CHAPTER 22

ENVIRONMENTAL REMEDIATION OF VOLATILE ORGANIC COMPOUNDS

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22.1 INTRODUCTION

Over the past 25 years, groundwater and subsurface contamination by volatile organic compounds (VOCs) has emerged as a widespread problem in industrialized countries. This class of compounds is broad, and it includes a variety of common organic chemicals such as aromatic hydrocarbons (e.g., benzene, toluene, and xylenes) aliphatic hydrocarbons, (e.g., pentane, hexane, and cyclohexane) and halogenated hydrocarbons (e.g., carbon tetrachloride, tetrachloroethylene, and trichloroethylene). These chemicals are widely used as chemical feedstocks, as cleaning solvents and degreasers, and, in the case of hydrocarbons, as fuels.

These chemicals, besides having a high vapor pressure, tend to have low aqueous solubilities, on the order of 50 to 2000 mg/l. The low solubility of most VOCs tends to result in high Henry’s constants, and strong partitioning into the gas phase from the aqueous phase.

Unfortunately, many of these common chemicals are also toxic, and have very low maximum contaminant levels (MCLs) in drinking water. For example, benzene, which is one of the most common industrial chemicals in the world, has an aqueous solubility of about 1760 mg/l, yet the United States MCL is only 5 ug/l.

Due to their low aqueous solubility, VOCs typically exist as nonaqueous phase liquids (NAPLs), and they are often released to the environment in this form. The hydrocarbon fuel mixtures such as gasoline, kerosene, diesel, jet fuel, and fuel oil form LNAPLs (lighter than water NAPLs), while the chlorinated cleaning solvents form DNAPLs (denser than water NAPLs). Due to capillary trapping, complete removal of NAPLs from the subsurface by mobilization is nearly impossible, and conventional fluid pumping operations typically leave behind NAPL saturations of 5 to 25%.
Removal of the trapped NAPL generally requires mass transfer of the NAPL components into either the gas phase or the aqueous phase, where they can be pumped out, or destroyed by aqueous or gas phase chemical or biological reactions. Arguably, the most successful NAPL/VOC remediation schemes have used the gas phase to transfer contaminants out of the subsurface, or to deliver beneficial chemicals or nutrients to the subsurface. Generally speaking, remediation methods that rely on gas phase extraction are most effective for chemicals that have high vapor pressures and Henry’s constants, while methods that rely on gas phase delivery of chemicals or nutrients can attack a wider range of contaminants.

Obviously, remediation schemes based on gas phase transport are applicable in the vadose zone, above the water table, however there are also effective remediation methods that involve injecting air or steam below the water table. The following sections describe some of the more popular gas-based remediation methods for VOCs.

22.2 SOIL VAPOR EXTRACTION

22.2.1 Introduction to SVE Applications, Induced Gas Flow

Soil vapor extraction is probably the simplest, most common, and most successful of all of the in-situ techniques for removing VOC’s from the vadose zone. SVE systems use one or more wells screened above the water table. A blower connected to the well normally provides the vacuum (typically from 0.05 to 0.2 atmospheres) that induces flow to the well. Typical gas flow rates are in the range of 50 to 300 cfm (0.024 m$^3$/s to 0.14 m$^3$/s) depending on the vacuum in the well and the gas phase permeability. Figure 22.1 from Shan et al. (1992) shows the calculated gas streamlines for a single SVE well in a homogeneous, isotropic system that is open to the atmosphere. Each of the streamtubes in this figure originate at the ground surface, and they each contribute 5% of the total gas flow to the well. As clean soil gas flows through the contaminated zone, NAPLs evaporate, and dissolved or adsorbed VOCs partition into the moving gas phase. Once the gas is removed from the well, it is treated, often by granular activated carbon adsorption. The gas travel time from a location inside the SVE well capture zone to the well determines how effectively that location is flushed by gas. Considering that several thousand pore volumes of gas are often needed for

\[ \text{Figure 22.1. Calculated gas streamlines around an SVE well for homogeneous, isotropic conditions, with an open ground surface (from Shan et al. (1992))} \]