of a contaminant will allow for the indirect detection of contamination. These gasses include methane, carbon dioxide, oxygen, and hydrogen sulfide. These gasses can provide useful information about the contaminant source area and plume. Measurement of these gasses is most useful when active soil-gas sampling methods are being employed and the volatile contaminant is not directly detected or is a semi-volatile compound.

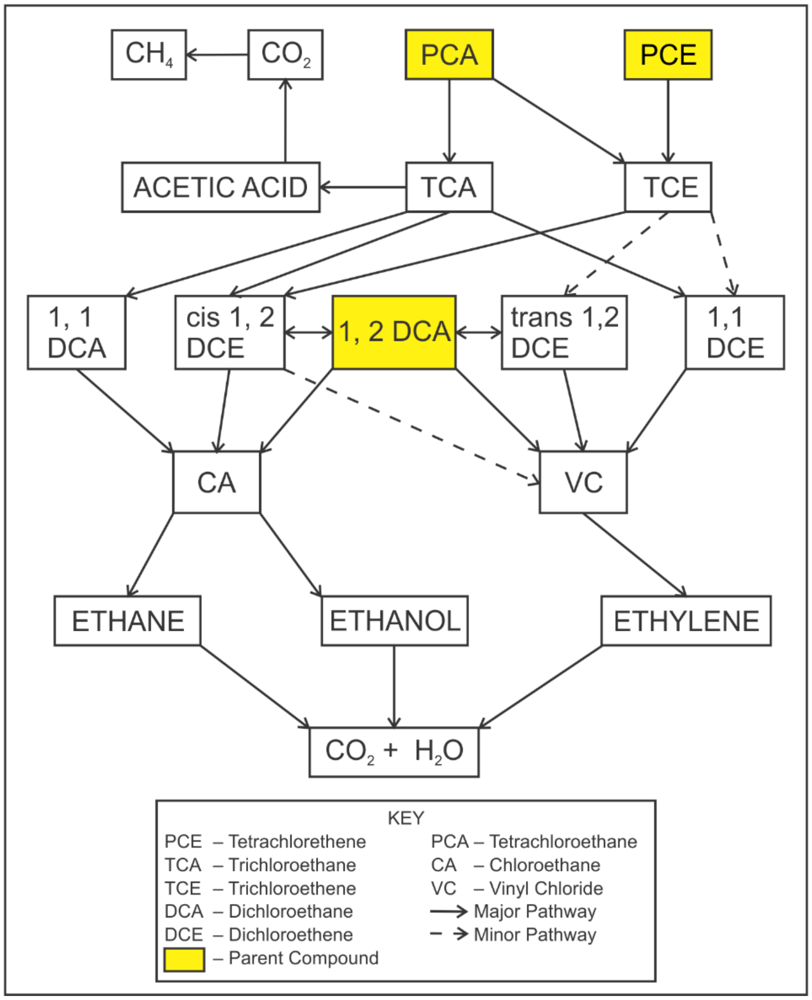

Figure 9.2 Transformations of Chlorinated Aliphatic Hydrocarbons

9.4.2 Geologic Factors

9.4.2.1 Soil Permeability

One of the most important factors in the movement of vapors through soil is the soil permeability. The soil permeability is the measure of the ease at which a gas or liquid can move through rock, soil, or sediment. Soil permeability is related to the grain size and the amount of water in the soil. Soils with smaller grain sizes are less permeable. When soils contain clay size particles, soil gas movement is severely limited. Or if the soils become poorly sorted with increased fine-grained material content, the pore space is decreased, water content increases and the rate of vapor diffusion decreases. The most retarding layer will dictate the rate of diffusion of vapors in the vadose zone.

Heterogeneous soil conditions

across a site under investigation can lead to poor delineation and misinterpretation of site contaminants due to the interference from the different soil conditions. Data from areas of horizontal low permeability zones within the vadose zone could be interpreted as being an area of low contamination, when the level of contamination could be the same or higher. Conversely, data from an area of high permeability in an otherwise low permeability area can be interpreted as an area of high contamination. High porosity areas such as sewer and utility trenches can serve as conduits for rapid vapor or gas migration, giving a false indication of high contamination areas. In situations where little or no soil data is available, several soil borings should be logged to aid in the interpretation of the generated soil gas data.

Soil gas sampling is most applicable to sites where the vadose zone is comprised of dry coarse-grained homogeneous sediments with a minimal amount of organic material. At sites where tight or wet silts and clays are present, or the contaminated aquifer lies beneath a clean aquifer, soil gas sampling cannot be used effectively to detect ground water contamination.

The presence of moisture in the soil decreases the rate of vapor migration. This occurs because as the volume of soil water increases, the soil airspace decreases thereby inhibiting vapor movement. Soil moisture decreases the amount of contaminant available for transport by allowing contaminants to partition into the pore water. Active soil-gas sampling methods are not effective in soil conditions where the water content is 80-90% saturated.

9.4.2.2 Thickness of the Unsaturated Zone

The thickness of the unsaturated zone will determine the distance vapors must migrate from the ground water to an area for sampling. The greater the thickness of the vadose zone, the greater the chance for soil texture changes, the greater distance the concentration gradient must be established, and the deeper soil gas probes would be required to be placed for detection of the vapors. Conversely, if the thickness of the vadose zone is small there is a greater chance of dilution of the soil gas by ambient air and a severe alteration of the concentration gradient. A steep concentration gradient can cause misinterpretation of data by small variations in sample depths. The deeper samples will show a greater concentration of contaminants, which may erroneously be interpreted as a “hot spot” of contamination.

9.4.2.3 Barriers and Conductive Zones

Two geologic factors that can lead to misinterpretations of the data are barriers and conductive zones. Barriers to soil gas diffusion are obstructions, either manmade or natural, which will impede the movement of vapor. The obstacles can be structures, blacktop, cement, landfill caps, clay layers, perched water, frozen soil, irrigated or recently disturbed soils. The location and extent of the barrier will dictate the direction of movement of the soil vapor around the obstacle. Figures 9.3 A through E illustrate the effect of barriers on the soil gas concentration gradient.

Conductive zones are areas where soil gas vapors and gases will preferentially move since vapors will move along the path of least resistance to gas movement. Conductive zones can be natural, such as buried former stream beds, and gravel lenses and fractures, or manmade, for example bedding around pipelines.

Figure 9.3 Soil Gas Concentration Gradients

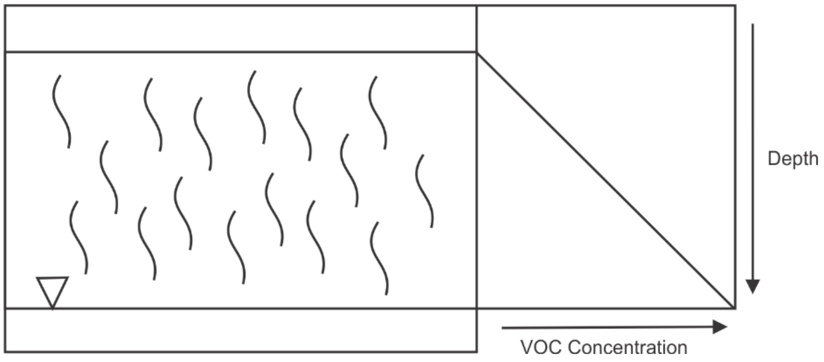

Figure 9.3A Homogenous Soils in the Vadose Zone

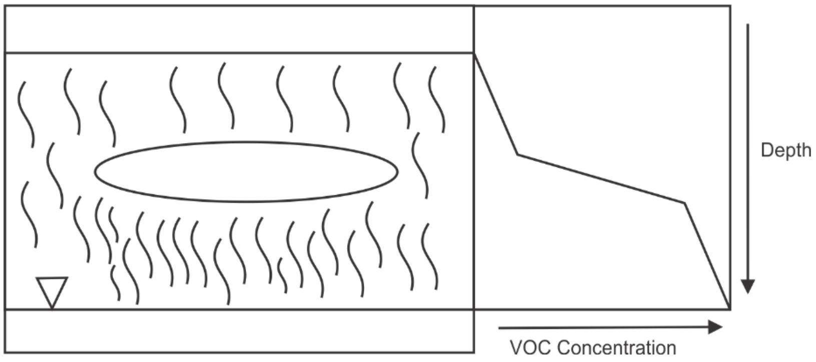

Figure 9.3B Impermeable Clay Subsurface Layer

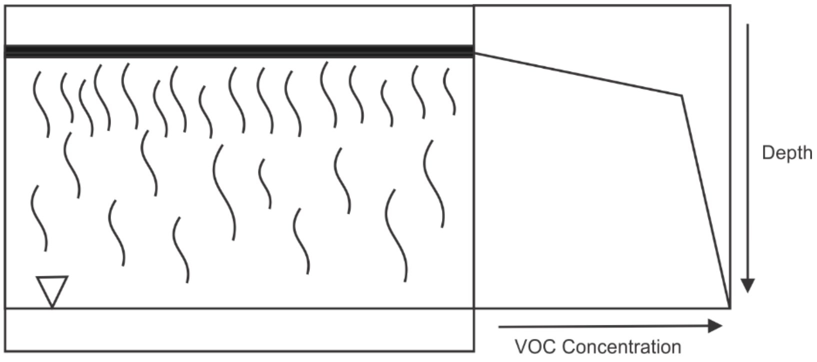

Figure 9.3C Impermeable Surface Layer

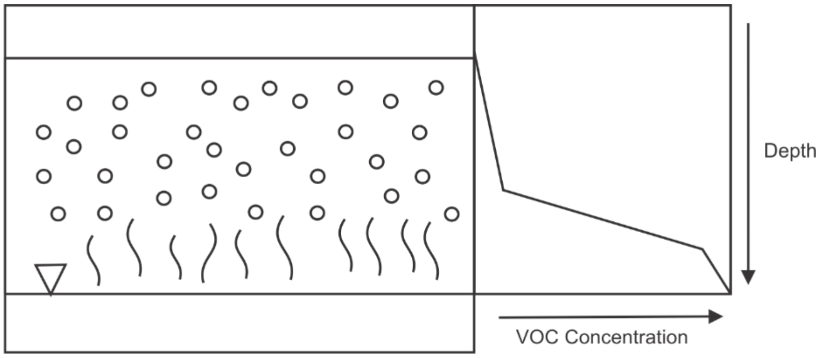

Figure 9.3D Zone of High Microbial Activity

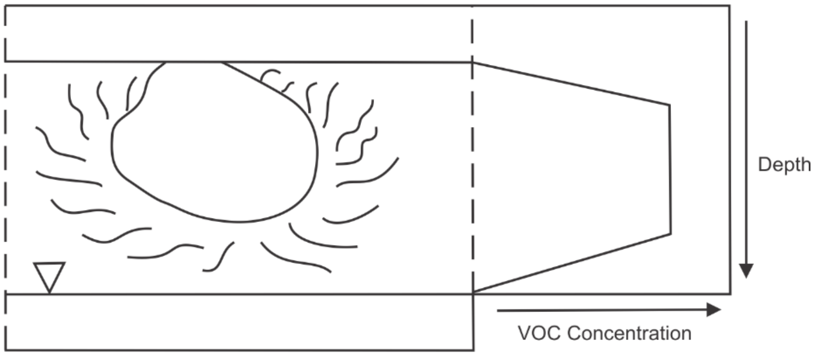

Figure 9.3E Source of VOCs in the Vadose Zone

Figures source: Marrin,D. and Kerfoot, H.B.

9.4.3 Hydrologic and Hydrogeologic Properties

9.4.3.1 Water Table Oscillations

Changes in the depth of the water table can have a large impact on the vertical transport of contaminants. The movement of ground water allows the contaminated water to “smear” across the sediments, increasing the surface area of contamination. A significant water level rise followed by a decline in the water table will have a greater effect of introducing VOCs into the vadose zone than other types of water table fluctuations.

9.4.3.2 Background Water Quality

The background water quality can have a significant effect on a soil gas survey. The presence of other contaminants can increase the difficulty of delineating a particular contaminant in question. Background water quality can be affected by off-site sources, or other sources on the site. At some locations, several plumes may exist that are partially or completely overlapping from different discharges. In such cases, greater instrument sensitivity or laboratory analyzed samples may be required to separate the contaminant of interest from the comingled plume.

9.4.3.3 Rainfall, Barometric Pressure and Wind

All of these weather conditions will have varying degrees of influence on soil gas concentrations and movement. In general, rainfall has a short-term effect on soil gas measurements. Even in heavy rains, if the soils are normally unsaturated, the rain will not produce a saturated condition for more than an hour. However, soils consisting of large amounts of silts and clays and a shallow water table (6 feet or less) can be a problem for soil gas sampling and therefore is not recommended. These soils will remain saturated for long periods of time.

Low barometric pressure and increasing winds will increase the out-gassing of soil vapors in the soil pores at or near the surface (upper 1%) and will not have an effect on samples collected several feet below the surface. Barometric pressure changes can affect soil venting discharge rates and soil gas probes where an air conduit exists to the subsurface.

The key to limiting these effects is to acquire all the samples in the shortest period of time possible under the same meteorological conditions. This leads to reducing the effects of meteorological changes and therefore, a greater confidence in the correlation of results can be made.

9.5 Investigation Sampling Designs

The design of the investigation should be constructed to obtain all necessary and required information with a minimal expenditure of time and resources. The development of the design should be based on background information obtained regarding physical and chemical properties of the contaminant, properties of the vadose zone and hydrologic and hydrogeologic properties of the area. All this information should be used to design a sampling strategy specific to the characteristics of the site. Soil gas survey technique(s) should be provided in the project work plan or QAPP.

9.5.1 Grids

Grids consist of sampling points set on perpendicular lines at equal distances along the line from each other. Grid pattern sampling will vary in size and design depending upon the site characteristics and objectives of the soil gas survey. Grid sampling is an effective way to provide data over a large area for a low cost.

Small areas of potential source(s) or complex vadose zone geology will require grid spacing as small as 100 ft^2 to 400 ft^2. Smaller grids are applied best in UST investigations and determining contaminant plume boundaries. Wide grid spacing is best applied for site reconnaissance work. An example of a grid utilized in a soil gas survey design is shown in Figure 9.4.

9.5.2 Transect Lines

For transect lines sampling points are placed on a line between the impacted area and a suspected source area(s) of contamination. This network is most commonly used to quickly find a source area(s) of contamination. Further sampling methods are then used to pinpoint the exact source(s) of contamination. This can significantly decrease the number of sampling points. An example of using a transect line investigation technique is shown in Figure 9.5.

9.5.3 Biased

In this approach, sample points are placed near a suspected source in an area of contamination to find "hot spots" for further delineation or remediation. This type of network can be used to find potential source areas or, once a source area is determined it can be used to determine the extent of contamination.

9.5.4 Random

Random sampling networks use a grid pattern with numbers designating nodes or areas. A random number generator is used to designate which areas are targeted for sampling. This type of network is used in areas where no information is known, or no contamination is suspected.

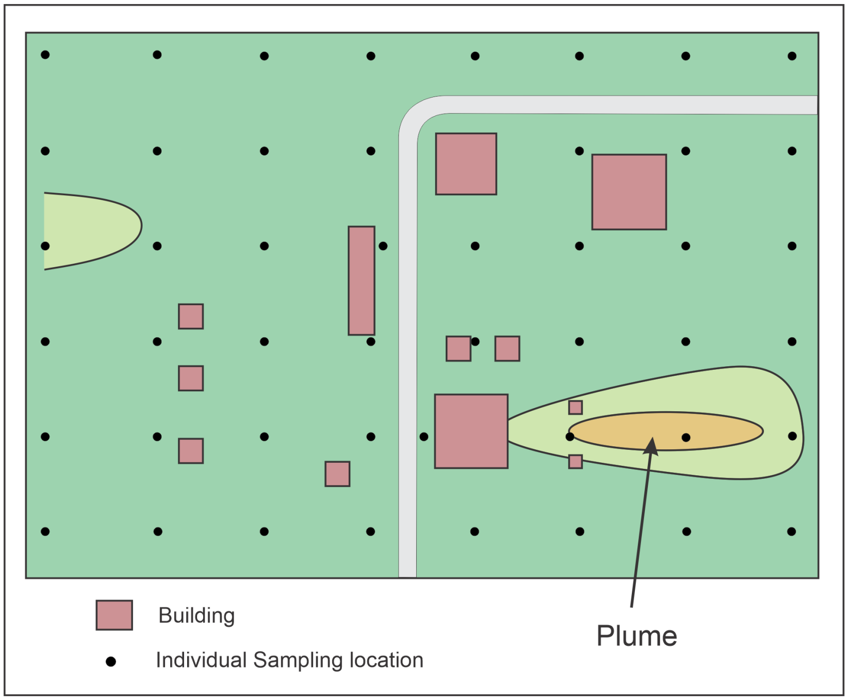

Figure 9.4 Site Monitoring Network Grid Sampling

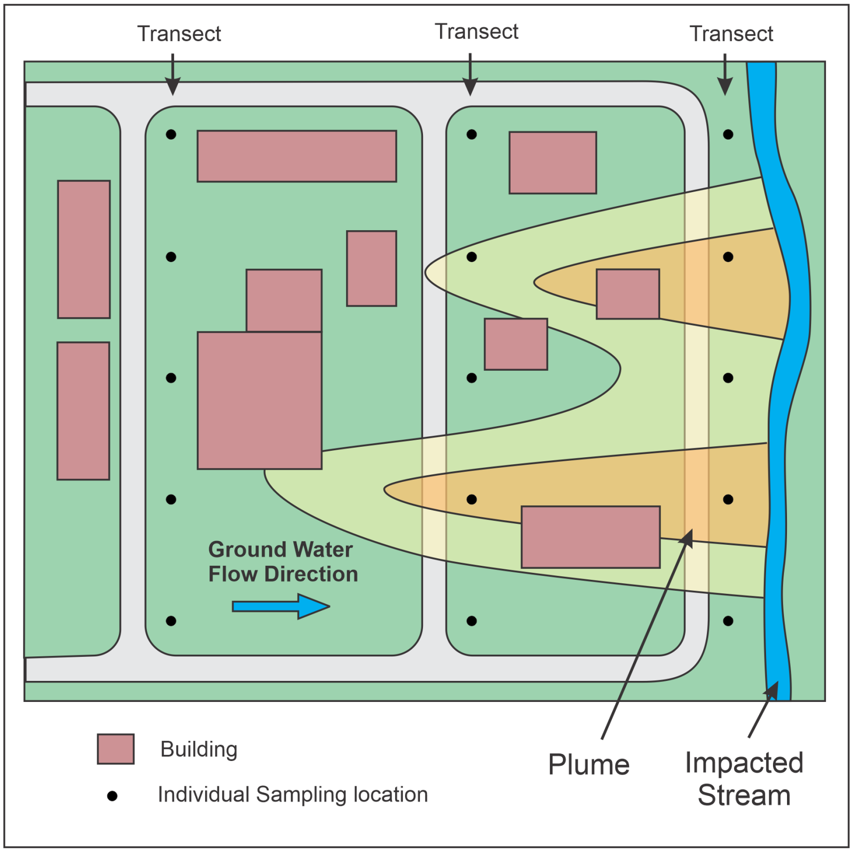

Figure 9.5 Site Monitoring Network Transect Lines

9.5.5 Combined

This type of sampling design is the most used. It is a combination of the four sampling designs. As contamination is detected, the sampling pattern and locations will change to accomplish the goal of the sampling plan. When performing a soil gas survey, the sampling plan is most effective when it is fluid and subject to change. This allows for the evaluation of data as it is generated, then incorporating the collected data in the decision process to dictate the locations and depths of additional data point if required. Keep in mind that safety concerns and utility mark outs must take precedence in a fluid sampling design.

9.5.6 Vertical Profiling

Vertical profiling is the acquisition of multiple soil gas samples at various depths from the same location. Ideally, the VOC soil gas concentration gradient in the vadose zone will increase towards the source of contamination. Subsurface heterogeneity, soil porosity, biodegradation, moisture content and source VOC concentrations will affect the soil gas concentration gradient. Vertical profiling can determine the differences in the physical nature of the soil to aid in detecting contaminant sources and pathways.

Vertical profiling can aid in:

- Determining the concentration gradient of contaminants at the site
- Evaluating optimum sampling depth
- Determining the effects of biodegradation on the contaminants of interest
- Providing a vertical concentration gradient across the vadose zone to aid in differentiating if a surface spill or ground water contamination is responsible for the concentration profile
- Determining if vadose zone barriers are present

When performing vertical profiles, sample depths should be corrected for changes in surface elevation changes so concentration contours represent a horizontal layer.

One of the difficulties with vertical profiling is the potential for cross contamination when the same sampling equipment is used for each subsequent sample. Also, the tools being withdrawn and reinserted into the borehole may lead to venting of the soil gas from the open hole. Both of these conditions will lead to a reduction in the representativeness of the subsequent sample.

9.5.7 Sample Spacing

Sample spacing is the horizontal distance between sample locations across a site. Spacing of sample locations depends upon the objectives of the investigation, size of the site and size of the potential contaminant sources. Sample spacing may also be dependent upon the number of subsurface conditions that allow or impede the migration of vapors.

For small 1–2 acre UST sites, sample spacing can be 10-50 feet between samples. On large industrial sites or landfill perimeters, sample spacing can be as large as 400-500 feet. In general, sample spacing should be at a minimum of two to three times the depth to ground water. If two sample locations have two to three orders of magnitude difference in concentration, samples should be collected between the two points. Reducing the sample intervals below this distance across a site will not necessarily provide for better resolution of contamination. It may demonstrate the variability in the soil horizon rather than changes in VOC concentrations. Soil gas sampling is not a high-resolution technique for contamination delineation and should not be used for this type of interpretation.

9.5.8 Sampling Frequency

The sampling frequency will depend upon the objective and the results of the soil gas survey. For initial site screening only one round of sampling may be required to find potential VOC sources with possibly a second round of sampling for further delineation or exploration. Soil gas monitoring programs using permanent probes at landfills and UST sites may use a quarterly or monthly program sampling frequency. A greater frequency can be used for monitoring remediation activities or monitoring the migration of explosive landfill gasses near buildings. In these cases, it may be best to employ the use of a continuous monitor.

9.6 Active Sample Collection Methodologies

Active sample collection methods involve "pulling" a vapor sample through a temporary or permanent probe to a collection or analytical device. Samples are then transported to a laboratory for analysis or analyzed on site so real-time data can be obtained and used for directing the investigation. Active sample collection gives a snapshot of the soil gas conditions at a particular time and depth. This method allows for rapid soil-gas sample collection and analysis from target depths. Contamination from VOCs can be detected directly with contaminant specific analysis or VOCs and SVOCs can be detected indirectly by measuring the concentrations of oxygen, carbon dioxide, methane and hydrogen sulfide produced from the biodegradation processes on contaminants or waste.

9.6.1 Ground Probes

There are several different types of ground probes that can be used for collecting soil gas samples. One type, a passively placed ground probe is used by first making a hole with the use of a bucket auger or slide hammer. The initial size of the hole must be kept to a minimum in order to reduce excessive purge volumes. The probe is then placed into the hole and the annular space at the surface is sealed with an inert impermeable material, such as pottery clay. Different probe designs can be used with this method.

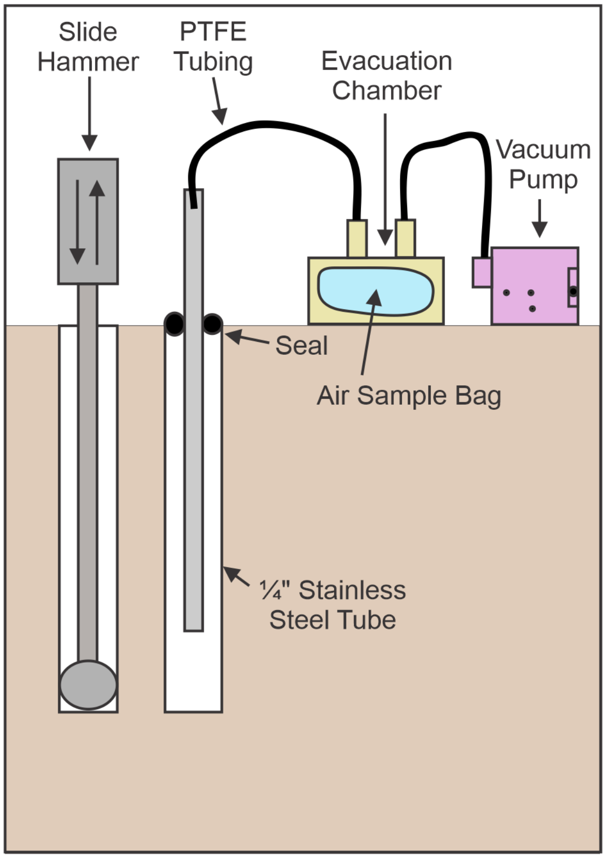

Figure 9.6 Passive Placed Probe

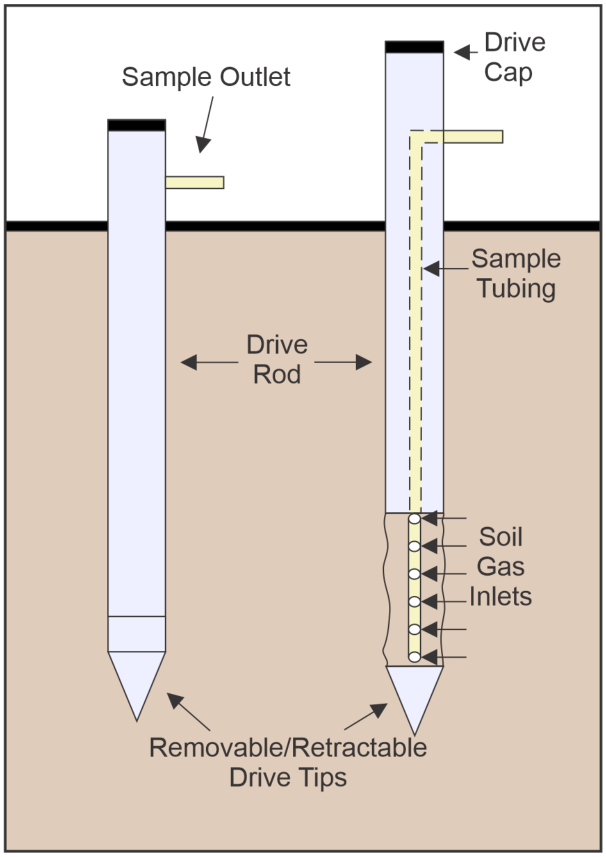

Figure 9.7 Drive Ground Probe

One probe is designed with predrilled holes or a small diameter well casing (½" or ¼" PVC) on the leading end. Another probe design uses a ¼" tubing, such as a brake line that has an open end (Figure 9.6). A wire is placed in the probe during installation to prevent the probe from being clogged. It is recommended that the drill cuttings not be used to seal the surface annular space since they will not provide an effective seal. The annular surface seal must be made with an inert impermeable material such as clay. Once sealed, the probe is evacuated, and a sample withdrawn for analysis.

Other types of ground probes are driven to the targeted depth by a slide, electric or hydraulic hammer. Drive ground probes consist of a tube, which has a removable or retractable drive tip (Figure 9.7).

Once at the targeted depth, the drive rods are pulled back to “open” the probe. One type of drive ground probe has a removable drive tip. When this type of probe is driven to the desired sampling depth, the drive rods are pulled back and the removable drive tip is opened, exposing the open end of the drive rod for sample collection; the tip is not recovered. The trailing end has a drive cap to protect it when the tube is driven into the ground. A sample port of the manifold for gas extraction can be located on the trailing end of the probe. Another type of drive ground probe that is available has a retractable tip. This probe is used for obtaining soil gas samples at discrete depths with fewer failures due to hole clogging. This probe consists of two parts, an outer tube and a small inner tube with sample parts connected to the drive point. The probe is driven to the desired depth and the probe is pulled up to “open” the probe for sampling.

The annular seal is maintained by the soil against the probe rods. Therefore, the drive tip cannot be larger than the probe rods or there will be no annular seal provided when the probe is pulled back to open the probe (Figure 9.8). Probes or rods, which have an irregular shape, will not allow for a competent seal, and can lead to sample dilution and erroneous results.

Modifications in the probes can be made to vary the length to attain greater depths or to decrease the inside volume of the probe or allow for disposable tubing to be used. A decreased probe volume will cut down on the volume needed to purge the system, thereby giving a more representative sample of the gas present at the sampling depth.

The success of the use of active sampling methods will depend upon the amount of clay, organic material, and moisture content. Driven probes also destroy the natural soil permeability around the probe due to the displacement and compaction of soil during placement. This can be a severe limitation in some soils. In very dry cemented soils, driven probes can form cracks that can cause “short circuiting” with atmospheric air and can result in sample dilution. Use of a predrilled hole for probe insertion can also encourage contaminant venting and lower sample representativeness.

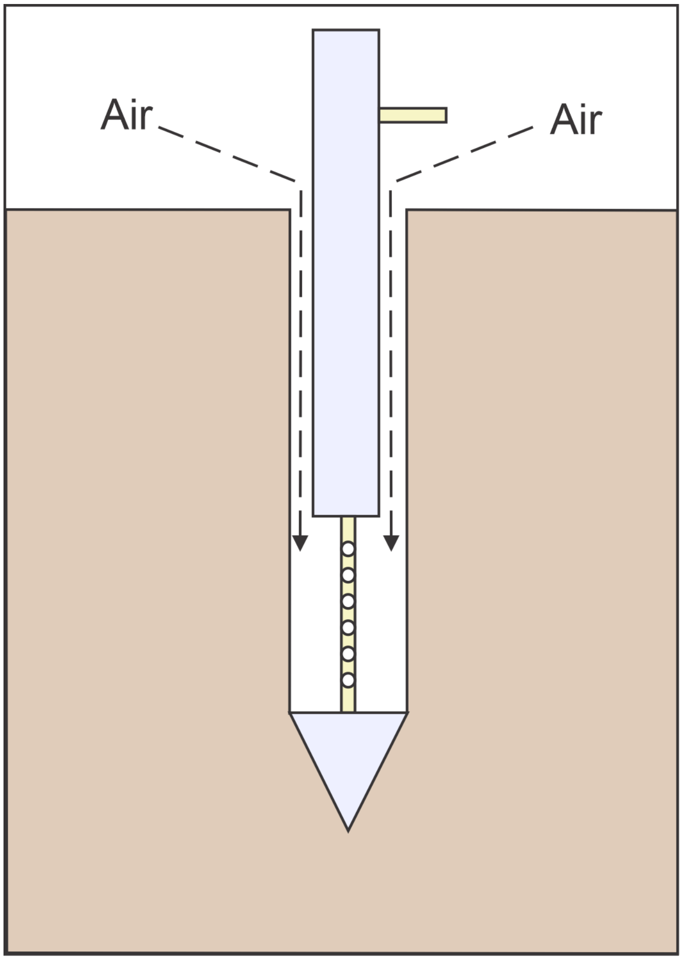

Figure 9.8 Ground Probes Ambient Air Short Circuiting

9.6.2 Permanent Soil Gas Probes

Permanent soil gas probes are constructed so soil gas samples can be obtained from the same location over time. They are used to obtain data on changes in soil gas concentrations over time. Single or multiple probes may be installed into a single borehole to obtain vertical profile data. Permanent probes are recommended for projects requiring more than one soil gas sampling event to monitor subsurface gas conditions for gas migration control or to monitor remediation activities. (UST's, landfills, SVE Systems). The use of permanent soil gas probes can aid in optimizing remediation activities and decrease the number of man-hours required to complete the remediation effort.

Location and depth of permanent soil gas probes will be based on the objective of the monitoring program. Their placement can be based on the results of previous soil gas surveys or in specific areas to obtain monitoring data.

The method of installation and construction of permanent soil gas probes vary. Probe holes can be advanced with hand or power augers, soil cores, hollow or solid stem augers and direct push methods. The probes can be constructed of various size PVC pipe (¼ inch schedule 80) with predrilled small diameter holes, ½" schedule 40 PVC slotted well screen and riser with flush jointed threads (FJT) or commercially available soil gas well points manufactured by companies specializing in soil gas equipment (Figure 9.9).

The construction of a permanent soil gas probe is the same as a monitor well, only above the water table. The length of screens can vary, depending upon the objective of the monitoring but should not be longer than 5 feet. A Morie Number 1 or 2 sand is used for the gravel pack with a minimum two-foot bentonite seal above the screen to eliminate infiltration of ambient or non-sample zone air. The probe can be completed with a surface protective casing, either flush mount or above grade. The probe casing should

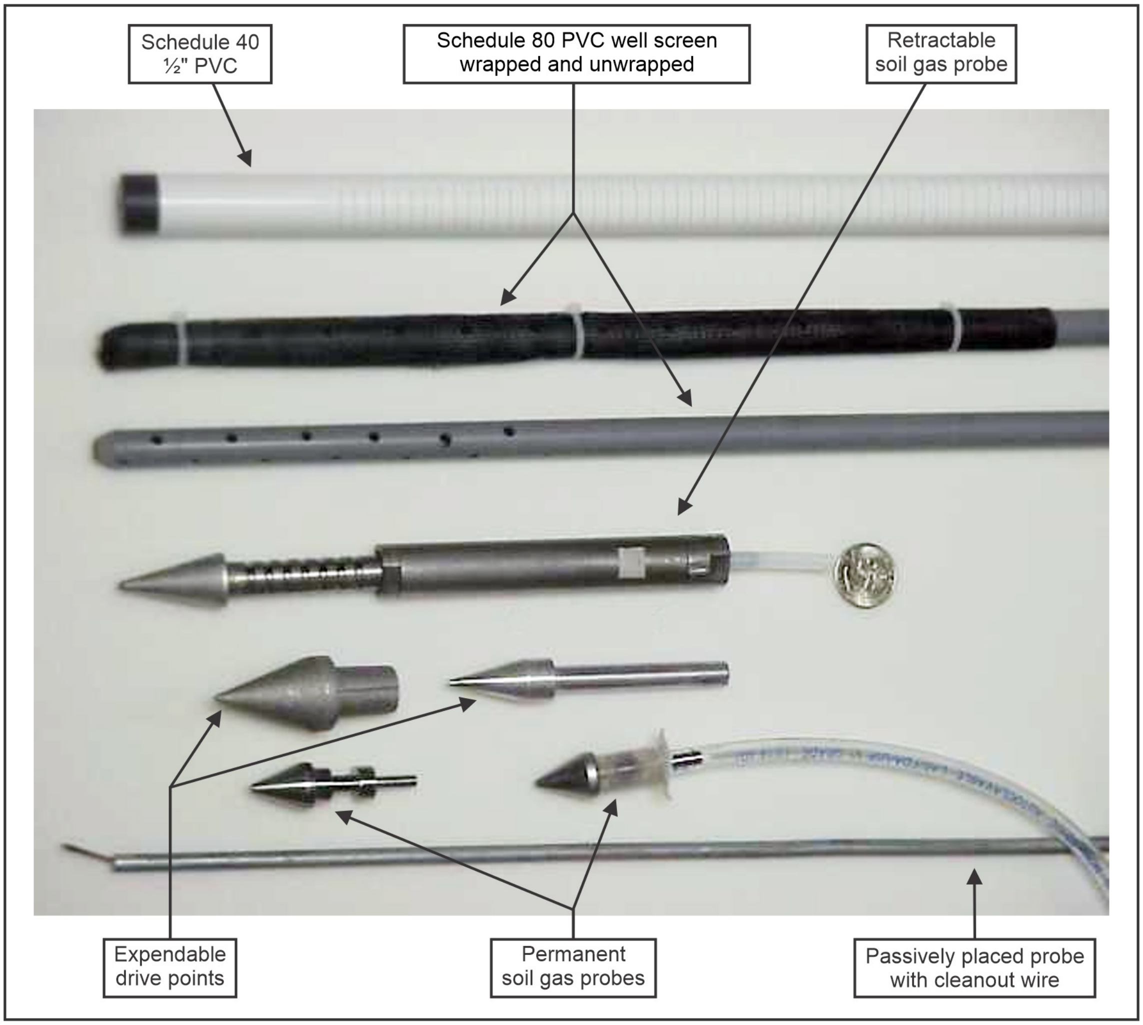

Figure 9.9 Soil Gas Sampling Probes, *Photographed by C. Van Sciver*

be covered with a cap to prevent venting of the soil gas or providing a home for insects. As an alternative, a small ball valve can be installed on the probe that will aid in obtaining pressure measurements (Figure 9.10 & 9.11).

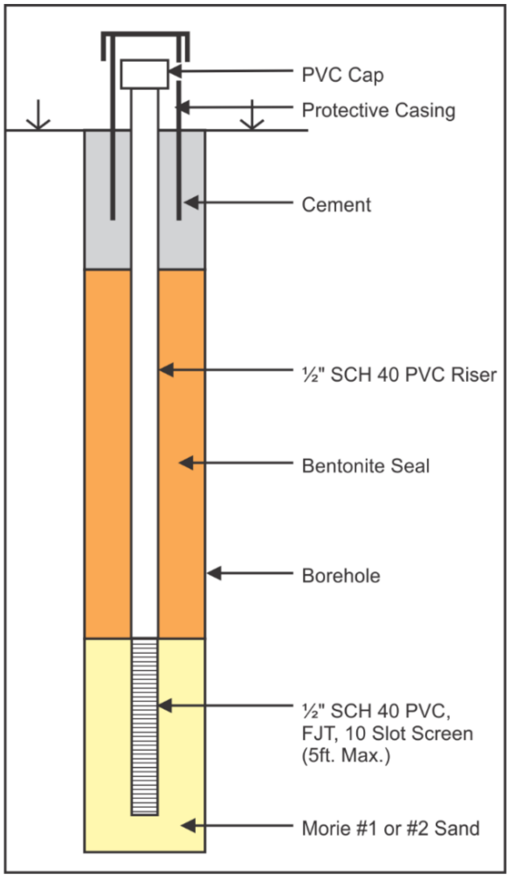

Figure 9.10 Soil Gas Well Schematic

Figure 9.11 Ball Valve for Soil Gas Well, *Photographed by C. Van Sciver*

If multiple depths are targeted for monitoring, the installation of the soil gas probes can be completed using various designs (Figure 9.12). Probes can be installed using several designs they are as follows:

- Cluster
- Nested
- Multi-Screen
- Multi-port

If probes are placed in a single borehole, a 2-foot bentonite seal must separate the zones.

If permanent probes are placed with direct push tools, the probe screen must be protected during advancement by the drive rods. This will prevent damage to the screen during advancement. Direct push rods are available which are designed for this purpose. The drawback to this technique is the potential for soil compaction during installation reducing the permeability in some soils and the inability to place a gravel pack or a bentonite seal other than at the surface. Therefore, the use of direct push probe installations may be limited to shallow probe applications.

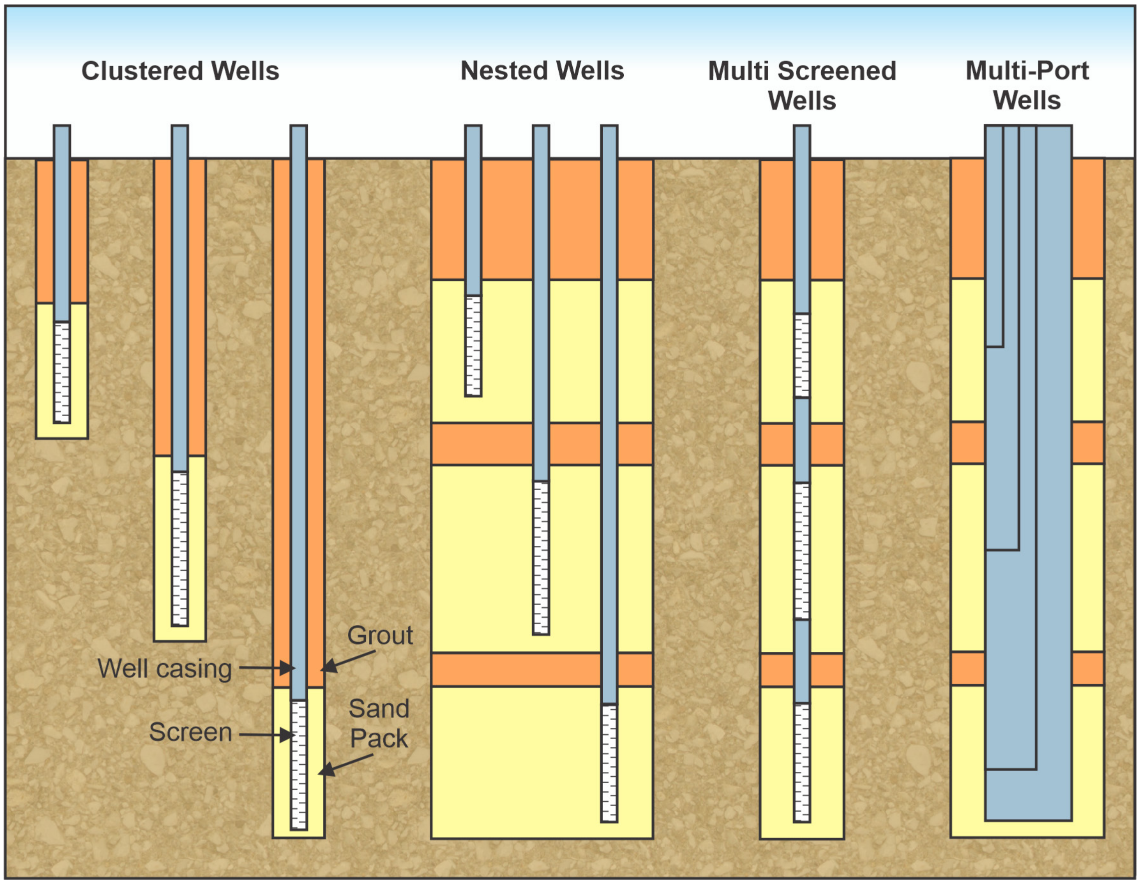

Figure 9.12 Comparison of Multi-Depth Soil Gas Well Designs

9.6.3 Materials of Construction

During any soil gas sampling, the materials used for sampling must not impact sample integrity. The material of construction for soil gas probes and sampling equipment will depend upon the objective of the sampling, contaminants of concern, concentration, analytical sensitivity, and type of soil gas probe. The lower the expected concentration of contaminants and increased analytical sensitivity, the higher the quality of materials required for sampling (sample tubing, syringes, level of quality assurance / quality control (QA/QC)) to prevent the alteration of the contaminant quality or quantity through sorption, desorption, or cross contamination. If materials cannot be decontaminated between samples, they must be replaced between samples or replaced by a more suitable material. The quality of materials for sampling percent levels of landfill gasses will not have to be as high as the material used in delineating a dissolved VOC contaminant plume. Generally, the more inert the sample tubing, the more suitable it would be for lower concentration soil gas sampling. Checks on the material applicability must be included in good QA/QC procedures.

9.6.4 Purge Rates and Volume

After a soil gas probe is installed, the air inside the probe must be purged to bring a soil gas sample to the surface for analysis. The purge rate and volume are a critical factor in soil gas sampling and will vary from site to site. Prior to initiating a soil-gas sampling event, tests should be conducted at several areas of the site to determine the optimum purge volume and rates. Optimum flow rate and purge volumes are achieved when vacuum pressure is at atmospheric, and the contaminant concentration is stable. Use of the optimal purge rates and volumes should be made a “standard” sampling technique for the site investigation. Deviation of the procedures may give variable concentrations and make interpretation of the results difficult. The probe volume and evacuation time can be calculated using the following formula:

Purge Time Calculation for One Probe Volume:

$$\frac{D^2 \times P_d \times 9.27}{P_r} = P_t$$

D = Diameter of probe, inches

P_d = Probe depth, feet

P_r = Pump rate, liters per minute

P_t = Purge time for one probe volume, seconds

Volumes for various probe diameters are included in Table 9.2.

Table 9.2. Purge Volumes for Select Tubing Sizes

Tubing Size (inches ID*)	Volume/ft. (liters)
3/16	0.005
1/4	0.010
1/2	0.039
3/4	0.087
1	0.15
2	0.62
4	2.46
6	5.54

*ID = Inner Diameter

Purging of the soil gas probe is best performed with a small air pump. The pump should have a flow meter and an in-line vacuum gauge so changes in the flow rate and vacuum can be monitored (Figures 9.13A and 9.13B). The use of an inline vacuum gauge and flow meter allows the operator to determine if soil vapors are being pulled into the probe and at an accurate volume and rate. This will ensure constant evacuation volumes for all probes during a sampling event thereby eliminating variability in sampling technique. Variations in the sampling technique can lead to variability in results. Use of this device also allows for estimates of soil-air permeability. Flow and vacuum readings should be recorded to help identify low permeability areas to aid in interpretation of the data.

If soil gas probes were constructed of larger diameter pipe (2 inches or greater) it has been shown that a "drop tube" or "feeder tube" can be used to reduce the time for purging a soil gas probe to obtain a representative sample. A drop tube is a small diameter tube (usually ¼ inch) installed in a soil gas probe from a bulkhead fitting on an airtight cap to the screened interval of the probe. As the probe is evacuated,

Figure 9.13A Purge pump with flow control and vacuum gauge, *Photographed by C. Van Sciver*

Figure 9.13B Purge pump with DRI inline, *Photographed by C. Van Sciver*

soil gas is drawn directly into the screened interval for sampling. The stagnant air in the riser does not need to be removed and the airtight cap eliminates air intrusion that could dilute the sample. This greatly reduces the time required for purging larger diameter deep soil gas probes.

Monitoring vacuum pressure during and after purging allows for sampling from the probe with no vacuum pressure. This is important when sampling with a syringe for direct injection. For example, if a probe is sampled with a syringe while the system has 15 inches Hg vacuum, the concentration in the syringe will be half what it should be before removing it from the system (assuming normal atmospheric pressure is 30 inches Hg). When the syringe is removed from the system it has 15 inches of Hg and will quickly go to atmospheric pressure by drawing in ambient air, diluting the sample by half of the original concentration. If the syringe is worn and has a weak seal between the plunger and the syringe barrel wall, then ambient air can be drawn into the syringe through this weakness, diluting the sample. After purging the soil gas probe, the vacuum pressure on the probe must always be allowed to return to atmospheric pressure before taking a syringe sample.

Many people employ the use of direct reading instruments (DRI) for the analysis of vapor samples in a soil gas survey. The DRI (e.g., photoionization detector (PID) or flame ionization detector (FID)) is usually connected directly to the soil gas probe for analysis. This can be problematic since the DRI is sensitive to the mass of contaminant flowing to the detector. As the operational flow rate to a DRI is decreased, the response of the instrument decreases. Spatial variations in soil permeability across a site due to changes in soil lithology, texture and moisture will introduce variations in soil gas readings which are not concentration related. This will complicate the interpretation of soil gas survey results. Use of a purge system with flow and vacuum readings will determine if the DRI can be connected directly to the soil gas probe for sampling. If vacuum pressures are at atmospheric pressure and the flow rate is above the operational range of the instrument during purging, then the instrument can be connected directly to the soil gas probe. If flow rates and/or vacuum pressures during purging are outside the operational range of the instrument, a bag sample must be collected. This allows the instrument to analyze the sample at ambient conditions and obtain accurate readings.

9.6.5 Short Circuiting

During soil gas sampling, it is important to have a good annular seal between the probe and soil. A poor annular seal will lead to “short circuiting” of vapors by ambient air as it moves down the annulus (Figure 9.8). This will lead to results that are non-representative and difficult to interpret. The type and need for an annular seal will depend upon the type of soil gas probe being employed. Some probes require a clay seal to be placed at the surface while others use the design of the probe, the drive point being smaller than the probe and rods. A poor annular seal can also be caused from multiple insertions into the same hole during vertical profiling.

9.6.6 Pressure Measurements

Pressure in soil gas wells can be measured with a pressure/vacuum gauge that measures pressure in inches of water. The gauge can be installed permanently at the well head, or a portable gauge can be used for measurements. The soil gas probe can be sealed with the sampling cap or a ball valve. The ball valve can be permanently installed to minimize the time for pressure stabilization by not exposing the well to ambient pressure prior to measurement. Measurements must be made prior to obtaining a gas sample. After pressure and gas measurements are obtained, the cap to the gas probe must be replaced to reduce the effects of venting or barometric pressure variations on future gas sample compositions.

Pressure measurements from soil gas wells at various depths have shown a strong correlation with atmospheric pressure oscillations. These oscillations in barometric pressure occur twice daily due to solar and lunar gravitational forces (atmospheric tides), with high pressures at 10:00AM and 10:00PM and low pressures at 4:00 AM and 4:00PM. The deeper the interval the greater the lag time for the change in pressure. These data can be used to determine the depth and magnitude of pressure fluctuations that might induce “barometric pumping” in the vadose zone. When the curve for soil gas and barometric pressure cross, a reversal of the pressure gradient has occurred and the direction of gas flow changes from "soil to atmosphere" to "atmosphere to soil." This will be seen as a negative pressure in the soil gas well compared to barometric pressure (Figure 9.14).

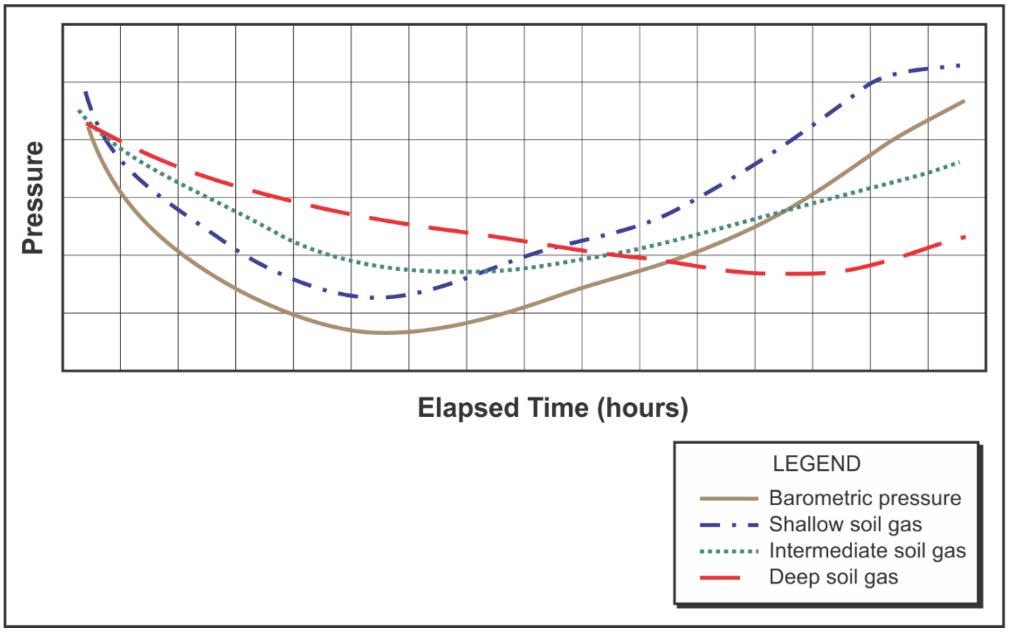

Figure 9.14 Soil Gas Pressure vs. Barometric Pressure

For example, in landfills with vigorous microbial activity, gas pressures of 1-3 inches of water relative to atmospheric pressure are common with higher pressures recorded. Falling barometric pressures may cause an increase in the convective transport of landfill and methane gas content as gas readily migrates from the landfill due to an increased pressure differential. Negative gas pressures are commonly observed and are a delayed result of the passing of a high-pressure system or atmospheric tides. High-pressure systems will introduce atmospheric oxygen into the surface soils in shallow portions of the landfill, which can alter methane concentrations and production from microbial activity. The relative gas pressure measurements at a particular area of a landfill along with the ability of site conditions to contain landfill gas, barometric pressure variations and the rate of gas production will control pressure induced landfill gas migration.

9.7 Passive Sample Collection Methodologies

Passive sample collection includes two general sample collection techniques. These techniques include the passive collection of contaminants onto sorbent material placed in the vadose zone and a whole-air passive collection technique for collecting vapors emissions from the soil surface using an emission isolation flux chamber.

9.7.1 Sorbents

Passive sorbent sample collection utilizes diffusion and adsorption for soil gas collection onto a sorbent collection device over time. Depending upon the sorbents, they can be used to sample both VOCs and semi-volatiles (Figure 9.15).

The upward movement of contaminant vapors creates a concentration gradient in the vadose zone. The passive sorbent collection method uses this to collect long-term non-disruptive samples of VOCs, SVOCs and biogenic gases. The principal of passive sorbent sample collection relies on the sorbent reducing the

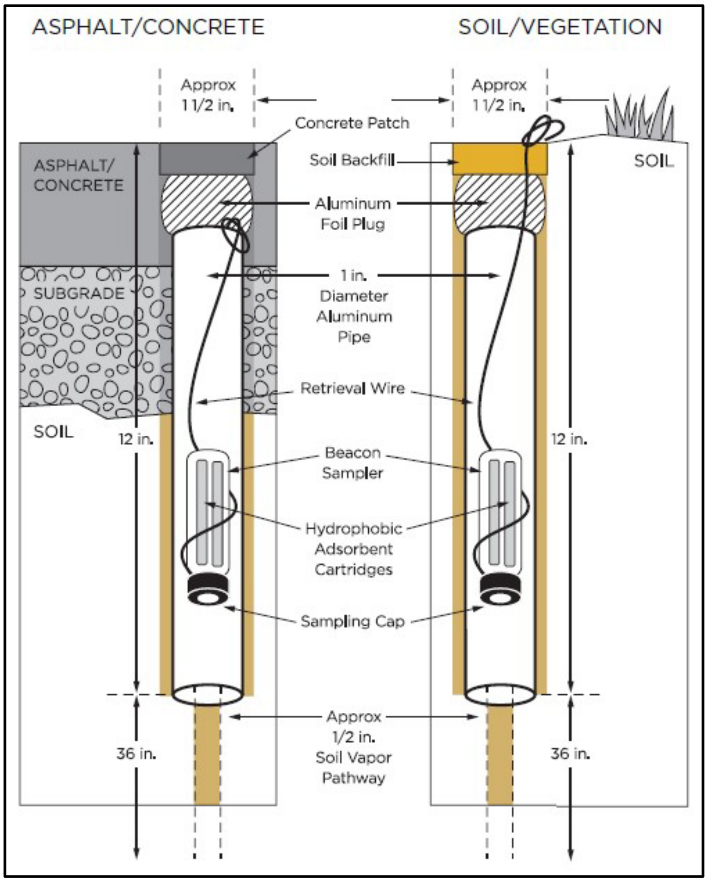

Figure 9.15 Passive sorbent sampler
Illustration by Beacon Environmental

concentration of contaminants around the sampler over time. This creates a concentration gradient that decreases toward the sampler. This concentration gradient sustains the movement of vapors toward the sampler. Also, since the sorbent can collect contaminants over a long period of time, this concentrates the mass of contaminants absorbed to the sampler, enhancing detection sensitivity. The quantity of VOCs collected by passive sorbent samplers is proportional to the concentration gradients of the contaminants near the passive sorbent sampler and the affinity of the contaminants to the sorbent material.

Passive sorbent samplers can be used in a variety of geologic and environmental conditions. The sorbents are placed in small diameter holes, made with simple hand tools, that vary in depth, from a few inches to 5 feet deep. They are left in the ground for a few days or weeks depending upon the application and site conditions. The characteristics of the vadose zone and the chemical and physical properties of the contaminant will control migration of the contaminants. Passive sorbent samplers provide an integrated sample that compensates for any short-term fluxes in soil gas concentrations. This method is recommended when the ground water contaminants are not known, and concentration is low.

9.7.1.1 AGI Sampler (formerly Gore-Sorber)

The Amplified Geochemical Imaging (AGI) Sampler (formerly Gore-Sorber) passive sampler is constructed of a hollow polytetrafluoroethylene (ePTFE) cord, used for insertion and retrieval of the sampler. The cord contains smaller ePTFE tubes that contain the granular adsorbent material. The granular sorbent material consists of various polymeric and carbonaceous adsorbents selected for their affinity to a wide variety of compounds. The adsorbents also minimize the uptake of water vapor. The sampler is stored and transported in a glass vial.

The AGI sampler is typically media contained in a one foot (approximately) "cord" that is suspended in a hole below the ground surface on string. This allows for enough sorbers for two samples. This allows for duplicate analysis or as a backup. The membrane allows for the transport of vapors across its entire surface area while providing strength for the retrieval of the sampler. The contaminant vapors move unimpeded through the membrane to the adsorbent contained in the sorbers. This design prevents impact to the sorbers from soil particles and water vapor.

AGI Samplers are analyzed at their laboratories. They are analyzed by thermal desorption in accordance with EPA Method 8260/8270 using gas chromatography/mass spectrometry (GC/MS). The AGI Sampler can detect VOCs, SVOCs, explosives, PCBs, chemical agents, and breakdown products. The sample concentrations are reported in mass, by target compound and will be organized on a data table. The results can also be mapped based on mass concentration, with a supplied base map.

The AGI Samplers are installed into a small diameter hole, ½-inch or greater. The hole can be advanced with a slide hammer with tile probe, rotary hammer equipped with a 3-foot drill bit or direct push probe. Once the hole is opened, tie a length of cord to the loop on the sampler and a cork is tied to the surface end of the cord. The cork will seal the hole and the cord will allow for retrieval of the sampler. A stainless steel insertion rod, which is supplied by AGI, is placed in the pocket at the opposite end of the sampler and the sampler is inserted into the hole. The insertion rod is then removed, and the cork tamped flush with the soil surface. The sample location should be marked to relocate the sampler for retrieval. Retrieval of the sampler requires pulling the sampler out of the hole using the retrieval cord. The cord is separated from the sampler and the sampler is returned to its respective container.

9.7.1.2 Beacon Soil Gas Sampler™

The Beacon Soil Gas Sampler™ provided in BeSure Kits™ consists of two sets of hydrophobic adsorbent cartridges sealed in a 7ml screw top borosilicate glass vial that is pre-wrapped with a length of retrieval wire. The adsorbents used are chosen to concurrently target a broad range of compounds from the lighter VOCs (e.g., vinyl chloride) to the heavy SVOCs (e.g., PAHs), with the system calibrated to target over 100 compounds. Each cartridge contains the same measured amount of adsorbents, which are hydrophobic and not required to be wrapped in a membrane. The sampler is designed in compliance with ASTM Standard D7758.

To install a Beacon Sampler™, the solid shipping cap is removed and replaced with a sampling cap that allows for the free transfer of compounds onto the adsorbent. A small diameter hole is then advanced to a typical depth of 1 to 3 feet and the sampler is lowered into the upper portion of the hole, which is then sealed in the ground by plugging the hole with aluminum foil and collapsing the upper two inches of soil above this foil plug. For locations covered by asphalt or concrete surfacing, an approximately 1" diameter hole is drilled through the surfacing to the underlying soils, and the upper portion of the hole is sleeved with a sanitized metal pipe provided in the kit. After the sampler is installed inside the metal pipe, the hole is patched with an aluminum foil plug and a thin concrete patch to protect the sampler from surface runoff and ambient air. Following the exposure period, the samplers are retrieved and shipped under chain of custody to Beacon's laboratory for analysis. A minimum of one trip blank, which remains with the other samples during preparation, shipment, and storage, is included with the field samples. A two-person team can install approximately 50 to 100 samplers per day depending on the number of sample locations that are covered with asphalt or concrete. Sample exposure periods range from days to weeks depending on the sampling objectives and site conditions, with a typical exposure period being 7 or 14 days.

Analysis of the samplers is completed by Beacon using thermal desorption/gas chromatography/mass spectrometry (TD-GC/MS) instrumentation, following modified EPA Method 8260C or TO-17 procedures. Analytical results are based on an initial five-point calibration and internal standards and surrogates are included with each sample analysis. Data are reported in units of mass (nanograms) and/or concentration (ug/m3). With a 14-day sampling period, the laboratory's reporting limit for each of the targeted compounds is in the parts per trillion by volume range. Data are provided in tabular format as well as depicted on color isopleth maps showing the distribution of compounds identified.

9.7.1.3 Sample Depths

It is recommended that Passive Soil Gas Samplers be placed in holes created to a depth of 1 to 3 feet. This allows for the use of hand tools for the installation of the samplers. Samplers can be placed deeper, but deeper installations will require more time and sample retrieval from deeper depths is difficult. Shallow installations should be avoided due to affects from changing weather, off-gassing from pore spaces in the near surface and biologic degradation of contaminants in the near surface.

Surface barriers such as paved areas will yield areas of artificially high concentrations or false positives as vapors collect and migrate along the barrier. These characteristics are discussed in further detail in Section 9.4, Site Specific Characteristics.

9.7.1.4 Sample Spacing

The size of the site, the objectives of the sampling and the amount of funds available will determine the sample spacing. The range of sample spacing for environmental investigations is 25-75 feet, with many surveys using 50-foot sample spacing. Smaller sample spacing should be used if the objective is to locate areas that are likely sources of contamination or small permeable zones of contamination migration. Larger sample spacing should be used in suspected non-contaminated areas or a broad screening of a large area. If contamination is discovered in these areas, then a soil gas survey with a higher density of sampling points can be conducted at a later time and the data combined on one set of maps.

9.7.1.5 Sample Exposure Time

Samplers should be exposed to the soil gas vapors for about 3-14 days depending on the type of sampler, soil characteristics, contaminant concentrations and the compounds of interest. This will allow the samplers to reach equilibrium with the soil gas environment to provide for a representative sample. Longer exposure time does not improve sensitivity except during prolonged rain events that can cause soil saturation and interrupt the vapor migration in the subsurface.

9.7.1.6 Multiple Surveys

In some site investigations, the results of the soil gas survey may warrant returning to the site and collecting additional samples. This may be due to requiring further delineation in contaminated areas, sampling beyond the initial site sampling area or confirming results that were not expected. In these cases, it is desirable to tie in two or more soil gas surveys together. To accomplish this, several new samplers are placed in locations of prior samplers. If variables such as the exposure time, installation depth and analytical parameters are held constant from one soil gas survey to the next, the results can be comparable. It is best to place the co-located samplers in areas that will provide a range of mass levels reported in the original soil gas survey. This will provide duplicity in the data and tie the soil gas surveys together.

9.7.1.7 Data Interpretation

The soil gas data will delineate the nature and extent of subsurface contamination. The soil gas data at one location can be compared relative to the soil gas data from other sample locations in the survey. The mass levels will show patterns of the spatial distribution indicating areas of greatest subsurface impact. These areas can then be targeted for further investigation.

9.7.2 The Emission Isolation Flux Chamber

The use of the emission isolation flux chamber is used for specific applications. The flux chamber is an enclosure device used to sample gaseous emissions from a defined surface area. These data can be used to develop emission rates for a given source for predictive modeling of population exposure assessments. This technique is applied to determine contaminant emissions from soils, landfills, or water to determine the health risk to the public. The data can also be used to develop emission factors for remedial action designs.

The emission isolation flux chamber is a dome superimposed on a cylinder (Figure 9.16). This shape provides efficient mixing since no corners are present and thereby minimizing dead spaces. Clean dry sweep air is added to the chamber at a controlled volumetric flow rate. The gaseous emissions are swept through the exit port where the concentration is monitored by a real time or discrete analyzer. Real time measurements are typically performed with portable survey instruments to determine relative measurements of flux chamber steady state operation and hot zones. Discrete samples are taken when absolute measurements are required for steady state concentrations and emission rate levels. The emission rate is calculated based upon the surface area isolated, sweep airflow rate, and the gas concentration. An estimated average emission rate for the source area is calculated based upon statistical or biased sampling of a defined total area.

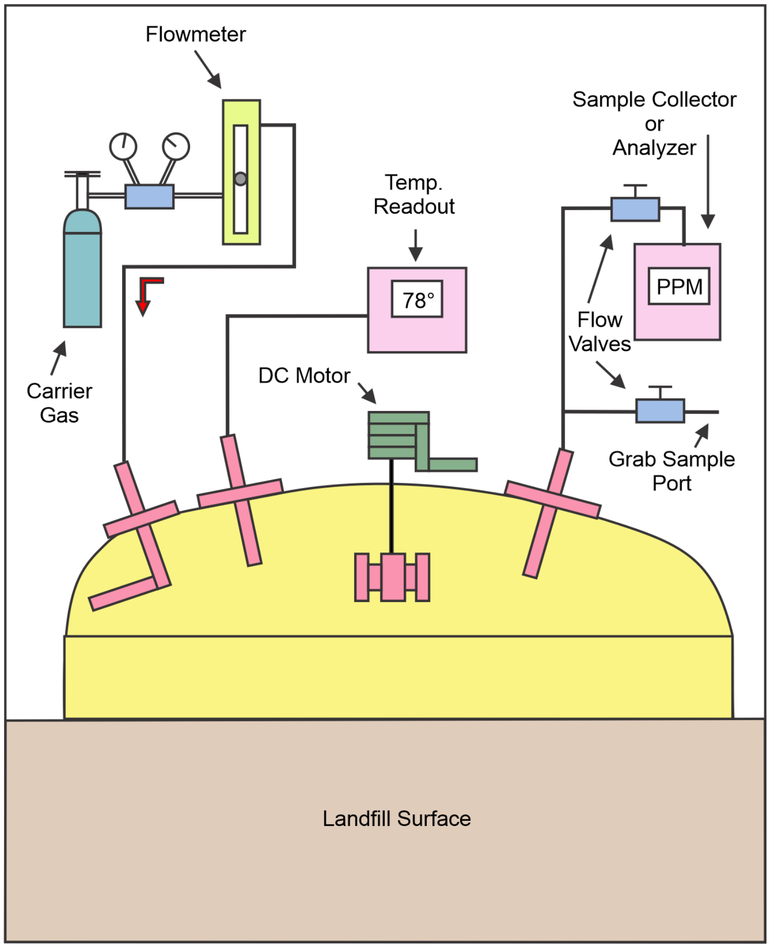

Figure 9.16 Surface flux chamber

9.8 Soil Gas Sample Containers

The collection of the soil gas sample for analysis will vary depending upon probe design and analytical methodology. The most common types of collection methods (Figure 9.17) are as follows:

9.8.1 Gas Sample Bags

One of the more common soil gas sample container and collection techniques is using a gas sample bag (Tedlar®, Teflon®, metal-coated Tedlar®, etc.) with an evacuation chamber. The use of an evacuation chamber allows an air sample to be collected without the sample passing through a pump. The evacuation chamber is an airtight container, which can hold a gas sample bag and has two fittings. One fitting is a through hull fitting for connection of the tubing from the soil gas probe directly to the gas sample bag and the other allows the removal of the air around the gas sample bag in the chamber. A gas sample bag is connected and placed in the evacuation chamber. The air surrounding the bag in the container is pumped out; creating a vacuum that causes the bag to fill. Vacuum chambers can be made from common materials or purchased commercially.

All gas sample bags must be checked for leaks and cross contamination between each sample. Sample bags can be purchased with septum ports and hose valves. These fittings can be a major source of leakage from the bags so they must be checked for tightness and integrity. Sorption of the contaminants to the bag is another area where loss of contaminants can occur and be a source of cross contamination. Depending on the contaminants, the holding times for samples in the gas sample bags will vary. In general, Tedlar® bags are the best choice for short holding times of samples (<3hr.). Aluminized bags are the best choice for longer holding times. Gas sample bags are cleaned between samples by purging with air or nitrogen until contaminants are non-detect.

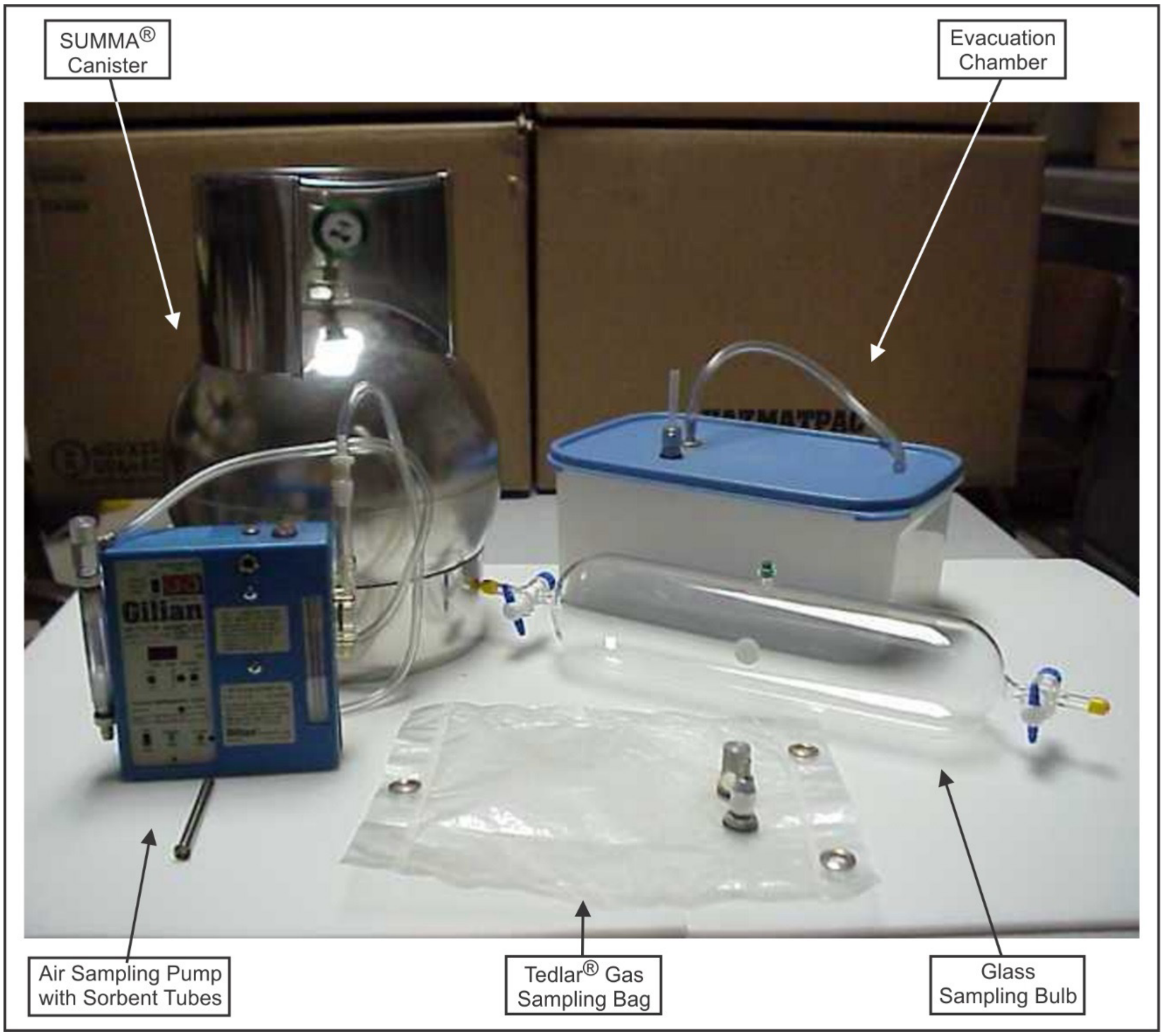

Figure 9.17 Air sampling equipment, *Photographed by C. Van Sciver*

9.8.2 Glass Bulbs

A second technique uses glass bulbs, which are glass cylinders with openings at each end, and having a septum port to withdraw sample aliquots with a syringe. The air sample is collected by connecting one end of the bulb to the probe and the other to a pump. The pump then draws the sample through the bulb. The sample of air does not go through the pump prior to collection. The advantage of glass bulbs is the material is inert and they are easy to use. The limitations of the glass bulbs are they are easily breakable and can lose contaminants through the Teflon® valves. Sample holding times for the glass bulbs is 24 hours.

9.8.3 Syringes

Syringes are used to withdraw a soil gas sample from a probe and inject it directly into an analytical instrument for on-site analysis. Syringes come in varying volumes, materials of construction and designs to meet the analytical criteria. They are easy to clean and replace. They have a short sample holding time (minutes) due to the potential for leakage and sorption of contaminants. As the seal of the plunger and barrel becomes worn, the syringe must be discarded due to the potential of sample dilution from leakage and short-circuiting around the plunger.

9.8.4 Stainless Steel Canisters

Stainless steel canisters are excellent for the collection and holding of soil gas samples. They can be used for sampling with a pump system or be pre-evacuated, so samples are collected by vacuum pressure. Laboratory calibrated valves may be attached to the canisters to allow for a time composite sample, as is required under certain lab methods. These samplers are commonly used for indoor air sampling. For more information see the *Vapor Intrusion Technical Guidance* available at: https://www.nj.gov/dep/srp/guidance/vaporintrusion/. To use these devices the sample lines must be purged with sample air prior to opening for sampling to prevent sample dilution. They cannot be decontaminated in the field; a laboratory must clean them. Sample holding time is 14 days.

9.8.5 Sorbents

Soil gas samples can be collected on sorbents dependent upon the species of interest. Some of the sorbents used are charcoal, Tenax®, Carbotrap®, polyurethane foam (PUF) and carbon molecular sieve (CMS). A sorbent tube is connected to the soil gas probe and a sample is pumped through the tube while the sorbent strips the analytes from the air. Sample volumes must be measured accurately. The tube is then analyzed by thermal or solvent extraction and analyzed. Sorbent tubes allow for the concentration of low-level contaminant concentrations, not detectable by other methods. Holding time for the samples depend upon the type of sorbent but are generally 14 days.

9.9 Analytical Methodologies

The method selected to analyze the soil gas samples must be consistent with the collection methodology to achieve the objectives of the investigation. Some basic criteria for selection of the proper analytical method includes:

- Sensitivity: Is parts per billion (ppb), parts per million (ppm) or percent concentration required? Is the relative concentration or the absolute concentration required?
- Selectivity: Will the analytical methodology identify specific compounds, or will a total value satisfy the data objectives?
- Cost: Is the analytical methodology cost effective?

Based on these criteria, an analytical methodology can be chosen which will achieve the objectives of the soil gas investigation. Some of the methods used in soil gas sampling are as follows.

9.9.1 Detector Tubes

Detector tubes operate by drawing a known amount of gas through a tube with the use of a mechanical pump. If the indicator chemical is present in the sample, a stain will appear. The length of the stain will correspond to the concentration of the chemical in the sample. This analytical method is the most inexpensive, has good selectivity, and the sensitivity is usually high. Also, the user must be aware of the influence other gases and water moisture, which may be high in soil gas, will have on the method.

9.9.2 Direct Reading Instruments (DRI)

There are many types of DRIs available, which can provide dependable data if used within their limits. These units can be cost effective for obtaining analytical data, which has ppm sensitivity and limited selectivity. DRIs include organic vapor monitors (PID, FID), combustible gas monitors, (oxygen, methane, hydrogen sulfide) and landfill gas analyzers with infrared detectors (IR) for monitoring methane and carbon dioxide. For additional information on direct read instruments see the FSPM Chapter 7.

These instruments have been used successfully in delineating VOC and SVOC contaminant plumes and monitoring landfill gas migration. These instruments can measure the subsurface contamination directly by measuring the VOC concentrations or indirectly by measuring the oxygen, methane, hydrogen sulfide and carbon dioxide concentrations, which are microbial byproducts from the breakdown of hydrocarbons and other organic material.

There are some problems with the use of these instruments for soil gas sampling. They include:

- Readings will be biased low if the sample flow rates are less then operational flow rates
- Variations in readings from multi-component vapor samples, which will vary across a site
- Soil gas concentrations above the linear range of the instrument
- Relative humidity of the sample
- Low levels of oxygen can cause a "flame out" in the FID
- Elevated levels of methane and alkanes in a sample can "quench" the PID signal, resulting in a reading biased low
- Sensitivity of the FID is increased with elevated levels of carbon dioxide and nitrogen
- Combustible gas instruments with catalytic sensors do not function properly in anaerobic atmospheres

When methane concentrations greater than the LEL are expected, instruments equipped with thermal conductivity sensors should be used. These sensors are less sensitive below the LEL of methane.

To compensate for these potential problems, sampling techniques such as serial dilutions of samples or use of a dilutor for sampling must be used.

9.9.3 Portable Gas Chromatographs (GC)

Gas chromatography is a physical separation technique. The sample is carried through the column by the carrier gas, which separates the contaminants. As the gas stream emerges from the column, it passes into a detector providing a response. The responses are recorded as a function of time required for the sample to pass through the column. The sample response is compared to the response of a known standard to determine the contaminant identity and concentration. These instruments, though more expensive, can be very sensitive (sub ppb) and selective to the contaminant. This is due to the ability to select the type of detector (FID, PID, electron capture detector) and column most amenable to the contaminants of concern.

9.9.4 Gas chromatography/Mass Spectroscopy (GC/MS)

This method of analysis is a combination of gas chromatography and mass spectroscopy. The GC separates the contaminants, and the mass spectrometer is used to obtain a mass spectrum of each compound. Positive identification of compounds is obtained by comparison of the compounds mass spectrum with a known spectral library. This method is very selective for target compounds. The drawback of the use of this analytical method is the cost.

9.10 Quality Assurance/Quality Control

QA/QC must be an integral part of any sampling activities. QA/QC procedures must be included in any sampling activities to ensure the samples are representative of the subsurface conditions. Without attention to detail the project becomes suspect and the data meaningless. QA/QC checks are required for any project will be dependent on the sampling and analytical methods selected. More details about QA/QC requirements can be found in Chapter 2 of the FSPM and in the *Vapor Intrusion Technical Guidance Document* available at: https://www.nj.gov/dep/srp/guidance/vaporintrusion/.

Soil gas equipment and containers must be leak-checked to prevent loss of sample, which may yield false negative results. When sampling with probes, the annular space between the probe rod and the borehole must be sealed at the ground surface with an inert material or with the drive rods to prevent "short circuiting" during purging and sampling. The sample tubing and connections must also be leak checked to ensure no ambient air is entering the system. This includes tubing fittings, connections, pumps, and septa.

9.11 Soil Gas Data Interpretation

Soil gas measurements are an approximation of the contaminant of interest in the subsurface. There is a considerable amount of interpretation that must be incorporated before the selection of a down gradient ground water monitor well location or approximating the boundaries of ground water or soil contamination.

Because of site and compound specific considerations, soil gas surveys should be planned with a thorough knowledge of the site. Site history and other factors as previously discussed may impact the results that are important to the survey. A preliminary site reconnaissance can be valuable when determining the shallowest depth, which will provide the most adequate sensitivity, appropriate sampling and analytical methods, purge volumes while optimizing other operational details.

When selecting the target contaminant(s), the persistence of that contaminant in the subsurface must be evaluated. VOCs can be altered or eliminated by biological or chemical transformation. Examples include microbial degradation of TCE by sequential dehalogenation to cis-1, 2-DCE, trans-1, 2-DCE and vinyl chloride or the reduction of organic hydrocarbons to methane and carbon dioxide by oxidation.

Interpretation of soil gas data begins in the field. When using on-site analysis of samples, data can be placed on a site map. As new data are generated, it can be used to direct or refine the sampling program. Recent advances in mapping technology allow for real-time laser survey mapping to produce concentration contour mapping. This type of mapping can be applied and incorporated into Geographical Information System (GIS) databases.

When using survey instruments for measuring total VOCs, the nature or individual components of the volatiles cannot be determined. Influences such as humidity, oxygen content and the presence of naturally occurring volatile organics will complicate the measurements. Although each naturally occurring compound may be present in small amounts, when combined, these compounds can have a significant influence on the total volatile organic level.

In the analysis of soil gas, the phase or "mode of occurrence" can be estimated by the differing properties of the components comprising the contaminant. For example, the relative concentrations of benzene to xylene can be an indicator if the sample was collected above an area of free product or a recent release. Since benzene has a higher solubility in water, it is readily stripped out of the liquid hydrocarbon as it is flushed with water. A high ratio will represent a more recent release or free product while a low ratio will represent an older release. The relative concentrations of these components can also be used to differentiate between different sources and spills of different composition (diesel, heating oil, gasoline).

In contrast to other major fuel components, xylenes have the lowest solubility in water and have a higher K_{oc} value. Xylenes do not migrate easily in a dissolved or liquid phase. Therefore, their occurrence in soil gas is more closely associated with the presence of the liquid hydrocarbons.

Combining the knowledge of the site, soil characteristics and contaminant aids in a making an accurate interpretation of results. One of the most common reasons for false negatives is due to barriers including perched water, buried foundations, clay lenses and disturbed soils. Conversely, false positives are usually a result of site-specific factors, the most common being the presence of unknown, near surface source areas that may be mistakenly identified as ground water contamination.

Another useful tool generated by soil gas surveys is the "fuel fingerprint". This technique encompasses the comparison of soil gas chromatograms with those of pure product, which can then be used to identify volatile petroleum products in soil gas. Fuel fingerprinting, however, is limited due to the significant differences in volatilization, migration, and degradation that affect individual fuel products. This method is most successfully used at sites where recent spills have occurred creating free product layers in shallow aquifers.

Generally, to determine the occurrence of recent spills and ground water contamination, vertical soil gas concentration gradients can be used. The success of this method will depend upon the characteristics of the soil, contaminant, and age of the spill.

When conducting soil gas surveys and mapping subsurface contamination from petroleum hydrocarbons, it is important to measure the concentration of biogenic gases that are generated from the bacteria that biodegrade hydrocarbons. Under aerobic conditions carbon dioxide is generated and oxygen is depleted. Under anaerobic conditions carbon dioxide and methane are generated. The biogenic gases can be measured with infrared detectors with reasonable accuracy. Concentration of carbon dioxide in ambient air is 0.03%, biodegradation of soil organic material will yield concentrations of 3-5%. In the vicinity of hydrocarbon contamination, concentrations of carbon dioxide can be in the range of 5-30%. Concentrations of methane in the ambient air are in the range of 1-4 ppm by volume.

Methane concentrations in soil where there is no contamination will range from 0.5-3 ppm by volume. Biogenic methane generated under anaerobic conditions will be deeper in the subsurface than carbon dioxide, and is usually associated with the presence of free product. Biogenic methane and carbon dioxide data, when used in conjunction with specific organic vapor components (C1-C4 and C5+) are very useful in defining the extent of hydrocarbon contamination in the subsurface. The presence or absence of specific petroleum related hydrocarbons could aid in the interpretation of the data and confirm the relationship of the biogenic gases to their source. These biogenic gases can be used for mapping contaminant plumes even if the contamination is old and the lighter hydrocarbons are absent.

Gases that are monitored to indicate biological activity in a landfill are methane, oxygen, and carbon dioxide. Carbon dioxide is monitored to assess the condition of the landfill. Carbon dioxide levels that exceeded the levels of methane may indicate the landfill is operating anaerobically. This condition is known as composting which can lead to landfill fires. Methane is measured as an indicator of the quality of the landfill gas in extraction systems. If the methane gas concentrations are below 50% by volume, this may indicate that ambient air is intruding into the landfill. Intrusion of ambient air into an extraction system can be confirmed by the measurement of the % oxygen. Oxygen concentrations should be in the range of 0-2% by volume in the landfill.

Differences in landfill gas composition will be reduced due to partial pressure gradients that allow gases in and outside the landfill gas unit to commingle. Although methane gas is lighter than air and carbon dioxide gas is heavier than air, these gases are concurrently produced at the microbial level and will not separate by their individual density. The gases will remain mixed and will migrate according to the concentration gradients between the landfill gas and the surrounding gasses.

The most common mistake associated with interpretation of soil gas data is to extend the interpretation beyond the scope of the survey design. For example, the relationship between volatile concentrations obtained in a soil gas survey rarely match the ground water contours. Differences in the ground water contaminant plume and the soil gas concentrations will vary as a result of varying soil conditions at a site. Quantitative relationships between soil gas data and ground water contamination are also difficult to interpret due to the varying soil conditions. Correlation coefficients between ground water contamination and soil gas results can have a difference in orders of magnitude. The lack of a statistical correlation between soil gas and ground water does not indicate that soil gas results are not indicative of ground water contamination, but that the variability of each set are different. A good example of the difference in variability is when duplicate ground water analyses results are not within two percent whereas adjacent VOA soil gas concentrations can vary by a factor of 4 to 5 times and still be indicative of the same subsurface contamination.

An important issue for interpretation of data is the unit of measurement of the results. Two types of units are used for reporting soil gas data. Volume per volume (ppmV, ppbV) or mass per volume (µg/l or mg/m^3). At standard temperature and pressure the conversion factor is as follows:

$$\text{ppbV} = \mu\text{g/l}^{*} \times \frac{2.447 \times 10^{4}}{\text{MW}}$$

ppmV = parts per million by volume
ppbV = parts per billion by volume
µg/l = microgram per liter
mg/m^3 = milligrams per cubic meter
MW = Molecular weight of the gas
* = At standard temperature and pressure

Soil gas sampling and its analyses are designed as a screening tool to be used in conjunction with water quality data. It will always be necessary to confirm the predictions of contamination identified by a soil gas survey through the analysis of soil borings or monitoring wells. Soil gas surveys can be used as one tool in an array of investigative techniques for a phased approach to site characterization.

The successful use of soil gas surveying in determining subsurface contamination is dependent upon collection and analysis as well as planning and data interpretation.

9.12 Data Reporting

The reporting of the data generated from soil gas sampling and analysis must include information required to interpret results for the particular application (See Figure 9.18 the Soil Gas Probe Monitoring Record form below). Information that should be included in the final report is as follows:

- The purpose and objective of the soil gas survey
- The criteria used for the selection of the soil gas sampling and analytical procedures including information on the physical and chemical properties of the targeted chemical compounds
- The type of QA/QC procedures including samples, detection limits units of measure, decontamination procedures, reliability of results, data representativeness, etc.
- If known, characteristics of the contaminant source or spill
- Potential impacts of the vadose zone on the sampling and analytical results (hydrologic conditions, soil types, paved areas, etc.) and interpretation
- A site map including above and below ground structures, paved areas, and all underground utilities past and present (i.e., pipelines, etc.). GPS coordinates for incorporation into GIS databases
- Weather conditions during sampling including rainfall, temperatures, passing weather fronts, barometric pressure, etc.
- Chart of sample location and contaminant concentrations
- Results of QA/QC procedures
- Results of analyses set on a site plan for horizontal and vertical data
- Conclusions and recommendations including identifying potential source(s), the contaminants detected, activities that may have impacted the results need for additional data acquisition, etc.

Soil Gas Probe Monitoring Record

Site: **Date:**

Instrument Used: **Page** **of**

Barometric Pressure: **Weather:**

Technician:

Probe Number	**Time**	**Probe Depth (ft.)**	**Probe Volume (l)**	**Evac. Rate (lpm)**	**Volume Purged (l)**	**Vacuum Press. (in. $H_2$0)**	**% CH_4**	**% CO_2**	**% O_2**

ND = Non-Detect
NM = Not Measured
WOS = Water Over Screen
OR = Over Instrument Range

½" = 0.039 l/ft.
2" = 0.62 l/ft.
4" = 2.47 l/ft.

Figure 9.18 Soil Gas Probe Monitoring Record form

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