EXECUTIVE SUMMARY

This document provides state-of-the-practice information on off-gas treatment technologies for soil vapor extraction (SVE) systems currently being used to clean up hazardous waste sites. It provides information on a wide variety of processes, including common practices as well as innovative emerging alternatives to illustrate the state of the practice. This information can help SVE project managers and practitioners with the following:

- Identifying available technologies for off-gas treatment and understanding their applicability
- Understanding principles of the various off-gas treatment technologies, their strengths, and their limitations
- Screening technologies based on site-specific off-gas attributes, treatment goals, and costs
- Finding detailed information about conventional technologies and new emerging alternatives

Treatment of remediation system off-gases is necessary because the volatile organic compounds (VOC) typically present in SVE off-gases are hazardous because of their toxicity (acute or long-term carcinogenicity), ignitability, or other reasons. Often, the direct discharge of off-gases without treatment is unacceptable because of health, safety, or public concerns. The goal of off-gas treatment is to improve the off-gas quality for release to the atmosphere, with minimal impact to human health or the environment.

SVE is one of the most efficient and cost-effective methods of removing VOCs from contaminated soil. In the United States, SVE is an accepted technology that has been used at landfill sites and leaking underground storage tank (UST) sites since the 1970s. In 1993, the U.S. Environmental Protection Agency (U.S. EPA) approved SVE as a presumptive remedy for treating soils contaminated with VOCs. Multi-phase extraction (MPE) is a related technology, and the types of off-gas treatment technologies used for MPE are often very similar to those used for SVE. The nature of the off-gas streams produced by SVE and MPE systems affects the selection of the vapor treatment technology and engineering requirements for the treatment system.

Depending on the site and specific remediation goals, a typical SVE or MPE system operates for six months to several years. Sites with the most stringent soil clean-up criteria or with very large contaminant masses may require the use of SVE systems for much longer. Off-gas streams generated from these remediation systems are generally low- to medium-flows containing dilute concentrations of VOCs. The vapor flow rates encountered by most SVE systems generally range from 100 to 1,500 standard cubic feet per minute (scfm).

The nature of SVE and MPE off-gas depends on the nature and distribution of VOCs in the subsurface. Site attributes and physical properties of the chemical constituents in the off-gas directly influence the selection of the off-gas treatment technology and overall remediation strategy. Some
important site attributes include the presence of nonaqueous-phase liquid (NAPL) sources of contamination and the capacity of the soil to release vapors (soil permeability). Physical properties of the chemical compounds that influence the treatment technology include molecular weight and Henry’s law constants.

Treatment technologies for off-gas treatment are categorized into the following four groups in this report:

1. Thermal – An oxidation process in which the temperature is increased to destroy vapor-phase contaminants; for this report, internal combustion engine (ICE) is included as a thermal technology
2. Adsorption – A process separating contaminants using a medium or matrix
3. Biological – Use of living organisms that consume or metabolize chemicals in the off-gas
4. Emerging technologies – Including photocatalytic and non-thermal plasma treatment, which destroy contaminants using ultraviolet (UV) light and electrical energy, respectively

This document presents the state of the practice for these technologies based on applicability, limitations, performance, engineering considerations, residuals management, cost and economics, and developmental status. This information is intended to assist project managers and engineers in evaluating and selecting appropriate off-gas treatment technologies for SVE systems. The information is also applicable to vapors generated from groundwater treatment systems. Project managers and engineers seeking guidance for design and operation of such systems should consult engineering manuals and other specific guidance documents referred to throughout this document.

**Thermal treatment technologies** include thermal oxidation and ICEs. Thermal oxidation systems (including direct-flame, flameless, and catalytic oxidizers) can treat a broad range of SVE off-gas streams and are often chosen for their reliability in achieving high VOC destruction and removal efficiencies (DRE). These systems can be designed to oxidize 95 percent to more than 99 percent of the influent VOCs. Target contaminant groups in SVE off-gas suitable for thermal oxidation treatment include non-halogenated VOCs, semivolatile organic compounds (SVOC), and fuel hydrocarbons at a wide range of concentrations. Specific classes of compounds readily destroyed in thermal oxidizers include alcohols, aliphatics, aromatics, esters, and ketones. If halogenated compounds are present in the SVE off-gas (chlorinated VOCs such as trichloroethene [TCE]), acid gases may be generated and require further treatment. Limitations of thermal oxidation for treating SVE off-gas include its comparatively high capital expense and the potentially high cost of energy to heat the incoming SVE off-gas. ICEs can treat high VOC concentrations and achieve relatively high DREs.

**Adsorption systems** are most effective (in terms of both cost and waste management) for remediation projects involving moderate flow rates and dilute contaminant concentrations (less than 100 parts per million by volume [ppmv]). Well-designed adsorption systems may achieve 95 to 98
percent DREs at input concentrations of 500 to 2,000 ppmv. At lower concentrations, removal is generally greater than 98 percent. The main limitation of this technology is the high operating cost associated with adsorbent replacement or regeneration when high influent concentrations are treated.

Granular activated carbon (GAC) is the most common adsorbent used to treat SVE off-gas. Although GAC systems can be used to treat a wide range of VOCs, they are not effective for treating VOCs with high polarity (such as alcohols and organic acids) or high vapor pressures (highly volatile compounds such as vinyl chloride, methyl tert-butyl ether [MTBE], and methylene chloride). System flow rates can range from 100 to 60,000 scfm. The relatively low initial capital cost of carbon adsorption systems makes them particularly attractive for short-term SVE applications when dilute concentrations of VOCs are present. High humidity diminishes the adsorptive ability of GAC. Zeolites and polymers are two other types of adsorbents. Their adsorptive capacities are not as affected by high humidity levels, but their costs are significantly higher than GAC costs. Highly polar and volatile VOC degradation products, such as vinyl chloride, formaldehyde, sulfur compounds, and alcohols, are better adsorbed by hydrophilic zeolites than by GAC. Polymeric adsorption is applicable to a wide range of VOCs and chlorinated VOCs at a wide range of vapor flow rates.

**Biofiltration** can be used to treat relatively dilute VOC concentrations (typically less than 1,500 total ppmv). If optimum conditions are maintained, a properly designed biofilter may achieve greater than 90 percent and sometimes greater than 95 percent DREs. System flow rates typically range from 20 to 500 scfm. Specific classes of compounds readily biodegradable by biofilters include mono-aromatic hydrocarbons, alcohols, aldehydes, and ketones. Biofiltration is most effective in treating vapor streams from SVE systems remediating leaking USTs at gas stations. At these sites, destruction of aliphatic petroleum hydrocarbons and aromatic compounds (such as benzene, toluene, ethylbenzene, and xylene [BTEX] compounds) is required. One limitation is that the technology is sensitive to variations in operating parameters, such as moisture content, temperature, pH, and nutrient levels. A limited number of biofiltration systems are currently being used for SVE applications.

**Emerging technologies** for SVE off-gas treatment include non-thermal plasma, photolytic and photocatalytic, membrane separation, gas absorption, and vapor condensation technologies. These technologies have not been used widely for SVE off-gas treatment. Also, several of the technologies are mostly in the research and development stage. Non-thermal plasma treatment can achieve high DREs for a wide range of chemicals, including aromatic VOCs (such as BTEX) and chlorinated VOCs. This treatment can address a wide range of concentrations but only at lower flow rates than thermal and adsorption technologies. Photolytic and photocatalytic technologies are effective for treating a broad range of halogenated and non-halogenated VOCs, aromatic and aliphatic hydrocarbons, alcohols, ethers, ketones, and aldehydes. These technologies work best on concentrated VOC waste streams (1 to 3,000 ppmv) at low flow rates. Membrane separation is best suited for chlorinated and non-chlorinated VOC concentrations exceeding 1,000 ppmv (up to 10,000 ppmv). The capacity of current systems generally ranges from 1 to 100 scfm.
Thermal oxidation and carbon adsorption are the two most common technologies used for SVE off-gas treatment. These two technologies are robust, demonstrated, and mature vapor treatment methods that can address a wide variety of contaminants and concentrations. At present, the selection of off-gas treatment technologies for SVE is based on cost and operational considerations that differentiate thermal oxidation and carbon adsorption systems. Although many factors affect the cost of off-gas treatment, the general rule for selecting thermal oxidation or carbon adsorption is that dilute off-gases are more cost-effectively treated by carbon adsorption. Thermal oxidation becomes more cost-effective for off-gases that contain greater concentrations of vapor contaminants. Some sites have both thermal oxidation and GAC systems. Thermal oxidation systems have been used to treat higher initial concentrations and are replaced by GAC systems once concentrations have decreased. The following table summarizes evaluation factors for selecting thermal oxidation and carbon adsorption technologies.

Although thermal oxidation and carbon adsorption are currently the most common treatment technologies for SVE off-gas, some emerging technologies presented in this document have the potential to be cost-effective alternatives to thermal oxidation and carbon adsorption. In the future, cost-efficiency improvements or reports of new, positive experiences in applying these alternatives may result in their selection more frequently.
## Evaluation Factors for Thermal Oxidation and Carbon Adsorption Technology Selection

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<tr>
<th>Factor</th>
<th>Thermal Oxidation</th>
<th>Carbon Adsorption</th>
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<tbody>
<tr>
<td>Concentration</td>
<td>More commonly used for higher contaminant concentrations (&gt; 500 ppmv); treatment costs per pound of contaminant decrease as VOC concentrations increase because less supplemental energy is required per pound removed.</td>
<td>More frequently used for dilute vapor concentrations (&lt; 1,000 ppmv); treatment costs per pound of contaminant tend to stay same or increase as concentration of vapors increase because carbon replacement frequency increases.</td>
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<td>O&amp;M requirements</td>
<td>Tends to require more labor and more skilled labor to operate because of safety considerations.</td>
<td>Tends to be simpler and less labor-intensive to operate and maintain unless vapor-phase concentrations are high and &quot;breakthrough” occurs frequently.</td>
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<tr>
<td>Safety</td>
<td>More safeguards necessary if it is possible for off-gases to reach high concentrations (significant fractions of the lower explosive limits of the contaminants in the vapor); formation of dioxins and furans is possible if not properly operated.</td>
<td>Tends to be very safe under most conditions; however, high levels of ketones or similar compounds may pose a fire hazard.</td>
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<td>Chlorinated vs. non-chlorinated VOCs</td>
<td>Less commonly used for chlorinated VOCs because of formation of hydrochloric acid during vapor combustion, which requires special acid-resistant materials for piping and equipment after combustion chamber.</td>
<td>Equally applicable to chlorinated and non-chlorinated VOCs; acid formation not typically an issue.</td>
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<td>Variety of compounds that can be treated</td>
<td>Except for acid formation during combustion of chlorinated VOCs, wide variety of compounds can be treated.</td>
<td>Not all compounds adsorb well to activated carbon (depends on sorptive capacity); some common compounds (such as vinyl chloride) not readily treated; therefore, each compound in off-gas must be considered.</td>
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<td>Capital vs. O&amp;M costs</td>
<td>Equipment significantly more expensive to purchase than carbon units; however, at high VOC concentrations, O&amp;M costs lower than carbon units.</td>
<td>Capital costs fairly low; O&amp;M costs proportional to off-gas flow rates and vapor concentrations.</td>
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**Notes:**
- O&M = Operation and maintenance
- ppmv = Part per million by volume
- VOC = Volatile organic compound