20
Site Remediation and Groundwater Decontamination

Lawrence K. Wang
Zorex Corporation, Newtonville, New York, U.S.A., and
Lenox Institute of Water Technology, Lenox, Massachusetts, U.S.A.

20.1 INTRODUCTION

20.1.1 Summary

Hazardous waste pollution, hazardous waste terminologies, various onsite, offsite, in situ, and ex situ environmental remediation technologies, and case histories are presented in this chapter. The topics of soil remediation technologies covered here include excavation, stabilization, solidification, vapor stripping, vacuum extraction, thermal desorption, incineration, starved air combustion, pyrolysis, hot air enhanced stripping, steam enhanced stripping, thermal extraction, subsurface volatilization and ventilation, vitrification, soil surfactant flushing, soil washing, soil bioremediation, bioventing, slurry bioreactor, chemical treatment, KPEG treatment, and natural attenuation. The topics of groundwater decontamination technologies covered here include air stripping, ultraviolet radiation, oxidation, carbon adsorption, groundwater bioremediation, sewer discharge, liquid/liquid (oil/water) separation, free product recovery, in situ flushing, trenching, containerizing, and dissolved air flotation.

20.1.2 Site Remediation and Groundwater Decontamination: a Joint UN–USEPA Effort

At the end of 1993, the United Nations Industrial Development Organization (UNIDO), the World Bank, and the United Nations Environment Programme Industry and Environment Programme Activity Centre (UNEP/IEPAC) started issuing new Industrial Pollution Prevention and Abatement Guidelines. In later years, pollution prevention, waste minimization, and manufacturing process integration together have been referred to as “cleaner production” by the international community in order to build awareness of sustainable industrial development, sustainable agricultural development, and environmental protection. The objectives of all these international efforts are to disseminate information on pollution prevention options, end-of-pipe treatments, and cleaner production technologies. The emphasis of the international efforts has been on pollution prevention at source, treatment at the end of pipe, and manufacturing process integration through cleaner production, because there is increasing evidence of the economic and environmental benefits to be realized by preventing or reducing pollution, rather than by managing hazardous wastes after they have been produced, and the environment has been polluted.
Until recently, industry has not been overly concerned with cleaner production, hazardous waste management, and environmental protection, so there have been many direct and indirect damages caused to the environment by mishandling of hazardous wastes. This chapter will discuss various in situ, ex situ, onsite, and offsite technologies for site remediation and groundwater decontamination, assuming that the worse situation has happened – the environment has already been polluted by the hazardous wastes.

Site remediation and groundwater decontamination are pressing issues in all industrial and developing countries, especially for European countries due to limited availability of land. As a result, much progress is being made in the development of various technologies for effectively remediating contaminated industrial, agricultural, and commercial sites. These site remediation technologies, developed by Holland, Germany, and Belgium, include vacuum extraction of volatile organic compounds from contaminated soils, in situ washing of cadmium-polluted soil, high-temperature slagging incineration of low-level radioactive wastes, in situ steam stripping, and a number of bioremediation and soil washing operations. The United Nations (UN) and the US Environmental Protection Agency (USEPA) have played the leadership roles in information dissemination, technology promotion, in-depth R&D, and commercialization of most of the site remediation technologies for the benefit of entire world [1–25].

20.1.3 Terminologies

The hazardous substances at contaminated sites cannot be properly managed without knowing the correct terminologies. According to the 1978 Resource Conservation and Recovery Act (RCRA) of the United States, a waste is considered hazardous when it poses a treat to human health or the environment. The US Comprehensive Environmental Response, Compensation and Liability Act (CERCLA; otherwise known as Superfund) was established in 1980 [1]. Under the 1984 reauthorization of the RCRA, the USEPA land disposal restrictions (LDRs) (also known as land bans) of 1985–1990 were imposed. Using the toxicity characteristic leaching procedure (TCLP), a concentration of any listed constituent in the leachate at or above these levels designates the wastes as hazardous. The waste remains hazardous until treated to reduce its leachability below the TC levels. The heavy metal levels apply not only to the definition of a hazardous waste, but to the LDR maximum leaching levels for disposal of “characteristic waste” at an RCRA treatment, storage, and disposal facility (TSDF), otherwise known as a secure landfill.

At an industrial, commercial, or agricultural site that has been contaminated by hazardous wastes, both the environmental samples (such as contaminated soil, air, or groundwater), and hazardous wastes (such as PCB-containing transformers, waste oil, waste gasoline, old chemicals, spent activated carbons, precipitated heavy metals, etc.) must be handled with care in accordance with government rules and regulations and standard engineering practices. Characterization of hazardous wastes and environmental samples [26] is a critical step in determining how a hazardous waste or sample should be handled. The first step in waste and sample characterization is to determine the phase of the wastes or samples. Nonaqueous-phase liquids (NAPLs) are organic liquids that are relatively insoluble in water. There are two classifications of nonaqueous-phase liquids:

1. Light nonaqueous-phase liquids (LNAPLs), such as jet fuel, kerosene, gasoline, and nonchlorinated industrial solvents (benzene, toluene, etc.), which have densities smaller than water, and will tend to float vertically through aquifers.
2. Dense nonaqueous-phase liquids (DNAPLs), such as chlorinated industrial solvents (methylene chloride, trichloroethylene, trichloroethane, dichlorobenzene, trans-1,2-dichloroethylene, etc.), which have densities greater than water, and will tend to sink vertically through aquifers.
The next step is to determine whether or not the hazardous wastes or samples can be handled separately, together in bulk or in packaged form. Only the qualified environmental engineers can wisely decide how the hazardous wastes or samples should be properly handled. Mixing small quantities of hazardous substances with other nonhazardous substances, water, or soil, may generate larger quantities of hazardous wastes, creating more environmental troubles, or even danger. There are two kinds of hazardous wastes to be handled:

1. **Designated hazardous waste**: a waste that is specifically listed by the national government (such as USEPA) as hazardous (such as hydrogen cyanide).
2. **Characteristic hazardous waste**: a waste that exhibits any one of the characteristics of ignitability, corrosiveness, reactivity, or extractive procedure (EP) toxicity [21].

Furthermore, an ignitable waste is defined as any liquid with a flash point of less than 60°C, any nonliquid that can cause a fire under certain conditions, or any waste classified by the national government (such as the US Department of Transportation in the United States) as a compressed ignitable gas or oxidizer. A corrosive waste is defined as any aqueous material that has a pH less than or equal to 2, a pH greater than or equal to 12.5, or any material that corrodes SAE 1020 steel at a rate greater than 0.25 in. per year. (1 in. = 2.54 cm). A reactive waste is defined as one that is unstable, changes form violently, is explosive, reacts violently with water, forms an explosive mixture with water, or generates toxic gases in dangerous concentrations. An extractive procedure toxicity (EP Toxicity) waste is one whose extract contains concentrations of certain constituents in excess of those stipulated by the national government’s drinking water standards (such as the USEPA Safe Drinking Water Act).

The third step is to determine whether or not the hazardous wastes or samples should be treated or handled **in situ** or **ex situ**, which are defined as follows [22–28]:

1. **In situ treatment**: the hazardous wastes or environmental samples are not removed from the storage or disposal area to be processed. In general, treatment is accomplished by mixing the reagent into the waste storage zone by some mechanical means such as auger, backhoe, rotary tilling device, etc. Site remediation by “in situ solidification” is a typical example.
2. **Ex situ treatment**: the hazardous wastes or environmental samples are removed from the storage or disposal area to be processed elsewhere through a mechanical system. Soil remediation by excavation and incineration is a typical example. Another example is application of the “pump-and-treat” technology for groundwater decontamination.

Another step is to decide whether or not the ex situ treatment should be carried out onsite or offsite, which are defined as follows [22–25]:

1. **Onsite treatment**: the hazardous wastes or environmental samples are not removed from the contaminated site to be processed. Any kind of **in situ** treatment is onsite treatment. Application of the pump-and-treat technology for groundwater decontamination at the contaminated site is an **ex situ** treatment as well as an onsite treatment. Onsite treatment systems consist mainly of mobile or transportable equipment, installation, labor, and support services.
2. **Offsite treatment**: the hazardous wastes or environmental samples are removed from the contaminated site to be processed. If the contaminated soil must be excavated from the site, and transported to another location for incineration, it is an **ex situ** treatment as well as an offsite treatment. Offsite treatment systems involve mainly fixed operations using nonmobile or nontransportable equipment.
Mobile operations are generally taken to mean that the process equipment is on wheels and that the entire site remediation operation can be rapidly moved, set up, and ready for operation at a new contaminated site, within a few days. Transportable operations mean that the process equipment may be broken down into a number of segments that must be transported separately and are assembled at the operational site, often within a few weeks or months.

Once an industrial, agricultural, or commercial site is seriously contaminated by the hazardous waste, the government will list the site as a hazardous waste contaminated site, or a Superfund site. Delisting is an amendment to the lists of hazardous wastes or hazardous waste sites, granted by the national government when it is shown that a specific waste stream or waste site no longer has the hazardous characteristics for which it was originally listed.

Restoration of any industrial, agricultural, commercial or even residential sites that have been seriously contaminated by hazardous wastes is termed “site remediation.” A contaminated site may involve contaminated soil and/or groundwater. Purification of any groundwater by either in situ or ex situ means is called groundwater decontamination. Site remediation is a broader term that includes groundwater decontamination.

Where water penetrates, some of the hazardous wastes dissolve; there is no such thing as a completely insoluble material. Accordingly, when a hazardous waste, treated or not, is exposed to water, a rate of dissolution can be measured. This process is termed “leaching.” The water with which we start is the “leachant,” and the contaminated water that has passed through the waste is the “leachate.” The capacity of hazardous waste material to leach is called its “leachability.”

A test can be conducted in situ, ex situ, onsite, or offsite, either using an actual waste sample, or a simulated synthetic waste sample, to determine whether or not a particular process method or equipment can be used to treat the waste sample. Such a test is called a treatability test or treatability study. Ambient air monitoring in the field can provide immediate data about contaminants and speed up cleanups [27].

Hyperspectral imaging has been employed by Howard and Pacifici [28] in environmental site assessments to detect and identify contaminated areas. Groundwater monitoring is also advancing due to a new technology for sampling and installing monitoring wells [29]. Parish and Fournier [30] offer a method for comparing horizontal wells with vertical wells for subsurface remediation.

20.2 SITE REMEDIATION MANAGEMENT

Analytical methods for determination of the concentrations of pollutants in solid wastes and hazardous wastes can be found from governmental agencies [3,21]. Because most site remediation projects involve the use of onsite treatment systems, it is necessary to define the required onsite service as follows, in normal chronological sequence: (a) obtaining samples of the hazardous waste, (b) preliminary laboratory treatability test, (c) preliminary quote, (d) meeting with customer, field sampling, and preliminary meetings with the regulatory agency, (e) final laboratory treatability tests, (f) firm quotation to customer, (g) regulatory approval, (h) mobilization, (i) setup at job site, or the contaminated site, (j) site remediation, treatment of the wastes and environmental samples, (k) close-down and cleanup at job site and return to home base, (l) final laboratory leaching and physical tests on solid and/or groundwater produced in job to satisfy contract requirements and protect warranty, (m) completion of a final project report, and (n) possible follow-up sampling and laboratory testing of waste samples at various times if required by contract or desired by contractor for information or warranty protection.

When groundwater is contaminated by hazardous wastes, the groundwater can either be treated in place using in situ technologies, or be pumped from subsurface to the ground surface for ex situ treatment. The later ex situ groundwater decontamination technology is also called the pump-and-treat technology.
The best demonstrated available technologies (BDAT) recommended by USEPA and many industrial nations are presented in the following sections [2–20, 22–25, 31–34]. The BDAT particularly recommended by the industrial nations and international communities for site remediation considerations are: incineration, soil washing, chemical treatment, low-temperature thermal desorption, and solidification.

Butcher and Dresser [35] offer tips for handling public meetings concerning releases of contaminants to industrial or commercial sites.

20.2.1 Soil Decontamination

According to the frequency of applications or popularity, the most popular soil decontamination technologies are the following, in decreasing order:

1. Excavation;
2. In situ subsurface volatilization and ventilation/aeration;
3. Bioremediation;
4. Thermal destruction or incineration;
5. Soil vapor stripping or soil vacuum extraction;
6. Soil washing or soil scrubbing;
7. Stabilization and solidification;
8. Natural attenuation; and
9. Chemical treatment (pH adjustment).

20.2.2 Groundwater Decontamination

The most popular groundwater decontamination technologies are the following, in decreasing order:

1. Air stripping;
2. Carbon adsorption;
3. Bioremediation;
4. Sewer discharge;
5. Liquid/liquid (oil/water) separation;
6. In situ flushing;
7. Trenching; and
8. Containerizing.

20.3 EXCAVATION

Contaminated soil may be excavated by mechanical means for treatment and/or disposal, or treated in situ. Excavation can be completed in a few days or take several months depending on site-specific complexities. Excavation is the unit operation used most commonly to remove the contaminated soil. However, its applicability so far is limited to small volumes of contaminated soil and shallow excavations.

20.4 IN SITU STABILIZATION AND SOLIDIFICATION OF CONTAMINATED SOILS

The process terms of chemical fixation, immobilization, stabilization, and solidification have been used interchangeably. The following are the common terminologies.
20.4.1 Stabilization

“Stabilization” refers to those techniques that reduce the hazard potential of a waste by converting the contaminants into their least soluble, mobile, or toxic form. The physical nature and handling characteristics of the waste are not necessarily changed by stabilization.

20.4.2 Solidification

“Solidification” refers to techniques that encapsulate the waste in a monolithic solid of high structural integrity. The encapsulation may be of fine waste particles (micro-encapsulation) or of a large block or container of wastes (macro-encapsulation). Solidification does not necessarily involve a chemical interaction between the wastes and the solidifying reagents, but may mechanically bind the waste into the monolith. Contaminant migration is restricted by vastly decreasing the surface area exposed to leaching, and/or by isolating the wastes within an impervious capsule.

20.4.3 Process Description

Solidification and stabilization are nevertheless used interchangeably in the field [2,4]. In actual site remediation operation, the process immobilizes contaminants in soils and sludges by binding them in a concretelike, leach-resistant matrix. Contaminated hazardous waste materials are collected, screened to remove oversized material, and introduced to a batch mixer. The hazardous waste material is then mixed with water; a chemical reagent; some selected additives; and fly ash, kiln dust, or cement. After it is thoroughly mixed, the treated waste is discharged from the mixer. Treated waste is a solidified mass with significant unconfined compressive strength (UCS), high stability, and a rigid texture similar to that of concrete.

This process treats soils and sludges contaminated with toxic organic compounds, hazardous metals, inorganic compounds, and oil and grease. Batch mixers of various capacities can treat different volumes of hazardous waste.

The solidification and stabilization process (Fig. 1) was once demonstrated in December 1988 at the Imperial Oil Company, Champion Chemical Company Superfund site, in Morganville, New Jersey.

Figure 1 Solidification process equipment. (Courtesy of USEPA.)
New Jersey. This location formerly contained both chemical processing facilities and oil reclamation facilities. Soils, filter cake, and oily wastes from an old storage tank were treated during the demonstration. These wastes were contaminated with petroleum hydrocarbons, polychlorinated biphenyls (PCB), other organic chemicals, and hazardous heavy metals.

A Technology Evaluation Report [5], an Applications Analysis Report [6], and a Demonstration Bulletin [7] are available from the USEPA, Washington, DC, United States. Long-term chemical and physical monitoring and mineralogic analyses have also been conducted by USEPA.

Key findings from the solidification and stabilization process demonstration are summarized below:

1. Extract and leachate analyses showed that heavy metals in the untreated waste were immobilized.
2. The process solidified both solid and liquid wastes with high organic content (up to 17%), as well as oil and grease.
3. Volatile organic compounds in the original waste were not detected in the treated waste.
4. Physical test results of the solidified waste showed: (a) UCS ranging from 390 to 860 pounds per square inch (psi); (b) very little weight loss after 12 cycles of wet and dry and freeze and thaw durability tests; (c) low permeability of the treated waste; and (d) increased density after treatment.
5. The solidified waste increased in volume by an average of 22%. Because of solidification, the bulk density of the waste material increased by about 35%.
6. Trace amounts of semivolatile organic compounds were detected in the treated waste and the toxicity characteristic leaching procedure (TCLP) extracts from the treated waste, but not in the untreated waste or its TCLP extracts. The presence of these compounds is believed to result from chemical reactions in the waste treatment mixture.
7. The oil and grease content of the untreated waste ranged from 2.8 to 17.3% (28,000 to 173,000 ppm). The oil and grease content of the TCLP extracts (USEPA, 1980) from the solidified waste ranged from 2.4 to 12 ppm.
8. The pH of the solidified waste ranged from 11.7 to 12.0. The pH of the untreated waste ranged from 3.4 to 7.9.
9. No PCBs were detected in any extracts or leachates from the treated waste.
10. Visual observation of solidified waste revealed dark inclusions about 1 mm in diameter. Ongoing microstructural studies are expected to confirm that these inclusions are encapsulated wastes.

The USEPA Risk Reduction Engineering Laboratory, Cincinnati, OH, United States, may be contacted for further information on this stabilization and solidification process.

### 20.5 IN SITU SOIL VAPOR STRIPPING OR SOIL VACUUM EXTRACTION

Soil vapor stripping (SVS), soil vapor extraction (SVE), soil venting (SV), vacuum extraction (VE), and soil vacuum extraction (SVE) are the terms used interchangeably to describe a process that removes volatile organic compounds (VOC) from the vadose, or unsaturated soil zone, by vacuum stripping. These compounds can often be removed from the vadose zone before they contaminate groundwater. The extraction process uses readily available equipment, including extraction and monitoring wells, manifold piping, a vapor and liquid separator, a vacuum pump,
and an emission control device, such as an activated carbon adsorption filter. After the contaminated area is completely defined, extraction wells are installed and connected by piping to the vacuum extraction and treatment system.

First, a vacuum pump draws the subsurface contaminants from the extraction wells to the liquid/gas separator. The vapor-phase contaminants are then treated with an activated carbon adsorption filter or a catalytic oxidizer before the gases are discharged to the atmosphere. Subsurface vacuum and soil vapor concentrations are monitored with vadose zone monitoring wells.

The technology is effective in most hydrogeological settings, and can reduce soil contaminant levels from saturated conditions to a nondetectable level. The process even works in less permeable soils (clays) with sufficient porosity. Dual vacuum extraction of groundwater and vapor quickly restores groundwater quality to drinking water standards. In addition, the technology is less expensive than other remediation methods, such as incineration. Figure 2 illustrates the SVS or VE process. Typical contaminant recovery rates range from 20 to 2500 lb/day (1 lb = 454 g), depending on the degree of site contamination and the VOCs to be removed.

The VE or SVS technology effectively treats soils containing virtually any VOCs and has successfully removed over 40 types of chemicals from soils and groundwater, including toxic organic solvents and gasoline- and diesel-range hydrocarbons. Nevertheless, the range of applicability of VE or SVS processes is bounded by the following constraints [34]:

1. The hazardous substances to be removed must be volatile or at least semivolatile (a vapor pressure of 0.5 torr or greater);
2. The hazardous substances to be removed must have relatively low water solubility or the soil moisture content must be quite low;
3. The hazardous substances to be removed must be in the vadose zone (above the groundwater table) or, in the case of LNAPLs, floating on it;
4. The soil must be sufficiently permeable to permit the vapor extraction wells to draw air through all of the contaminated domains at a reasonable rate.

The SVS or VE process cannot remove heavy metals, most pesticides, water-soluble solvents (acetone, alcohols, etc.), and PCBs because their vapor pressures in moist soils are too low.

![Figure 2](image-url)  
**Figure 2** In situ vacuum extraction process diagram. (Courtesy of USEPA.)
The technology is relatively cheap and rapid, has a comparatively low environmental impact, and results in elimination of the contaminated hazardous substances or its concentration into a small volume of highly concentrated, easily handled waste that may be disposed of by incineration or recycled for reuse.

The SVS or VE process was first demonstrated at a Superfund site in Puerto Rico. Terra Vac has since applied the technology at 15 additional Superfund sites and at more than 400 other waste sites throughout the United States, Europe, and Japan.

The process (Fig. 2) was demonstrated under USEPA supervision at the Groveland Wells Superfund site in Groveland, MA, United States, in 1987–1988. The technology successfully remediated soils contaminated by trichloroethene (TCE). The USEPA Technology Evaluation Report [8] and the USEPA Applications Analysis Report [7] have been published. During the Groveland Wells demonstration, four extraction wells pumped contaminants to the process system. During a 56-day operational period, 1300 lb (1 lb = 454 g) of VOCs, mainly TCE, were extracted from both highly permeable strata and less permeable clays. The vacuum extraction process achieved nondetectable VOC levels at some locations, and reduced the VOC concentration in soil gas by 95%. Average reductions were 92% for sandy soils and 90% for clays. Field evaluations have yielded the following conclusions:

1. VOCs can be reduced to nondetectable levels; however, some residual VOC concentrations usually remained in the treated soils.
2. Volatility of the contaminants and site soils is a major consideration when applying this technology.
3. Pilot demonstrations are necessary at sites with complex geology or contaminant distributions.
4. Treatment costs are typically $40 per ton of soil, but can range from $10 to $150 per ton of soil, depending on requirements for gas effluent or wastewater treatment (1989 costs).
5. Contaminants should have a Henry’s constant of 0.001 or higher.

20.6 EX SITU AND IN SITU LOW-TEMPERATURE THERMAL DESORPTION

There are three types of thermal treatment for site mediation: (a) incineration; (b) in situ thermal extraction process; and (c) thermal desorption. Only thermal desorption is introduced here. In a thermal desorption reactor, the moisture, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and volatile inorganics in the contaminated soil or hazardous wastes are reduced by the elevated high temperature, without combusting the solid materials. For this reason, the thermal desorption process is also called a pyrolysis process. For economic reasons, the moisture content of the contaminated soil or hazardous wastes must be reduced as much as possible through mechanical means prior to thermal desorption [34].

The following are the basic types of process equipment that have been developed and commercially available for the thermal desorption of hazardous organic and inorganic chemicals from contaminated soils and solids.

20.6.1 Ex Situ Rotary Thermal Desorption Dryer

This consists of a cylinder that is slightly inclined from the horizontal and revolves at about five to eight revolutions per minute. The inside of the dryer is usually equipped with flights or baffles throughout its length to break up the contaminated soils or solids. Wet cake is mixed with
previously heat-dried soils or solids in a pug mill. The system may include cyclones for soils/solids and gas separation, dust collection scrubbers, and a gas incineration step.

20.6.2 Ex Situ Hot Oil Heated Screws (Conveyors)

Multiple screws, or augers, are used to heat, mix, and convey the soil inside enclosed shells or troughs. Contaminated soil is fed into one end of the process reactor, which has a hot oil heat transfer fluid circulating inside the screw shaft, the screw flights, and the outer vessel’s shell. Heat is conducted to the soil from the hot oil, and the VOCs, SVOCs, inorganic volatile compounds, and water are vaporized. Vapors are ducted to a gas treatment system. Using commercial heat transfer fluids, it can routinely heat the soil to about 275°C, and it is effective for the decontamination of light solvents, fuel products, and some SVOCs.

20.6.3 Ex Situ Molten Salt Heated Screws (Conveyors)

The design of a molten salt heated screw is similar to the hot oil heated screws, except that a molten salt heat transfer system is used instead of a hot oil heat transfer system in order to reach higher operating temperatures, up to 450°C. Soil temperatures of up to 400°C have been achieved when using molten salts.

20.6.4 Ex Situ Electric Resistance Heated Screws (Conveyors)

The design of electric resistance heated screws is similar to the hot oil heated screws, except that electric resistance elements are attached to the outer wall of the screw conveyors for heating. The soil is heated up to 1100°C by a combination of conduction and radiation from the heated outer wall. Several such heated screws are manifolded together to make a unit of commercial capacity. PCBs, and other VOCs, and SVOCs can be effectively removed using this high-temperature thermal desorption system. The desorbed gases from the heated screws can be collected and treated in either condensation or afterburner gas systems.

20.6.5 Ex Situ Steam or Hot Air Heated Screw Dryer

This design is similar to that of the hot oil heated screws, except that steam or hot air will be used for heating and thermal desorption. This type of dryer is still in the developmental stage.

20.6.6 Ex Situ Fluidized Bed Dryer

This consists of a vertically oriented reactor through which hot gases are circulated from bottom to top. The contaminated soils and hazardous wastes are fed downward into the reactor, where they are suspended by the upward flowing gas stream. The gas flow rate can be adjusted until the drag force on the soil particles from the flowing gas compensates for the force of gravity, allowing the solid particles to be suspended in a fluidized bed in the center of the dryer reactor. High heat transfer efficiency can be reached with this kind of thermal desorption reactor. This type of process equipment has been fully commercialized.

20.6.7 Ex Situ Microwave or Radio-Frequency Thermal Desorption

This process reactor is similar to a household microwave oven. The microwave dryer consists of a chamber that is connected to a microwave generator by wave guides. The contaminated
soil or hazardous wastes are placed into the chamber, and the radio frequency radiation is focused on them by the wave guides. By using microwaves, the heating energy is focused inside the soil particles, achieving better thermal desorption efficiency. Also, the microwave generator can be remotely controlled without exposing workers to a contaminated environment. This type of thermal desorption unit is in the developmental stage because scaling up is not cheap [19,25].

20.6.8 In Situ Radio-Frequency Radiation

This is used for the in-place thermal desorption of contaminated soil. Radio-frequency source electrodes are placed either in or on the ground in the contaminated area, and energy is transmitted to the contaminated soil mass. A fume hood is erected over the contaminated area, and the vaporized VOCs, SVOCs, and inorganic volatile compounds are collected and treated in either condensation or afterburner gas systems.

20.6.9 In Situ Stream or Hot Air Heated Mixing Augers

This system is applied to contaminated soil directly in the field by the use of large, vertical stream or air-heated soil mixing augers common to the construction industry for boring holes. Steam or hot air is injected into the contaminated soil, in place, through the auger as a hole is bored. The VOCs, SVOCs, and inorganic volatile compounds are collected in a hood and treated in a condensation or afterburner gas treatment system.
All the *in situ* or *ex situ* thermal desorption systems described above have generally been configured with two types of gas treatment systems attached to the primary soil desorption unit: (a) a condensation gas treatment system, and (b) an afterburner treatment system.

A condensation gas treatment system (Fig. 3) recovers the bulk of the organic substances (as a concentrated liquid or sludge) using a condenser, a cyclone separator, baghouse, or filter for particulate removal, a granular activated carbon (GAC) adsorber for vapor reduction, an afterburner, or catalytic oxidizer for residual VOCs and SVOCs emission control.

An afterburner gas treatment system employs mainly a combustion chamber to destroy the separated VOCs and SVOCs. The system also needs supplemental process equipment, such as a cyclone separator, baghouse or filter for particulate removal, and/or acid gas control, depending on the gaseous waste streams.

### 20.7 INCINERATION, THERMAL DESTRUCTION, STARVED AIR COMBUSTION AND HIGH-TEMPERATURE PYROLYSIS

There are three operational modes of high-temperature thermal treatment reactor: (a) incineration or thermal destruction; (b) starved air combustion or thermal gasification; and (c) high-temperature pyrolysis.

High-temperature incineration is one of the five promising site remediation technologies being used and is continuously studied by industrial nations [4,25,36]. Incineration or thermal destruction is a two-step process involving drying and combustion after preliminary drying. A typical feed soil is composed of the soils contaminated by volatile organic compounds (VOCs) or semivolatile organic compounds (SVOCs). At very high temperatures (over 1000°C) and in the presence of oxygen, the organic contents in the contaminated soil in an incinerator are burned and converted to carbon dioxide gas, water steam, and small amounts of organic vapors, which are then collected and treated in an afterburner gas treatment system. The soil after incineration is clean, disinfected, and ready to be returned to the site.

The starved air combustion (SAC) or thermal gasification process utilizes equipment and process flows similar to incineration except that less than the theoretical amount of air for complete combustion is supplied. Auxiliary fuel may be required, depending on the volatiles in the contaminated soil. The high temperature decomposes or vaporizes the hazardous organic matters. The gas-phase reactions are pyrolytic or oxidative, depending on the concentration of oxygen remaining in the gaseous stream. The dried soil or solid residue is dark in color. The SAC has a higher thermal efficiency than incineration due to the lower quantity of air required for the process. In addition, capital economies can be realized due to the smaller gas handling requirements. Again, an afterburner gas treatment system will be required for air stream purification. The soil after SAC is clean, disinfected, and ready to be returned to the site.

The high-temperature pyrolysis process utilizes equipment and process flow diagrams similar to incineration except that it is operated in the absence of oxygen, but at a high temperature. It should be noted that while the low-temperature pyrolysis process, also known as thermal desorption, is one of the best demonstrated available technologies (BDAT) for site remediation, high-temperature pyrolysis is still in the research stage.

The above are three different operational modes for high-temperature thermal treatment reactors. Theoretically, each type of high-temperature thermal treatment reactor can be operated in three different operational modes, depending on the amount of oxygen to be supplied to the reactor.

There are different types of thermal treatment reactors or incineration reactors: (a) the rotary kiln furnace; (b) the multiple hearth furnace; and (c) the fluidized bed furnace.

The rotary kiln furnace, or rotary kiln incinerator, is unique in that it is designed to allow a portion of its hazardous waste load to be charged in batch rather than continuous mode. In this
batch mode of operation, solid contaminated soils, solid wastes, and “containerized” liquid wastes are introduced through entrance chutes, typically concurrent with the gas flow. Kiln angle and rotation speed continuously expose fresh surface for oxidation, determine the residence times of noncombustible materials, and provide for continuous ash removal. Upon entry into the incinerator, the liquid waste container, typically cardboard, plastic, or steel drums, ruptures or burns, exposing the contents to the hot kiln environment. The hazardous liquid then rapidly vaporizes and reacts with the excess oxygen present in the combustion gases from the continuous primary flame. An afterburner and other supplemental air treatment equipment will be required for purification of the produced gaseous streams.

The fluidized bed furnace (FBF) is a vertically oriented, cylindrically shaped, refractory lined, steel shell, which contains a sand bed and fluidizing air distributor. The FBF is normally available in diameters of 9–25 ft and heights of 20–60 ft (1 ft = 0.3048 m). The sand bed is approximately 2.4 ft thick and rests on a refractory lined air distribution grid through which air is injected at a pressure of 3–5 psi to fluidize the bed. Bed expansion is approximately 80–90%. The temperature of the bed is controlled at between 1400 and 1500 °F. Ash is carried out of the top of the furnace and is removed by air pollution control devices. It is effective for incineration of “containerized” liquid hazardous wastes.

20.8 IN SITU HOT AIR/STEAM ENHANCED STRIPPING AND IN SITU THERMAL EXTRACTION

This process (Fig. 3) is a modification to the soil vapor stripping (SVS) or soil vacuum extraction (SVE) process presented earlier. Again there are many terminologies that are being used interchangeably for description of this same process, because the terminology has not been standardized [22–25,34]:

- in situ thermal extraction (ISTE);
- thermally enhanced vapor stripping (TEVS);
- vacuum-assisted steam stripping (VASS);
- steam/hot air stripping (SHAS);
- in situ steam extraction (ISSE);
- in situ steam enhanced extraction (ISSEE);
- steam injection/vapor extraction (SIVE);
- in situ steam/hot air extraction (ISSHAE), etc.

This process can be operated under two environmental conditions, as follows.

20.8.1 Operation Above the Water Table, or in the Vadose Zone

Hot air and/or steam is first injected into the soil and then removed, possibly under vacuum, together with the desorbed volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs). Then, gas steam should undergo treatment for air purification. The condensed steam should be pumped from the ground and treated. The required supplemental process equipment includes: demisters, scrubbers, condensers, chillers, heaters, and so on, which are all well-established technologies. The system should be properly operated so that the vadose zone does not become saturated with water and exhibit reduced or no permeability for the gases and vapors targeted for removal. General site requirements include: adequate soil permeability, penetrable soils for insertion of augers, wells, minimal subsurface obstacles, and appropriate ambient temperatures in the range 20–100 °F [15].
20.8.2 Operation Both Above and Below the Water Table

Steam is introduced to the soil through injection wells screened in contaminated zones both above and below the groundwater table. The steam flow sweeps contaminants to extraction wells. Groundwater and liquid contaminants are pumped from the extraction wells; steam, air, and vaporized contaminants are then extracted under vacuum. After the soil is heated by steam injection, the injection wells can introduce additional agents to facilitate the cleanup. Recovered vapors pass through a condenser. The resulting condensate is combined with pumped liquids for processing in separation equipment. This in-situ thermal extraction (ISTE) process to be operated both above and below the water table will enhance the soil vapor extraction (SVE) and pump-and-treat processes used to treat VOCs and SVOCs. Heating the soil with steam injection is an effective and relatively inexpensive technique to raise a target soil volume to a nearly uniform temperature.

In general, the separated nonaqueous-phase liquids (NAPL) from either of the above two operations can be recycled or disposed of, and the water treated prior to discharge. The noncondensable gases are directed to a vapor treatment system that consists of: (a) oxidation equipment, (b) activated carbon filters, or (c) treatment onsite in a catalytic destruction process.

In general, the process to be operated either above or below the water table uses conventional injection, extraction, and monitoring wells, off-the-shelf piping, steam generators, condensers, heat exchangers, separation equipment, vacuum pumps, and vapor emission control equipment.

Specifically, the in situ thermal extraction (ISTE) process to be operated both above and below the water table removes VOCs and SVOCs from contaminated soils and groundwater. The process primarily treats chlorinated solvents such as trichloroethene (TCE), perchloroethene (PCE), and dichlorobenzene; hydrocarbons such as gasoline, diesel, and jet fuel; and mixtures of these compounds. The process can be applied to rapid cleanup of source areas such as dense NAPL pools below the water table surface, light NAPL pools floating on the water table surface, and NAPL contamination remaining after conventional pumping techniques. Subsurface conditions are amenable to biodegradation of residual contaminants, if necessary, after application of the thermal process. A cap must exist to implement the process near the surface. For dense NAPL compounds in high concentrations, a barrier must be present or created to prevent downward percolation of the NAPL. The process is applicable in less permeable soils using novel delivery systems such as horizontal wells. For more information about this technology, the reader is referred to USEPA, Risk Reduction Engineering Laboratory, 26 West Martin Luther King Drive, Cincinnati, OH 45268, United States.

20.9 IN SITU SUBSURFACE VOLATILIZATION AND VENTILATION (COMBINED SATURATED ZONE SPARGING AND IN SITU VADOSE ZONE VAPOR STRIPPING)

The contaminated soil and groundwater in the saturated zone can be remediated for VOCs removal through sparging. The technology involves the use of combined saturated zone sparging and in situ vadose zone vapor stripping [34]. It is also called subsurface volatilization and ventilation [22–25], in situ sparging, in situ air stripping, in situ aeration, and aeration curtain.

There are two broad approaches to the process, which involves sparging volatile organics compounds (VOCs) from the saturated zone using compressed air:

1. **Throughout the contaminated zone.** Individual sparging wells are placed with a combination of saturated zone sparging and in situ vadose zone vapor stripping throughout the contaminated zone to remove VOCs and SVOCs from across a wide area. Wells are screened over a narrow interval located at the bottom of an aquifer or below the...
deepest contamination within the aquifer. Compressed air is forced from the well screen and flows radically outward and upward through the contaminated soils. As the air bubbles move upward through the contaminated groundwater and soils, VOCs and SVOCs dissolved in the groundwater and absorbed to the soil particles’ surface are volatilized and swept to the unsaturated zone with the air bubbles. The extracted air is then collected by vacuum through the screened vacuum extraction well, and further purified by air purification means (such as dryer, activated carbon, or equivalent) before its release to the ambient air. Biodegradation may occur within the remediation system, thus reducing the need for off-gas treatment.

2. **Combination of saturated zone sparging and in situ vadose zone vapor stripping to form aeration curtains oriented at right angles to the flow of the groundwater plume.** Aeration curtains can be created in trenches backfilled with porous media. The trenches have a horizontal slotted pipe (air injection well, or air distribution pipe) near the bottom of the trench to supply compressed air. As the groundwater flows through the trench, the rising air bubbles strip the VOCs and SVOCs to the top of the trench, reaching the unsaturated zone with the air bubbles. The extracted air is then collected by vacuum through the screened vapor recovery pipe (or vacuum extraction well) and further purified by air purification means (such as dryer, activated carbon, or equivalent) before its release to the ambient air. Biodegradation may occur within the remediation system, thus reducing the need for off-gas treatment.

A well-established subsurface volatilization and ventilation system (SVVS) is presented below as a case study. The SVVS (Fig. 4) was developed by Billings and Associates, Inc. (BAI), Albuquerque, NM, United States, and operated by several other firms under a licencing agreement, uses a network of injection and extraction wells (collectively, a reactor nest) to treat subsurface contamination.

![Subsurface volatilization and ventilation system (SVVS).](image)

**Figure 4** Subsurface volatilization and ventilation system (SVVS). (Courtesy of USEPA.)
VOCs and SVOCs contamination through *in situ* biodegradation using compressed air below the water table combined with soil vacuum extraction in the vadose zone (above the water table). Each system is custom designed to meet site-specific conditions. A series of compressed air injection wells and vacuum extraction wells is installed at a site. One or more vacuum pumps create negative pressure to extract contaminant vapors, while an air compressor simultaneously creates positive pressure, sparging air through the subsurface treatment area. This placement allows the groundwater to be used as a diffusion device. Control is maintained at a vapor control unit that houses pumps, control valves, gages, and other process control hardware.

The number and spacing of the wells depends on the modeling results of applying a design parameter matrix, as well as the physical, chemical, and biological characteristics of the site. The exact depth of the injection wells and screened intervals are additional design considerations.

To enhance vaporization, solar panels are occasionally used to heat the injected compressed air. Additional valves for limiting or increasing air flow and pressure are placed on individual reactor nest lines (radials) or, at some sites, on individual well points. Depending on groundwater depths and fluctuations, horizontal vacuum screens, “stubbed” screens, or multiple-depth completions can be applied. The system is dynamic: positive and negative air flow can be shifted to different locations at the site to place the most remediation stress on the areas requiring it. Negative pressure is maintained at a suitable level to prevent the escape of vapors.

Because it provides oxygen to the subsurface, the SVVS, or equivalent, can enhance *in situ* bioremediation at a site. Thus, it can decrease site remediation time significantly. These processes are normally monitored by measuring dissolved oxygen levels in the aquifer, recording carbon dioxide levels in transmission lines and at the emission point, and periodically sampling microbial populations. If air quality permits require, VOC emissions can be treated by a biological treatment process unit that uses indigenous microbes from the site.

The SVVS, or equivalent, is applicable to sites with leaks or spills of gasoline, diesel fuels, and other hydrocarbons, including halogenated compounds. The system is very effective on methyl tertiary-butyl ether (MTBE), benzene, toluene, ethylbenzene, and xylene (BTEX) decontamination. It can also contain contaminant plumes through its unique vacuum and air injection techniques.

The technology should be effective in treating soils contaminated with virtually any material that has some volatility or is biodegradable. The technology can be applied to contaminated soil, sludges, free-phase hydrocarbon product, and groundwater. By changing the injected gases to induce anaerobic conditions and by properly supporting the microbial population, the SVVS can remove nitrates from groundwater. The aerobic SVVS or equivalent raises the redox potential of groundwater to precipitate and remove heavy metals.

### 20.10 EX SITU AND IN SITU VITRIFICATION

Vitrification is a process of melting contaminated soil, buried hazardous wastes, or toxic sludges at a temperature as high as 1600–2000°C, in an electric furnace or in place at a contaminated site, to render the materials nonhazardous. The final nonhazardous product is a glassy and/or crystalline solid matrix that is resistant to leaching and more durable than natural granite or marble. If the vitrification process is carried out in an electric furnace, it is called ex situ vitrification (ESV). If it is carried in place at a contaminated site, it is called in situ vitrification (ISV).

The technology is based on the concept of joule heating to melt the contaminated soil or sludges electrically in order to destroy toxic organic and inorganic contaminants by pyrolysis. It was initially developed by the US Department of Energy (USDOE) to provide enhanced isolation of previously disposed radioactive wastes. Today over 160 bench-scale (10 kW, 5–10 kg), engineering-scale (30 kW, 0.05–1 ton), pilot-scale (500 kW, 10–50 ton), and
large-scale (3755 kW, 400–1000 tons) vitrification tests have been conducted and have demonstrated the general feasibility and its widespread applications in treating or containing hazardous wastes: contaminated soil sites, burial grounds, and storage tanks that contain hazardous materials in the form of either sludge or salt cakes, process sludges, and many others.

A case history of ex situ vitrification using electric furnace vitrification is presented first. The ex situ vitrification technology uses an electric furnace to convert contaminated soils, sediments, and sludges into oxide glasses at over 1500°C, chemically rendering them nontoxic and suitable for landfiling as nonhazardous materials. Successful vitrification of soils, sediments, and sludges requires: (a) development of glass compositions tailored to a specific waste, and (b) glass melting technology that can convert the waste and additives into a stable glass without producing toxic emissions. There are two types of melters:

- **Electric melter.** In an electric melter, glass, which is an ionic conductor of relatively high electrical resistivity, stays molten with joule heating. Such melters process waste under a relatively thick blanket of feed material, which forms a counterflow scrubber that limits volatile emissions. Commercial electric melters have significantly reduced the loss of inorganic volatile constituents such as boric anhydride (B₂O₃) or lead oxide (PbO). Because of its low emission rate and small volume of exhaust gases, electric melting is a promising technology for incorporating waste into a stable glass.

- **Fossil fuel melter.** In contrast, fossil fuel melters have large, exposed molten glass surface areas from which hazardous constituents can volatilize. Because of its high toxic emission rate, a fossil fuel melter may not be more beneficial than an electric melter for vitrifying toxic wastes.

Ex situ vitrification using an electric melter and furnace (Fig. 5) stabilizes inorganic components found in hazardous waste. In addition, the high temperature involved in glass production (over 1500°C) decomposes anthracene, bis(2-ethylhexyl phthalate), and

![Figure 5](image)

**Figure 5** Electric furnace vitrification system. (Courtesy of USEPA.)
pentachlorophenol in the waste. The decomposition products can easily be removed from the low volume of melter off-gas. Several glass compositions suitable for processing synthetic soil matrix have been developed and subjected to toxicity characteristic leaching procedure testing (TCLP). Ten independent replicates of the preferred composition produced the results in Table 1 for the ex situ vitrification through electric melting.

The mean analyte concentrations were less than 10% of the remediation limit at a statistical confidence of 95%.

The readers are referred to Ferro Corporation, Independence, OH, United States, and Geosafe Corporation, Richland, Washington, United States, for detailed information regarding the vitrification process [20].

Many large-scale in situ vitrification (ISV) processes have been developed. To accomplish ISV, four electrodes are inserted into the contaminated soil to the desired treatment depth. In addition to the four electrodes, the supplemental components include: the off-gas hood to cover the contaminated area and the electrodes, an off-gas trailer with off-gas purification units (quench, scrubber, dewatering unit, heater, filter, and adsorber), a support trailer for holding cooler, instrumentation, and support transformer, an electrical trailer holding a main transformer, and a backup generator.

There are three operational sequences of the ISV process:

1. *Initiation of vitrification*. To initiate the ISV process, a conductive mixture of flaked graphite and glass frit is placed among the electrodes to act as the starter path for the electric circuit. An electric current passed between the electrodes through the graphite and frit path initiates the vitrification melting process. Eventually the graphite starter path is consumed by oxidation and the electric current is transferred to the surrounding molten soil, which is then electrically conductive.

2. *Subsidence during vitrification*. As the melt grows downward and outward, the nonvolatile elements become part of the melt matrix and the organic compounds are destroyed by pyrolysis. The pyrolyzed byproducts migrate to the surface of the vitrified zone, where they combust in the presence of air. Inorganic materials are dissolved into or are encapsulated in the vitrified mass. Convective currents within the melt uniformly mix materials that are present in the soil.

3. *Vitrification completion and backfill*. When the desired melt depth and volume have been achieved, the electric current is discontinued and the molten volume is allowed to cool and solidify. During the process, a hood is placed over the affected area to

<table>
<thead>
<tr>
<th>Metal</th>
<th>Remediation limit</th>
<th>Mean of glass replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>5</td>
<td>&lt;0.100</td>
</tr>
<tr>
<td>Cd</td>
<td>1</td>
<td>&lt;0.010</td>
</tr>
<tr>
<td>Cr</td>
<td>5</td>
<td>0.019</td>
</tr>
<tr>
<td>Cu</td>
<td>5</td>
<td>0.355</td>
</tr>
<tr>
<td>Pb</td>
<td>5</td>
<td>0.130</td>
</tr>
<tr>
<td>Ni</td>
<td>5</td>
<td>&lt;0.010</td>
</tr>
<tr>
<td>Zn</td>
<td>5</td>
<td>0.293</td>
</tr>
</tbody>
</table>
collect any combustion gases and entrained particles for off-gas treatment. A backfill with clean top soil on the top of the vitrified monolith will complete the ISV process.

20.11 IN SITU SOIL SURFACTANT FLUSHING AND EX SITU SOIL WASHING

The soil surfactant flushing is defined as a process for in situ treatment of the contaminated soil or other matrix with surfactant solution, while soil surfactant washing is defined as a process for soil excavation, slurry preparation, and subsequent ex situ treatment aboveground with surfactant solution. So soil flushing is an in situ treatment process, and soil washing is an ex situ treatment process, both of which involve the use of surfactant solutions.

Surfactants are amphipathic molecules or ions. One portion of the surfactant molecule is hydrophilic (water loving), while another portion is hydrophobic (water hating). Hydrophilic portions are ionic or polar heads. Hydrophobic portions are tails containing 12 or more carbon atoms as hydrocarbon chains.

In the presence of water and air, the surfactants tend to concentrate at solid/water interfaces and air/water interfaces of water mixtures. By concentrating at the air/water and solid/water interfaces of the water mixture, the surfactant species are able to reduce the surface tension of the contaminated soil particles, thereby enhancing the chances for separation of contaminants from the soil particles.

Many basic and applied engineering projects have been conducted by researchers [34,37]. The readers are referred to an excellent book by Wilson and Clarke [34] for the theory and principles of flushing and washing. The in situ soil flushing process is still in experimental stage. A typical large-scale ex situ soil washing process is described below [16,18,25].

An ex situ soil washing process system (Fig. 6) is a water-based volume reduction process used to treat excavated soil. The system may be applied to contaminants concentrated in the fine-size soil fraction (silt, clay, and soil organic matter) or contamination associated with the coarse (sand and gravel) soil fraction.

![Figure 6](http://www.usepa.gov/)

**Figure 6** Soil washing system process diagram. (Courtesy of USEPA.)
As a part of the soil washing process, debris is removed from the soil, and the soil is mixed with water and subjected to various unit operations common to the mineral processing industry. These operations can include mixing trammels, pug mills, vibrating screens, froth flotation cells, attrition scrubbing machines, hydrocyclones, screw classifiers, and various dewatering operations.

The core of the soil washing process is a multistage, countercurrent, intensive scrubbing circuit with interstage classification. The scrubbing action disintegrates soil aggregates, freeing contaminated fine particles from the coarser material. In addition, surface contamination is removed from the coarse fraction by the abrasive scouring action of the particles themselves. Contaminants may also be solubilized, as dictated by solubility characteristics or partition coefficients. Contaminated residual products can be treated by other methods. Process water is normally recycled after biological or physical treatment. Contaminated fines may be disposed of off site, incinerated, stabilized, and biologically treated.

This ex situ soil washing system was initially developed by Bio Trol, Inc., Eden Prairie, MN, United States, to clean soils contaminated with hazardous wood preserving wastes, such as polynuclear aromatic hydrocarbons (PAH) and pentachlorophenol (PCP). The system may also be applied to soils contaminated with petroleum hydrocarbons, pesticides, PCBs, various industrial chemicals, and hazardous metals.

The soil washing system was demonstrated under the SITE Program in 1989 at the MacGillis and Gibbs Superfund site in New Brighton, Minnesota, United States [16,18,25]. A pilot-scale unit with a treatment capacity of 500 lb/hour operated 24 hours/day during the demonstration. Feed for the first phase of the demonstration (2 days) consisted of soil contaminated with 130 ppm PCP and 247 ppm total PAHs; feed for the second phase (7 days) consisted of soil containing 680 ppm PCP and 404 ppm total PAHs. Contaminated soil washing process water was treated biologically in a fixed-film reactor and recycled. A portion of the contaminated soil washing fines was treated biologically in a three-stage, pilot-scale EIMCO Biolift reactor system supplied by the EIMCO Process Equipment Company. Key findings from the BioTrol demonstration are summarized below.

1. Feed soil (dry weight basis) was successfully separated into 83% washed soil, 10% woody residues, and 7% fines. The washed soil retained about 10% of the feed soil contamination; 90% of this contamination was contained within the woody residues, fines, and process wastes.
2. The soil washer removed up to 89% PCP and 88% total PAHs, based on the difference between concentration levels in the contaminated (wet) feed soil and the washed soil.
3. The system degraded up to 94% PCP in the process water during soil washing. PAH removal could not be determined because of low influent concentrations.
4. Cost of a commercial-scale soil washing system, assuming use of all three technologies, was estimated to be $168 per ton. Incineration of woody material accounts for 76% of the cost (1989 costs).

20.12 BIOREMEDIATION FOR SOIL AND/OR GROUNDWATER DECONTAMINATION

20.12.1 Bioremediation

Many terminologies are being used in the field of environmental biotechnology. They are briefly defined as follows for the purpose of clarification and comparison:

- **Biological treatment.** Any kind of water treatment, waste treatment, or even air treatment involving mainly the use of living organisms, especially microorganisms for breaking down organic substances in the influent under aerobic, anaerobic, or anoxic
conditions. The influent can be wastewater, sludge, solid waste, hazardous waste, contaminated soil, ground water, river water, lake water, storm runoff water, landfill leachate, or a contaminated air stream.

- **Biological waste treatment.** Biological treatment stated above to be used only for treatment of mainly wastewaters or hazardous wastes.

- **Biodegradation.** An action or reaction for breaking of organic compounds by living organisms, especially microorganisms, resulting in the formation of simpler intermediate compounds, carbon dioxide, water, and other gases. Alternatively, the disappearance of environmentally undesirable properties of a substances.

- **Mineralization.** Complete breaking down of organic compounds by living organisms, especially microorganisms, resulting in the formation of carbon dioxide, water, and other minerals or gases.

- **Biotransformation.** Biological conversion of some characteristic property (i.e., altering the toxicity, form, and mobility) of the original compounds with no decrease in molecular complexity.

- **Biostimulation.** Addition of nutrients, change of pH or temperatures, or optimization of soil or groundwater environmental conditions (such as humidity, porosity of soil) in order to enhance the efficiency of biological treatment.

- **Bioaugmentation.** Addition of microorganisms to a process system or a contaminated site to degrade specific contaminants readily.

- **Biofiltration, air biofilter or vapor phase bioreactor.** The terms loosely used by practicing engineers for a biological filter (with microorganisms attached on the filter media) for purification of air streams, aiming at removal of toxic organics and odors [67].

- **Bioventing.** The use of soil venting, or soil vacuum extraction, to promote aerobic biodegradation in soils is termed bioventing. Soil aeration and not vapor extraction is the primary purpose of the bioventing process.

- **Bioremediation, bioreclamation, enhanced biodegradation, or enhanced bioremediation.** Site remediation, groundwater decontamination, or environmental restoration through alteration, or optimization of environmental factors to enhance biological treatment.

- **Bioremediation process for soil decontamination.** This relies mainly on the soil microorganisms, soil nutrients, and oxygen (enhanced by aeration), and may be assisted by adding genetically engineered microorganisms to the contaminated soil.

- **Bioremediation process for groundwater decontamination.** This may be accomplished by: (a) adding nutrients and/or oxygen, or hydrogen peroxide, to the aquifer to enhance the growth and activity of indigenous microorganisms; (b) injecting the aquifer with genetically engineered microorganisms.

The theory, principles, and applications of all biological treatment and reactions are alike, and can be found elsewhere [17,25,38,59–60,66–67]. Vandenbergh and Saul [39] report a special bioremediation process that accelerates natural degradation of groundwater and soil contaminants.

Only the bioremediation processes that are suitable to remove hazardous substances from contaminated soil and groundwater will be introduced here. There are four in situ bioremediation technologies: (a) enhanced bioremediation; (b) bioventing; (c) anaerobic–aerobic sequential processes; and (d) sequencing batch reactor. Each is separately introduced below.

### 20.12.2 Enhanced Bioremediation System

An enhanced bioremediation system has been used for removal of petroleum hydrocarbon from contaminated soil and groundwater. Contamination has been caused by a leaky underground
storage tank (UST) upgradient of groundwater flow. Direction of the subsurface plume has been known based on available geological data for the region. It appears that the river nearby has not been polluted. To remove the hazardous contaminants by the enhanced bioremediation system will include the following engineering tasks:

- Install monitoring wells to confirm or determine the degree of contamination, and the direction of subsurface plume.
- Install Bentonite slurry cutoff along the river bank that intersects the subsurface plume to prevent river water contamination.
- Install the fuel oil collection trench, and extract free NAPL contaminants from the wells or trenches that intersect the subsurface plume. LNAPL lies on the water table, while DNAPL concentrates on impervious soil layers beneath the water table.
- Install groundwater pumping wells, treatment facilities (such as bioreactors, spray irrigation) and injection wells for pumping, treating, and reinjecting the groundwater to the subsurface, respectively.
- Add nutrients (inorganic soluble nitrogen and phosphorus compounds) and an oxygen source (sparged air or oxygen, hydrogen peroxide, or nitrate) to the groundwater, either above or below ground, and/or to soil for biostimulation.
- Add selected microorganisms to the contaminated soil for bioaugmentation.

To operate an enhanced bioremediation system will include all of the above. Accordingly, the enhanced bioremediation is defined as a complete technology system involving monitoring, pollution prevention, free contaminants removal, groundwater decontamination by biological treatment (either above or below ground), groundwater reinjection, biostimulation (adding nutrients, oxygen source) to contaminated groundwater and/or soil, and bioaugmentation to the contaminated soil.

### 20.12.3 Bioventing System

A typical bioventing system for soil decontamination is now introduced. Bioventing is defined as an in situ biotechnology for aerobic biodegradation of organic contaminants in soils using soil venting. Soil aeration and not vapor extraction is the primary purpose of bioventing, potentially making the technology effective in removing, through in situ biodegradation, organic contaminants having both high and low volatilities and water solubilities. Bioventing can remediate soils with low water permeabilities, such as silty and clay soils, as long as some air flow paths exist. Costs for bioventing should be comparable to or slightly lower than those for soil venting, excluding aboveground vapor treatment costs. Smaller pumps and decreased pumping rates are required to maintain minimal oxygen levels for aerobic respiration than are required by conventional soil venting.

### 20.12.4 Anaerobic/Aerobic Sequential Bioremediation System

An anaerobic/aerobic sequential bioremediation system (Fig. 7) for removal of PCE is now introduced. It has been demonstrated that sequential anaerobic/aerobic biodegradation of PCE is feasible if the proper conditions can be established. The anaerobic process can potentially completely dechlorinate PCE. However, conversion of vinyl chloride (VC) to ethylene is the slowest step in this process. Of the chlorinated ethenes, VC is the most amenable to treatment by aerobic methanotrophic processes. Therefore, a two-step process is thought to be the most efficient. The first step is anaerobic, which rapidly dechlorinates PCE and trichloroethylene (TCE) to break down products 1,2-dichloroethylene (DCE) and VC. Since the anaerobic dechlorination of DCE and VC to ethylene can be quite slow, a second aerobic step is
implemented that can more quickly complete the remediation process. The schematic diagram in Fig. 7 illustrates this technology.

In practical operation of an anaerobic/aerobic sequential bioremediation system, care must be taken to create and maintain the proper in situ conditions for chlorinated ethene degradation in an aquifer. Carbon and mineral nutrients should be injected and delivered into an aquifer contaminated with PCE or TCE. Groundwater chemical conditions should be monitored within and downgradient of the anaerobic treatment zone to gage the efficiency of the anaerobic process. If volatile organic compound analyses show that the resulting downgradient breakdown products include TCE, DCE, or VC, oxygen and methane will be added to the groundwater to stimulate aerobic degradation by indigenous methanotrophic bacteria. It has been demonstrated that this anaerobic/aerobic sequential bioremediation technology removes PCE, TCE, DCE, and VC from groundwater. The readers are referred to ABB Environmental Services, Inc., Wakefield, MA, United States, for the details of this commercially available process.

### 20.12.5 Sequencing Batch Reactor

A sequencing batch reactor (SBR) process has been successfully demonstrated for both soil decontamination [40] and groundwater decontamination [25,37,41]. An SBR system is very similar to a continuous complete mix activated sludge process system, except that SBR is operated as a batch unit. An SBR has the smallest footprint, and it is mobile and easy for field operation. A modern SBR process system can also be a physiochemical process, or a combined physicochemical and biological process [45,68].

### 20.12.6 Combined Sequencing Batch Reactor and Membrane Bioreactor (SBR–MBR)

A membrane bioreactor (MBR) process consists of two principal components: (a) a biological reactor tank, and (b) an ultrafiltration (UF), or microfiltration (MF) membrane to retain biological solids within this biological reactor tank [42]. The membrane may either be internal or external

---

*Figure 7* Anaerobic/aerobic sequential bioremediation system. (Courtesy of USEPA.)
to the reactor tank. The membrane provides a barrier to keep microorganisms in the reactor and renders a clarified, solids-free effluent stream for discharge. The microorganisms are essentially the same as those found within activated sludge systems. A combined sequencing batch reactor and membrane bioreactor (SBR–MBR) is technically and economically feasible for groundwater decontamination applications [23,25], because the SBR–MBR process equipment is commercially available [43] and mobile, and can be quickly erected on site for a remediation project.

20.13 SLURRY BIOREACTOR SYSTEM FOR SOIL DECONTAMINATION

The first ex situ bioremediation process to be introduced here is the Eimco Biolift Slurry Reactor, developed by Eimco Process Equipment Company, Salt Lake City, Utah, United States. The process (Fig. 8) has successfully removed toxic polynuclear aromatic hydrocarbons (PAH) in soil. Traditional biological treatments, such as landfarming and in situ bioremediation, may not reduce PAHs in soil to target levels in a timely manner. Slurry reactors are more efficient for bioremediation and more economical than thermal desorption and incineration.

In a typical onsite bioremediation project, a mixing bioreactor, a first slurry bioreactor, a second fermentation slurry bioreactor in semicontinuous plug-flow mode, and a third slurry bioreactor may be operated in the following manner for contaminants removal:

1. The mixing bioreactor receives and mixes the contaminated soil, makeup process water and supplements of salicylate and succinate as nutrients. Salicylate induces the naphthalene degradation operon on PAN plasmids. This system has been shown to degrade phenanthrene and anthracene. The naphthalene pathway may also play a role in carcinogenic PAH (CPAH) metabolism. Succinate is a byproduct of naphthalene metabolism and serves as a general carbon source. The first reactor in series will remove easily degradable carbon and increase biological activity against more recalcitrant PAHs (i.e., three-ring compounds and higher).

Figure 8  Biological slurry reactor system for soil decontamination. (Courtesy of USEPA.)
2. The fresh contaminated soil slurry and nutrients in the mixing bioreactor are pumped to the first slurry bioreactor (60 L) for treatment.

3. The effluent from the first slurry bioreactor overflows to the second fermentation slurry bioreactor (10 L) in series, where Fenton’s reagent is added to accelerate oxidation for four- to six-ring PAHs. Fenton’s reagent (hydrogen peroxide in the presence of iron salts) produces a free radical that can effectively oxidize multiring aromatic hydrocarbons.

4. The third slurry bioreactor (60 L) in series is used as a polishing reactor to remove any partially oxidized contaminants remaining after Fenton’s reagent is added.

5. Slurry is removed from this third soil slurry bioreactor and clarified using gravity settling techniques. The treated or reclaimed soil is settled at the bottom of the clarifier, ready to be returned to the site.

6. The effluent from the settling clarifier is pumped to a final effluent container, from where the effluent can be partially discharged and partially returned to the very first mixing bioreactor.

Operation of the slurry bioreactor system for soil decontamination will increase the rate and extent of PAH biodegradation, making bioslurry treatment of impacted soils and sludges a more effective and economically attractive remediation option. This technology is applicable to PAH-contaminated soils and sludges that can be readily excavated for slurry reactor treatment. Soils from coal gasification sites, wood-treating facilities, petrochemical facilities, and coke plants are typically contaminated with PAHs.

**20.14 ANAEROBIC–AEROBIC FIXED FILM BIOLOGICAL SYSTEM FOR GROUNDWATER DECONTAMINATION**

Another ex situ bioremediation process introduced here is an anaerobic–aerobic fixed film biological groundwater treatment system (Fig. 9) commercially known as the immobilized cell bioreactor biotreatment system. It is designed to remove organic contaminants (including nitrogen-containing compounds and toxic chlorinated solvents) from contaminated groundwater, and other heavily polluted aqueous streams. This groundwater decontamination system offers improved treatment efficiency by using (a) a unique reactor medium that maximizes biological activity in the reactor, and (b) a bioreactor design that maximizes contact between the biofilm and the contaminants.

This anaerobic–aerobic fixed film biological groundwater treatment system has a completely enclosed headspace, eliminating the possibility of air stripping of volatile organics or intermediates. These features result in quick, complete degradation of target contaminants to carbon dioxide, water, and biomass. Additional advantages include (a) high treatment capacity, (b) compact and mobile system design suitable for site remediation, and (c) reduced operations and maintenance costs resulting from simplified operation and low sludge production.

Basic system components of the anaerobic–aerobic fixed film biological groundwater treatment system include the bioreactors, media, mixing tanks and pumps, feed pump, recirculation pump, and a blower to provide air to the aerobic bioreactor. Depending on the specifics of the influent groundwater streams, some standard pretreatments, such as pH adjustment or oil and water separation, may be required. Effluent clarification is not required for the system to operate, but may be required to meet specific discharge requirements. The system is designed to treat 10 million gallons per day of contaminated groundwater streams, and has been successfully applied to groundwater containing contaminants including polynuclear aromatic hydrocarbons (PAH), phenols, gasoline, chlorinated solvents, diesel fuel, and chlorobenzene.
Figure 9  Dual anaerobic/aerobic immobilized cell bioreactor system diagram. (Courtesy of USEPA.)
The readers are referred to the USEPA Risk Reduction Engineering Laboratory, Cincinnati, OH, for more detailed information regarding this process system.

20.15 CHEMICAL TREATMENT (pH ADJUSTMENT, KPEG TREATMENT)

Theoretically chemical treatment involves the use of any kind of chemical(s) that can react with the hazardous wastes or soil, and convert them to either nonhazardous or less hazardous compounds. Chemical treatment is important when the soil or groundwater is contaminated by acidic chemicals, alkaline chemicals, toxic heavy metals [44], or toxic organics that cannot be treated by biological processes [69].

The most common chemical treatment processes for site remediation include:

- **pH adjustment.** Acidic chemicals are used to neutralize basic hazardous wastes or soils, while alkaline chemicals are used to neutralize acidic hazardous wastes or soils.

- **KPEG chemical treatment.** Chemical reagents prepared from polyethylene glycols and potassium hydroxide (KPEG) have been demonstrated under mild conditions (25–140°C) to dehalogenate PCBs, PCDDs, and PCDFs with destruction efficiencies exceeding 99.9999%. The reaction mechanism is nucleophilic substitution at an aromatic carbon.

- **Chemical precipitation and stabilization.** Chemical precipitation agents (such as hydroxides and sulfides) are used to precipitate, fix, and separate heavy metals, in turn, to purify the soil and groundwater [44].

The pH adjustment is one of the most common site remediation technologies, while KPEG chemical treatment of one of the five best demonstrated available technologies (BDAT).

In the KPEG reagent preparation, KOH reacts with HO-PEG (poly ethylene glycol; with a molecular weight approximately = 400) to form KO-PEG (alkoxide) and water. The KO-PEG (alkoxide) in turn reacts initially with one or more of the chlorine atoms on the aryl ring (aryl-Cl) to produce aryl-O-PEG (ether) and KCl (potassium chloride) salt.

In 1986, a 2700 gallon KPEG reactor was used in Montana, on a wood-preserving site, and in Washington, on a waste disposal site, to successfully detoxify PCDDs and PCDFs (120 ppb to 200 ppm) in 17,000 gallons of liquid waste to nondetectable levels. A reactor designed to treat both liquids and solids was tested by US Department of Defense sites. These field studies validated conditions for destruction of PCBs, PCDDs, and PCDFs, to acceptable levels required by the regulations [4].

Wang *et al.* [23–25,41,45,68,69] have developed a physicochemical sequencing batch reactor (PC-SBR) process, which is identical to a conventional biological sequencing batch reactor (SBR), except that the PC-SBR is a 100% physicochemical process. The PC-SBR has been adopted in full scale for recovering toxic chromium from tannery wastewater for reuse at Germanakos SA Tannery near Athens in Greece [23]. Naturally, PC-SBR can be adopted for chemical treatment of contaminated soil slurry or contaminated groundwater. Since the process equipment of conventional biological SBR can be adopted for the PC-SBR process operation, the PC-SBR process equipment is considered to be commercially available [46].

**Figure 10** shows a typical chemical treatment system for removal of toxic chromium from a contaminated groundwater. The process is developed by Geochem of Terra Vac Co., Lakewood, CO. In operation, the contaminated groundwater is brought to the surface and treated using conventional treatment systems, such as ferrous ion (Fig. 10). Next, a reductant is added to the treated water, which is reinjected around the plume margin. Here it reacts with and reduces residual levels of chromium, forming a precipitate. Such reinjection creates a “barrier” of elevated water levels around the plume, enhancing the gradient and associated hydraulic control.
The reinjection also allows for in situ reduction and subsequent fixation of residual chromium. The process is capable of treating dissolved hexavalent chromium in groundwater at concentrations ranging from the detection limit to several hundred ppm.

20.16 ULTRAVIOLET RADIATION AND OXIDATION FOR GROUNDWATER DECONTAMINATION

This ultraviolet (UV) radiation and oxidation process uses UV radiation, ozone, and hydrogen peroxide to destroy toxic organic compounds, particularly chlorinated hydrocarbons, in contaminated groundwater. The process oxidizes compounds that are toxic or refractory (resistant to biological oxidation) to parts per million (ppm) or parts per billion (ppb) levels.

The UV radiation and oxidation system (Fig. 11) consists of a treatment tank module, an air compressor and ozone generator module, and a hydrogen peroxide feed system. The system can be skid-mounted and portable, and may permit onsite treatment of a wide variety of liquid wastes, such as industrial wastewater, groundwater, and leachate. Treatment tank size is determined by the expected wastewater flow rate and the necessary hydraulic retention time needed to treat the contaminated water. The approximate UV intensity, and ozone and hydrogen peroxide doses, are determined by pilot-scale studies [61,62].

Treatment tank influent is simultaneously exposed to UV radiation, ozone, and hydrogen peroxide to oxidize the organic compounds. Off-gas from the treatment tank passes through an ozone destruction unit, which reduces ozone levels before air venting. The ozone destruction unit also destroys VOC stripped off in the treatment tank. Effluent from the treatment tank is tested and analyzed before disposal.

The UV radiation and oxidation system treats contaminated groundwater, industrial wastewaters, and leachates containing halogenated solvents, phenol, penta-chlorophenol, pesticides, polychlorinated biphenyls, explosives, benzene, toluene, ethyl-benzene, xylene, methyl tertiary butyl ether, and other organic compounds. The system also removes low-level total organic compounds, chemical oxygen demand, and biochemical oxygen demand.
A field-scale demonstration was completed in March 1989 at the Lorentz Barrel and Drum Company site in San Jose, CA, United States, under the supervision of the USEPA. The test program was designed to evaluate system performance for several combinations of five operating parameters: (a) influent pH, (b) retention time, (c) ozone dose, (d) hydrogen peroxide dose, and (e) UV radiation intensity [11,12].

The UV radiation and oxidation technology is fully commercial, with over 30 systems installed. Flow rates ranging from 5 gallons per minute (gpm) to 1050 gpm are in use at various industries and site remediations, including aerospace, US Department of Energy, US Department of Defense, petroleum, pharmaceutical, automotive, wood-treating, and municipal facilities.

Such UV oxidation technology has been included in Records of Decision for several Superfund sites where groundwater pump-and-treat remediation methods will be used. Contaminated groundwater treated by the system met regulatory standards at the appropriate parameter levels. Out of 44 VOCs in the wastewater, trichloroethene, 1,1-dichloroethane, and 1,1,1-trichloroethane were chosen as indicator parameters. All three are relatively refractory to conventional oxidation.

The ozone destruction unit reduced ozone to less than 0.1 ppm, with efficiencies greater then 99.99%. The VOCs present in the air within the treatment system were not detected after passing through the ozone destruction unit. The UV/oxidation reactor system produced no harmful air emissions. Total organic carbon removal was low, implying partial oxidation of organics without complete conversion to carbon dioxide and water. The UV itself is also an effective chemical reduction process (e.g., dechlorination process) in case the groundwater is contaminated by chlorine or similar oxidizing chemicals [47].

Energy and Environmental Engineering, Inc, East Cambridge, MA, has applied the principles of chemical oxidation, UV radiation, and photocatalysts, and developed a commercial process known as the PhotoCat process. Table 2 shows some representative
results from groundwater decontamination projects using the UV lamp and hydrogen peroxide system.

### 20.17 AIR STRIPPING FOR GROUNDWATER DECONTAMINATION

There are two types of pump-and-treat air stripping processes for decontamination of groundwater: (a) the countercurrent air stripping tower; and (b) air sparging system.

The countercurrent air stripping tower is very similar to a cooling tower, except that it is not for cooling. The contaminated groundwater is pumped from the underground, and is fed into the countercurrent air stripping tower from the top. Through a distribution means, the influent groundwater becomes water drops falling downward from the reactor tower, while the low-pressure air stream flows upward from the reactor bottom, powered by an air blower. The upward air stream strips out the VOCs and SVOCs from the water drops falling downward in the countercurrent air stripping tower. The purified water effluent is discharged from the tower bottom and may either be further treated by a granular activated carbon (GAC) process for final polishing, or reinjected into the underground. The air effluent collected from the tower top can be purified by either a condensation gas treatment system, or an afterburner gas treatment system before its discharge into the ambient air environment.

The air sparging system is very similar to the conventional aeration tank used in the activated sludge process, except that no microorganisms are seeded in the air sparging reactor, and the reactor depth is usually shallow and the reactor top is enclosed. Diffused air bubbles are generated at the reactor bottom to strip out the VOCs and SVOCs from the bulk of the groundwater in the reactor. The water effluent from the air sparging reactor may either be further treated by a GAC process for final polishing, or reinjected into the underground. The air effluent collected from the top by the reactor’s enclosure can be purified by either a condensation gas treatment system, or an afterburner gas treatment system before its discharge into the ambient air environment.

The air sparging system is very similar to the conventional aeration tank used in the activated sludge process, except that no microorganisms are seeded in the air sparging reactor, and the reactor depth is usually shallow and the reactor top is enclosed. Diffused air bubbles are generated at the reactor bottom to strip out the VOCs and SVOCs from the bulk of the groundwater in the reactor. The water effluent from the air sparging reactor may either be further treated by a GAC process for final polishing, or reinjected into the underground. The air effluent collected from the top by the reactor’s enclosure can be purified by either a condensation gas treatment system, or an afterburner gas treatment system before its discharge into the ambient air environment.

One of the advantages of using the air sparging system is that the reactor can be seeded with microorganisms and nutrients for biological treatment of the contaminated groundwater [25,37,48–50]. So the reactor is a combined air stripping and biological treatment unit.

Both of the above processes are fully developed and widely adopted for decontamination of groundwater. Although corrective actions for groundwater may entail treatment, containment, or dilution technologies, the environmental engineers in the field prefer to adopt treatment technologies, especially by air stripping treatment. Air stripping has been applied in 51% of all corrective actions requiring removal of VOCs from groundwater in the United States [4].

<table>
<thead>
<tr>
<th>Contaminant species</th>
<th>Molecular weight</th>
<th>Feed concn. (ppm)</th>
<th>Equivalence ratio</th>
<th>Resistance time (seconds)</th>
<th>Product cone ( C/C_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorobenzene</td>
<td>112</td>
<td>50</td>
<td>3.3</td>
<td>3.7</td>
<td>0.04</td>
</tr>
<tr>
<td>Benzene/toluene</td>
<td>78/93</td>
<td>100/100</td>
<td>3.5</td>
<td>3.8</td>
<td>0.4/0.4</td>
</tr>
<tr>
<td>Yellow 106</td>
<td>1374</td>
<td>110</td>
<td>4.2</td>
<td>7.7</td>
<td>0.08</td>
</tr>
<tr>
<td>Yellow 49</td>
<td>438</td>
<td>110</td>
<td>1.0</td>
<td>23.0</td>
<td>0.007</td>
</tr>
<tr>
<td>Blue 41</td>
<td>463</td>
<td>115</td>
<td>0.6</td>
<td>11.5</td>
<td>0.001</td>
</tr>
<tr>
<td>Red 83</td>
<td>1025</td>
<td>140</td>
<td>1.0</td>
<td>7.7</td>
<td>0.008</td>
</tr>
</tbody>
</table>

ppm, parts per million by weight.

Source: Courtesy of USEPA.
Adsorption is a process by which a solute, a liquid organic pollutant in this case, accumulates or concentrates on the internal and external surface of a solid, such as granular activated carbon.

Among all groundwater decontamination technologies available and feasible, granular activated carbon (GAC) adsorption is the second most popular process adopted by practicing environmental engineers. In the United States, GAC has been applied in 27% of the corrective actions requiring VOCs removal from contaminated groundwater [4]. GAC adsorbers are usually packed in similar manner to sand filters, except that GAC firms the media instead of sand.

In process operation, there are two types of applications. When the GAC adsorbers are used for groundwater treatment, they are “liquid phase GAC adsorbers.” When the GAC adsorbers are used for air stream purification, they are “gas phase GAC adsorbers” [37,48–50].

The GAC adsorbers are very effective for VOCs and SVOCs reduction. Because GAC costs are high, GAC adsorbers are usually used for final polishing of either the water stream or air stream. Periodically, the spent GAC must be either disposed of properly, or regenerated for reuse. Regeneration of GAC for desorption of VOCs and SVOCs can be carried out either in situ, ex situ, onsite, or offsite. Without regeneration, the spent GAC, which contains VOCs and SVOCs, may be classified as hazardous waste.

The gas phase GAC adsorber’s adsorption efficiency can be significantly increased if the humidity of the contaminated air stream can be reduced.

The most cost-effective and popular GAC regeneration process is the low-temperature thermal desorption process discussed earlier. The most efficient GAC regeneration process is high-temperature pyrolysis (in the absence of oxygen), discussed earlier. A complete onsite GAC regeneration process has been developed by Wangs et al. [37].

Purus, Inc., San Jose, CA, has developed a similar air stripping–adsorption system (Fig. 12) for groundwater decontamination. The difference between Wang’s system [37] and the Purus system (Fig. 12) is that the former uses GAC, while the latter uses polymeric adsorbent. A detailed operational diagram of a polymeric adsorption system is shown in Fig. 13.
20.19 SEWER DISCHARGE FOR GROUNDWATER TREATMENT

Sewer discharge is the third most popular method for groundwater decontamination, as popular as bioremediation. It has been applied in 13% of the corrective actions requiring VOCs removal from a contaminated groundwater source. In the case where there is a publicly owned treatment works (POTW) near the contaminated site, which has spare capacity to treat the groundwater, sewer discharge can be very attractive. The ease of operation, high removal efficiency, and relatively low cost account for its popularity and simplicity.

In operation, the contaminated groundwater is pumped from the underground, to the POTW for proper treatment. The treated effluent can be discharged either into a nearby river, or reinjected into the underground to balance the water table. The POTW can use biological and/or physical-chemical process systems for groundwater treatment.

20.20 LIQUID/LIQUID SEPARATION AND FREE PRODUCT RECOVERY FOR GROUNDWATER DECONTAMINATION

Many liquid/liquid separation (such as oil/water separation) reactors are commercially available and technically feasible for separation of either LNAPL (such as oil) or DNAPL (such as chloroform) from a contaminated groundwater source. There are three types of oil and water separation processes:

20.20.1 Gravity Separation Reactor

One liquid separates from another liquid based on their difference in densities. Groundwater density is one. For LNAPL (such as oil), where density is less than one, it will therefore float on
the top of groundwater if sufficient separation detention time is given. For DNAPL (such as chloroform), density is greater than one, thus it will settle near or at the bottom of the groundwater, if sufficient detention time is provided.

20.2.2 Absorption Reactor
Absorption is a process by which a solute, a liquid organic pollutant in this case, penetrates into the bulk phase of a solid (such as a sponge). When it is not clear whether adsorption or absorption is involved, the term sorption is sometimes used. Absorption can be either an in situ process, or an ex situ process, depending on how and when this process is to be applied.

20.2.3 Atomizing or Nebulization Reactor
This is a modification of gravity separation in which the mixture of the two liquids to be separated are forced to form extremely fine liquid drops at a temperature just over boiling point of the first liquid (water), but below the boiling point of the second liquid (oil) in order to enhance the efficiency of liquid/liquid separation. The first liquid drops (water) with lower boiling point (such as water at 100°C) are vaporized at the controlled reactor temperature (such as 105°C, which is higher than the first liquid’s boiling point), while the second liquid drops (oil) with much higher boiling point resettle and regroup to be the liquid again because the controlled reactor temperature is well below the boiling point of the second liquid drops (oil). The means used for atomizing or nebulization is called an atomizer or a nebulizer. This advanced liquid–liquid separation method is used for separation of small amount of free hazardous liquid from another liquid (such as water) [33].

Free product recovery usually involves groundwater pumping, which controls groundwater flow within a sphere of influence, and the depressed groundwater table around the pumping zone eventually accentuates free product (free hazardous liquid) accumulation and subsequent removal. Free hazardous liquid is generally recovered from various subsurface settings in large enough quantities that it can be removed by mechanical means. The free hazardous liquid may collect on impermeable strata, collect in small subsurface basins, or enter an aquifer where the free hazardous liquid will either float (such as LNAPL) on the water, or sink (such as DNAPL) to the bottom, depending on the density of the free hazardous liquids. The pump-and-treat method is used for recycling or disposal of the free hazardous liquids.

20.21 NATURAL ATTENUATION, NATURAL FLUSHING, TRENCH, AND CONTAINERIZING
It is believed that “mother nature” has her own self-purification capacity.

Natural attenuation (or natural dilution) has been applied in 2% of the corrective actions requiring soil remediation, in which LNAPL contamination of soil is simply diluted.

Natural flushing involves flushing the contaminated aquifer with large amount of clean water (such as river water, lake water, or another source of clean groundwater). The term is specifically applied to groundwater decontamination relying on dilution with clean water. About 3.5% of groundwater decontamination projects have adopted natural flushing for dilution of LNAPL, and refilling of an aquifer with clean water.
Trench technology has been used in about 3.5% of groundwater decontamination projects. It is frequently used in conjunction with a big bioremediation project. For instance, a Bentonite slurry trench cutoff wall can be built to intersect the subsurface plume to prevent the aquifer from further contamination at downgradient. Then a free product recovery trench can be built before the Bentonite slurry trench cutoff wall to directly intersect the subsurface plume to recover either LNAPL near the water table, or recover DNAPL near the aquifer bottom, or the impervious layer.

Containerizing involves collection of heavily contaminated groundwater in containers for treatment, disposal, or storage onsite or offsite. This is an undesirable method, but it has been encountered 1.8% of contaminated sites conducting groundwater purification.

20.22 DISSOLVED AIR FLOTATION FOR GROUNDWATER DECONTAMINATION

Dissolved air flotation (DAF) is a new process for groundwater decontamination; however, it is the most feasible and most cost-effective process to be used on a contaminated site due to its high treatment efficiency, air stripping effect, extremely short detention time, small footprint, high mobility, simplicity, and low cost.

The DAF process is used to remove LNAPL and suspended solids from contaminated groundwater by rising microbubbles by decreasing their apparent density. Dissolved air flotation consists of saturating a portion or all of the groundwater feed, or a portion of recycled effluent with air at a pressure of 25–90 psi. The pressurized groundwater is held at this pressure for about 30 seconds in a retention tank and then released to atmospheric pressure to the DAF chamber. The sudden reduction in pressure results in the release of microscopic air bubbles, which attach themselves to LNAPL and suspended particles in the groundwater in the DAF chamber. This results in agglomeration which, due to the entrained air, have greatly increased vertical rise rates of about 0.5–2 ft/min (1 ft/min = 0.375 m/min). The floated materials rise to the surface to form a scum layer (called “float”). Specially designed sludge scoops or flight scrapers on top continuously remove the float. The retention time in the DAF chambers is usually about 5–20 minutes. The effectiveness of DAF depends upon both the attachment of bubbles to the NAPL and other contaminants, and the air stripping effect of bubbles, resulting in cost-effective removal of the contaminants in groundwater.

The contaminants that can be removed by DAF include VOCs, SVOCs, heavy metals, surfactants (used in soil washing or flushing), phenols, and many other toxic organic and inorganic hazardous substances.

Because the detention time of DAF is only about 5–20 minutes (in comparison with conventional biological treatment requiring 7–9 hours detention time), and DAF has the air stripping effect and the highest mobility, it is the most cost-effective process to treat groundwater at a contaminated industrial site.

There are two types of DAF process equipment available for groundwater treatment:

1. Continuous DAF: the groundwater is continuously fed to DAF for treatment, and the effluent is reinjected into the aquifer for recharge. Continuous DAF process equipment is commercially available [51,52], and can all be on wheels ready for site remediation action [22–25,39,49,53–56].

2. Sequencing batch reactor (SBR–DAF): the reactor is similar to conventional SBR, except that DAF is used instead of sedimentation. It can be: (a) a 100% biological SBR–DAF process if microorganisms and nutrients are seeded, (b) a 100% physical-
A small volume of the recovered float (i.e., floated scum) having high concentrations of hazardous substances (NAPL, or heavy metals, or surfactants) must be properly disposed. The treated groundwater can be reinjected into the aquifer. The released air stream can be collected for treatment by either the condensation gas treatment system, or the afterburner gas treatment system, which have been discussed previously.

Ultraviolet, hydrogen peroxide, GAC, and so on, can all be easily adopted as a part of pre- or post-treatment to DAF, if a high quality of effluent meeting drinking water standards is desired.

### 20.23 PERVAPORATION PROCESS FOR GROUNDWATER DECONTAMINATION

Section 20.12.6 discussed the application of a combined Sequencing Batch Reactor and Membrane Bioreactor (SBR–MBR) system to groundwater decontamination. Figure 14 shows the flow diagram of the pervaporation process (one of the membrane processes), which is a feasible process for removing VOCs from contaminated water. Permeable membranes that preferentially adsorb VOCs are used to partition VOCs from the contaminated water. The VOCs diffuse from the membrane–water interface through the membrane by vacuum. Upstream of the system’s vacuum vent, a condenser traps and contains the permeating vapors, condensing the vapor to liquid while...
alleviating fugitive emissions. The condensed organic materials represent only a fraction of the initial wastewater volume and may be subsequently disposed of at significant cost savings. The membrane modules consist of hollow fibers with well-defined alignment that results in high mass transfer efficiencies, minimal pressure drop, and low operating costs. The process is commercially available from Zenon Environmental Inc., Ontario, Canada.

20.24 GLOSSARY [22–25,57–60,66–69]

*Adsorption.* A process whereby a solute (such as a liquid organic pollutant) accumulates or concentrates on the surface of a solid, such as granular activated carbon, polymeric adsorbent, activated alumina, etc.

*Aerobic.* Involving conditions in which oxygen is available.

*Air biofilter (vapor phase bioreactor).* Terms used to describe a biological filter (with microorganisms attached to the filter media) used for purification of air streams that aims to remove toxic organics or odors.

*Air stripping.* A process in which volatile organic compounds, semi-volatile organic compounds, and volatile inorganic compounds are stripped out from a contaminated soil, groundwater, or industrial effluent by air.

*Anaerobic.* Involving conditions in which oxygen is not available.

*Asbestos.* Six naturally occurring fibrous minerals most commonly used in building products, but also popular in other commercial products because they are strong, do not burn, resist corrosion, and insulate well. Because asbestos fibers are small and light, they remain in the air for many hours if they are released and may be inhaled by people in the building.

*Bioaugmentation.* The addition of microorganisms to a waste treatment process unit, an ex situ hazardous material processing system, or a contaminated site to degrade specific contaminants readily and biologically.

*Biodegradation.* The process by which living organisms, especially microorganisms, break down organic compounds, resulting in the formation of simpler intermediate compounds, carbon dioxide, water and other gases; or resulting in the disappearance of environmentally undesirable properties of substances.

*Biological treatment.* Any environmental treatment mainly involving the use of living organisms, especially microorganisms, for breaking down organic substances.

*Biological waste treatment.* Biological treatment of wastewater, solid waste, or hazardous waste.

*Bioremediation (bioreclamation).* Site remediation, groundwater decontamination, or environmental restoration through alteration or optimization of environmental factors to enhance biological treatment.

*Biostimulation.* The use of additional nutrients, a change in pH or temperature, or the optimization of soil or groundwater environmental conditions (i.e., humidity or porosity of soil) in order to enhance the efficiency of biological treatment.

*Biotransformation.* Biological conversion of some characteristic property (i.e., toxicity, form, or mobility) of the original compounds with no decrease in molecular complexity.

*Bioventing.* The in situ use of soil venting or soil vacuum extraction to promote aerobic biodegradation in soils; soil aeration, not vapor extraction, is the primary purpose of the bioventing process.

*BTEX.* Benzene, toluene, ethylbenzene, and xylene, which are a group of common toxic compounds.
Carbon adsorption. Adsorption (i.e., of hazardous substances or impurities) that occurs on either powdered, granular, or fiber carbon molecules.

Characteristic waste. A waste that exhibits any one of the characteristics of ignitability, corrosiveness, reactivity, or toxicity.

Chemical treatment. The use of any chemical(s) that can react with an influent material (water, effluent, hazardous waste, or contaminated soil) to render the influent material nonhazardous, less hazardous, or cleaner.

Cleaner production. Industrial production that creates fewer hazardous and other polluting byproducts.

Containerizing. The collection of heavily contaminated groundwater into containers for onsite or offsite treatment, disposal, or storage.

Corrosive waste. Any aqueous material that has a pH less than or equal to 2, a pH greater than or equal to 12.5, or any material that corrodes SAE 1020 steel at a rate greater than 0.25 in/year (1 in. = 2.54 cm)

Decarbonation. A process in which carbon dioxide or carbon monoxide is removed from a liquid medium.

Dematerialization. In an ideal industrial ecological system, material for industrial development is reduced for environmental conservation.

Dense nonaqueous-phase liquids (DNAPLs). Liquids that have densities greater than that of water, and will tend to sink vertically through aquifers, for example, chlorinated industrial solvents (methylene chloride, trichloroethylene, trichloroethane, dichlorobenzene, trans-1,2-dichloroethylene, etc.).

Design for environment. A profitable industrial system designed for sustainable environmental conservation.

Designated waste (listed hazardous waste). A waste specifically listed in the United States by the USEPA as hazardous.

Disposal site. Legally, any structure, well, pit, pond, lagoon, impoundment, ditch, landfill, or other place or area, excluding ambient air or surface water, where uncontrolled oil or hazardous material has come to be located as a result of any spilling, leaking, pouring, abandoning, emitting, emptying, discharging, injecting, escaping, leaching, dumping, discarding, or otherwise disposing of such oil or hazardous material. The term shall not include any site containing only oil or hazardous materials that are lead-based paint residues emanating from a point of original application of such paint, result from emissions from the exhaust of an engine, are building materials still serving their original intended use or emanating from such use, or result from release of source, byproduct, or special nuclear material from a nuclear incident, as those terms are defined elsewhere.

Dissolved air flotation. A cost-effective liquid treatment process in which pressurization is applied to dissolve air in water (under high pressure), then depressurization is applied to release and generate extremely fine air bubbles (under normal 1 atmospheric pressure) for separation of impurities, pollutants, light nonaqueous-phase liquids (LNAPLs) and other suspended particles from a contaminated water.

DNAPLs. Dense nonaqueous-phase liquids.

Emergency response action. A response action that is taken in response to a sudden release or a threat of release of oil or hazardous material.

Emission. Discharge of a gas into atmospheric circulation.

End-of-pipe treatments. Decontamination technologies that remove hazardous pollutants before industrial effluents are released into the surrounding environment. This is distinguished from technologies that prevent such hazardous substances from being created in the first place.
Enhanced biodegradation (enhanced bioremediation). A complete technology system involving monitoring of hazardous substances, pollution prevention, removal of free contaminants, groundwater decontamination by biological treatment (either above or below ground), groundwater reinjection, biostimulation (i.e., adding nutrients, bioventing) to contaminated groundwater and/or soil, and bioaugmentation of contaminated soil.

Environment. Waters, land, surface, or subsurface strata, or ambient air of the planet of Earth.

Environmental restoration. The restoration of environmental quality by removing hazardous environmental pollutants from an area.

Excavation. An engineering process in which soil is removed from the ground for direct application, or for decontamination and reuse.

Exposure. Any contact with or ingestion, inhalation, or assimilation of oil or hazardous materials, including irradiation.

Ex situ treatment. Site remediation treatment in which the hazardous wastes or environmental samples are removed from the storage or disposal area to be processed elsewhere through a mechanical system. Soil remediation by excavation and incineration is a typical example. Another example is application of the “pump-and-treat” technology for groundwater decontamination.

Ex situ vitrification. A vitrification process that is carried out in an electric furnace (see Vitrification).

Facility. An entire contiguous plant or installation, including the contiguous grounds of such plant or installation, which is under common ownership.

Free contaminant. An environmental contaminant that is in pure form almost free from impurities, water, or soil.

Free product recovery. Recovery of an environmental contaminant, which is almost free from impurities, water, or soil, and can be reused as an industrial product.

Friable asbestos. Soft, easily crumbled asbestos-containing material that has the greatest potential for asbestos release and therefore has the greatest potential to create health risks. This asbestos may also include previously nonfriable material that becomes broken or damaged by mechanical force.

Granular activated carbon (GAC). An insoluble, granular, and porous carbon particle that can adsorb impurities or pollutants onto the surface of the carbon particle’s micropores (see Adsorption and Carbon adsorption).

Greenhouse gas. A gas that accelerates global warming if it is released into the environment (i.e., carbon dioxide, methane).

Groundwater decontamination. The purification of groundwater that has been contaminated by hazardous wastes.

Halogen. One of the elements of Group VIIA of the Periodic Table (i.e., fluorine, chlorine, bromine, iodine, and astatine).

Hazardous material. Legally, material including, but not limited to, any material in whatever form that, because of its quantity, concentration, chemical, corrosive, flammable, reactive, toxic, infectious, or radioactive characteristics, either separately or in combination with any substance or substances, constitutes a present or potential threat to human health, safety, welfare, or to the environment, when improperly stored, treated, transported, disposed of, used, or otherwise managed. The term shall not include oil, but shall include waste oil and all those substances that are included by the government.

Hazardous substance. Any raw material, intermediate product, final product, spent waste, accidental spill, leakage, etc., that can be in the form of gas, liquid, or solid, and is ignitable, corrosive, reactive (explosive), toxic, infectious, carcinogenic, and/or radioactive, and is harmful to living beings and the environment.
Hazardous waste. A waste that can be in the form of gas, liquid, or solid, and is ignitable, corrosive, reactive (explosive), toxic, infectious, carcinogenic, and/or radioactive, and is harmful to living beings and the environment.

Heavy metals. Dense metals, specifically cadmium, mercury, lead, copper, silver, zinc, and chromium, which may be found in the waste stream in soluble or insoluble toxic forms.

Hot air (enhanced) stripping. A soil remediation process in which hot air without steam is used for enhanced stripping removal of volatile pollutants from the contaminated soil.

Ignitable waste. Any liquid with a flash point of less than 60°C (140°F), any nonliquid that can cause a fire under certain conditions, or any waste classified by the US Department of Transportation (USDOT) as a compressed ignitable gas or oxidizer.

Imminent hazard. A hazard that would pose a significant or otherwise unacceptable risk of harm to health, safety, public welfare, or the environment if it were present for even a short period of time.

Incineration (thermal destruction). A two-step hazardous waste treatment process involving drying and combustion of hazardous materials.

Industrial ecology (IE). A branch of systems science of sustainability or a framework for designing and operating industrial systems as sustainable living systems interdependent with natural systems. It seeks to balance environmental and economic performance within the emerging understanding of local and global ecological constraints.

Infectious waste. A waste that potentially carries a communicable disease; legal definitions can also include general, radioactive, and toxic chemical wastes from hospitals.

In situ flushing. See Natural attenuation.

In situ subsurface ventilation/aeration. A soil and groundwater remediation process in which air diffuses through spargers in the saturated zone of contaminated groundwater, and air flows through the contaminated soil in the vadose zone, both for stripping removal of volatile organic compounds and semivolatile organic compounds from the groundwater and the soil, respectively, under in situ conditions.

In situ thermal extraction. See Thermal extraction.

In-situ treatment. Site remediation treatment in which the hazardous wastes or environmental samples are not removed from the storage or disposal area to be processed. In general, treatment is accomplished by mixing a reagent into the waste storage zone by some mechanical means such as auger, backhoe, rotary tilling device, etc. Site remediation by “in situ solidification” is a typical example.

In situ vitrification. A vitrification process that is carried out in place at a contaminated site (see Vitrification).

KPEG treatment. A chemical treatment process in which chemical reagents prepared from polyethylene glycols and potassium hydroxide (KPEG) are used under mild temperatures (25–140°C) to dehalogenate the pollutants (such as PCBs, PCDDs, and PCDFs) containing halogens.

Leachability. The capacity of hazardous waste material to leach into passing water.

Leachant. The passing water into which hazardous wastes leach.

Leachate. Contaminated water that has passed through solid waste or hazardous waste.

Leaching. The process by which hazardous wastes dissolve into water that passes through the waste and thus contaminates the surrounding soils and groundwater.

Light nonaqueous-phase liquids (LNAPLs). Liquids that have densities smaller than that of water and will tend to float vertically through aquifers, such as jet fuel, kerosene, gasoline, and nonchlorinated industrial solvents (benzene, toluene, etc.).

LNAPLs. Light nonaqueous-phase liquids.
Manifest system. A government hazardous waste documentation system that ensures proper handling when waste is transported to another site for disposal.

Material balance. An accounting of the weights of material entering and leaving a process or system, usually made on a time-related basis.

Material substitution. An industrial ecological process in which a different new material is used for substitution of an old material in order to improve production, conserve energy, and/or protect the environment.

Migration pathway. A pathway by which an oil or hazardous material is transported at or from a disposal site.

Mineralization. The complete breaking down of organic compounds by living organisms, especially microorganisms, resulting in the formation of carbon dioxide, water, and other minerals or gases.

MTBE. Methyl tertiary butyl ether, which is a gasoline (or similar fuel) additive as well as a groundwater contaminant.

NAPLs. Nonaqueous-phase liquids.

Natural attenuation (natural flushing, natural dilution). A groundwater remediation technique that dilutes hazardous substances in a contaminated aquifer by flushing it with a large amount of clean water (i.e., river water, lake water).

Nebulization. A process or act of nebulizing, atomization. A process of causing a liquid to form small droplets.

Nonaqueous-phase liquids (NAPLs). Organic liquids that are relatively insoluble in water. There are two classifications of nonaqueous-phase liquids: light nonaqueous-phase liquids (LNAPLs) and dense nonaqueous-phase liquids (DNAPLs).

Offsite treatment. Site remediation treatment in which the hazardous wastes or environmental samples are removed from the contaminated site to be processed. If the contaminated soil must be excavated from the site and transported to another location for incineration, it is an ex situ treatment as well as an offsite treatment. Offsite treatment systems involve mainly fixed operations using nonmobile or nontransportable equipment.

Oil. Insoluble or partially soluble oils of any kind or origin or in any form, including, without limitation, crude or fuel oils, lube oil or sludge, asphalt, insoluble or partially insoluble derivatives of mineral, animal, or vegetable oils.

Onsite treatment. Site remediation treatment in which the hazardous wastes or environmental samples are not removed from the contaminated site to be processed. Any kind of in situ treatment is onsite treatment. Application of the pump-and-treat technology for groundwater decontamination at the contaminated site is an ex situ treatment as well as an onsite treatment. Onsite treatment systems consist mainly of mobile or transportable equipment, installation, labor, and support services.

Oxidation. A process reaction that increases the proportion of oxygen, acid-forming element, or radical in a compound. Generally, any process reaction that involves the loss of electrons from an atom.

Oxidizer. Any material that yields oxygen readily to stimulate the combustion or oxidation of organic matter.

PCB. Polychlorinated biphenyls.

pH adjustment. A chemical treatment (see Chemical treatment) involving the use of acids or bases for precipitation of pollutants, or for neutralization.

Process substitution. An industrial ecological methodology in which a different new process is used for substitution of an old process in order to improve production, conserve energy, and/or protect the environment.
Pump-and-treat technology. A groundwater decontamination technology in which contaminated groundwater is pumped from below the surface to the ground surface for ex situ treatment.

Pyrolysis (thermal desorption). The process by which moisture, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and volatile inorganics in contaminated soil or hazardous wastes are reduced by elevating the temperature without combusting the solid materials. This is a process similar to incineration except that it is operated in the absence of oxygen but at high temperatures.

Reactive waste. A waste that is unstable, changes form violently, is explosive, reacts violently with water, forms an explosive mixture with water, or generates toxic gases in dangerous concentrations.

Recycling. The process by which materials otherwise destined for disposal are collected, reprocessed or remanufactured, and reused.

Refuse derived fuel (RDF). Boiler fuel made by shredding and screening solid waste into a material of relatively uniform handling and combustion properties. Often, recyclables can be recovered from the RDF process.

Release. Any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment.

Resource recovery. A term describing the extraction and utilization of materials and energy from the waste stream. The term is sometimes used synonymously with energy recovery.

Route of exposure. A mechanism including, but not limited to, ingestion, inhalation, dermal absorption, and transpiration by which an oil or hazardous material comes into contact with a human or environmental receptor.

SBR. Sequencing batch reactor, which is a batch biological process involving the use of activated sludge process principles.

Sewer discharge. Discharge of a treated or untreated effluent, or contaminated groundwater to a sewerage system for subsequent treatment by a publicly-owned treatment works (POTW).

Sheen. Appearance of any oil or waste oil on the surface of any river, stream, lake, pond, spring, impoundment, estuary, or coastal water that is caused by the release of such oil or waste oil.

Site. Any building, structure, installation, ground, equipment, pipe or pipeline including any pipe discharging into a sewer or publicly-owned treatment works, well, pit, pond, lagoon, impoundment, ditch, landfill, storage container, motor vehicle, rolling stock, or aircraft, or any other place or area where oil or hazardous material has been deposited, stored, disposed of, or placed, or otherwise come to be located. The term shall not include any consumer product in consumer use or any vessel.

Site remediation. The restoration of any industrial, agricultural, commercial or residential sites whose soil or groundwater have been seriously contaminated by hazardous wastes.

Slurry bioreactor. An ex situ biological soil remediation technology that is more efficient than other bioremediation technologies and more economical than thermal desorption and incineration. It is also more efficient than other biological treatments in reducing PAHs in soil to target levels in a timely manner.

Soil surfactant flushing. An in situ site remediation process for contaminated soil that uses surfactant solution.

Soil surfactant washing. An ex situ site remediation process for soil excavation, slurry preparation, and subsequent ex situ treatment aboveground with surfactant solution.
Soil vacuum extraction (SVE). One of a number of terms used interchangeably to describe a process that removes volatile organic compounds (VOC) from the vadose, or unsaturated soil zone by vacuum stripping.

Soil vapor extraction (SVE). One of a number of terms used interchangeably to describe a process that removes volatile organic compounds (VOC) from the vadose, or unsaturated soil zone by vacuum stripping.

Soil vapor stripping (SVS). One of a number of terms used interchangeably to describe a process that removes volatile organic compounds (VOC) from the vadose, or unsaturated soil zone by vacuum stripping.

Soil venting (SV). One of a number of terms used interchangeably to describe a process that removes volatile organic compounds (VOC) from the vadose, or unsaturated soil zone by vacuum stripping.

Soil washing (soil scrubbing). A soil remediation water-based volume reduction process in which debris is removed from the soil, and the soil is mixed with water and subjected to various operations common to the mineral processing industry in order to break down contaminants.

Solidification. Hazardous waste treatment techniques that encapsulate the waste in a monolithic solid of high structural integrity.

Source reduction. The design, manufacture, acquisition, and reuse of materials so as to minimize the quantity and/or toxicity of waste produced. Source reduction prevents waste either by redesigning products or by otherwise changing societal patterns of consumption, use, and waste generation.

Stabilization techniques. Hazardous waste treatment techniques that reduce the hazard potential of a waste by converting the contaminants into their least soluble, least mobile, or least toxic form. The physical nature and handling characteristics of the waste are not necessarily changed by stabilization.

Starved air combustion (SAC) (thermal gasification). A hazardous waste treatment process similar to incineration except that less than the theoretical amount of air necessary for complete combustion is supplied.

Steam (enhanced) stripping. A soil remediation process in which hot air with steam is used for enhanced stripping removal of volatile pollutants from the contaminated soil (see Hot air (enhanced) stripping for comparison).

Storage. The interim containment of solid waste, hazardous waste, contaminated soil or groundwater, in an approved manner, after generation and prior to ultimate disposal or reuse.

Substantial hazard. A hazard that would pose a significant or otherwise unacceptable risk of harm to health, safety, public welfare, or the environment if it continued to be present for several years.

Subsurface volatilization. See in situ subsurface ventilation/aeration.

Subsurface ventilation. See in situ subsurface ventilation/aeration.

Surfactant. Any compound that reduces surface tension when dissolved in a solution, or that reduces the tension at the interface of two liquids or a liquid and a solid. There are three basic classes of surfactants: detergents, wetting agents, and emulsifiers.

Surfactant solution. A solution containing surfactants, or surface active molecules or ions. One portion of the surfactant molecule is hydrophilic (water loving), while the other part is hydrophobic (water hating).

Sustainable. Something (i.e., agriculture, industry, development) that can continue at its present (or a comparable) level in the future and does not interfere with future well-being by degrading or overusing natural resources.
Sustainability. The degree of capability for something (i.e., agriculture, industry, development) that can continue at its present (or a comparable) level in the future and does not interfere with future well-being by degrading or overusing natural resources.

SVOC. Semivolatile organic compounds (see Volatile compounds/solids and VOC).

System. A set of elements that are interrelated in a structured way; the elements are perceived as a whole with a purpose.

TCE. Trichloroethene, which is a common toxic organic solvent.

TCLP. Toxicity characteristic leaching procedure.

Thermal desorption (pyrolysis). The process by which moisture, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and volatile inorganics in contaminated soil or hazardous wastes are reduced by elevating the temperature without combusting the solid materials.

Thermal destruction (incineration). A two-step hazardous waste treatment process involving drying and combustion of hazardous materials.

Thermal gasification. A hazardous waste treatment process similar to incineration except that less than the theoretical amount of air necessary for complete combustion is supplied [see Starved air combustion (SAC)].

Threat of release. A substantial likelihood of a release that requires action to prevent or mitigate damage to the environment that may result from such release. Circumstances that represent a threat of release include, but are not limited to, sites or vessels containing or conducting an amount of oil or hazardous material in excess of the reportable quantity for that oil or hazardous material where no release has occurred but where (a) corrosion, damage, malfunction or other conditions are visible, known to exist or should be known to exist; and (b) where these conditions are likely to result in a release.

Treatability test (treatability study). A test using an actual or simulated waste sample to determine whether or not a particular process method or equipment can be used to treat the waste in question.

Trench. (a) An excavation made for installing pipes, masonry walls, Bentonite slurry wall, and for other construction or environmental purposes. A trench is distinguished from a ditch in that the opening is temporary and is eventually backfilled; (b) a relatively long but narrow structural or erosional feature of the Earth’s subsurface.

Trenching (trench technology). A common remediation process for decontamination of soil and groundwater involving the construction of trenches filled with Bentonite slurry or other materials (see Trench). For instance, a Bentonite slurry trench cutoff wall can be built to intersect the subsurface plume to prevent the aquifer from further contamination downgradient. Then, a free product recovery trench can be built before the Bentonite slurry trench cutoff wall to directly intersect the subsurface plume to recover either LNAPL near the water table or DNAPL near the aquifer bottom or impervious layer.

Ultraviolet irradiation. Very short wavelengths of light not visible to the human eye, sometimes used for disinfection.

UNIDO. United Nations Industrial Development Organization.

USEPA. United States Environmental Protection Agency.

Vapor. The gaseous phase of matter that normally exists in a liquid or solid state.

Vaporization. The process by which a substance such as water changes from the liquid or solid phase to the gaseous phase.

Vapor pressure. According to kinetic theory, liquids as well as gases are in constant agitation, and molecules are constantly flying from the surface of the liquid into the atmosphere above. In open systems most of these particles never return, and the liquid is said to be
undergoing evaporation. In a closed system, however, particles return to the liquid phase in proportion to their concentration in the gaseous phase. Eventually the rate of return equals the rate of flight, and a condition of equilibrium is established. The vapor is then said to be saturated. The pressure exerted by the vapor under these conditions is known as the vapor pressure. The vapor pressure of all liquids increases with temperature.

Vacuum stripping. See Vacuum extraction.

Vacuum extraction (VE). One of a number of terms used interchangeably to describe a process that removes volatile organic compounds (VOCs) from the vadose, or unsaturated soil zone by vacuum stripping.

Vadose zone. Unsaturated soil zone above the water table.

Vapor stripping. See Soil vapor stripping.

Vessel. Every description of watercraft, aircraft, or other artificial contrivance used, or capable of being used, as a means of transportation on water or air.

Vitrification. A process of melting contaminated soil, buried hazardous wastes, or toxic sludges at a temperature as high as 1600–2000 °C, in an electric furnace or in place at a contaminated site to render the materials nonhazardous. The final nonhazardous product is a glassy and/or crystalline solid matrix that is resistant to leaching and more durable than natural granite or marble.

VOC. Volatile organic compounds, referring to volatile organic solvents and emissions (see Volatile compounds/solids).

Volatile compounds/solids. Solids, dissolved or suspended, that are primarily organic, and can be lost on ignition of the total solids.

Volume reduction. The processing of waste materials so as to decrease the amount of space the materials occupy, usually by compacting or shredding (mechanical), incineration (thermal), or composting (biological).

Waste derived fuel (WDF). See Refuse derived fuel.

Waste exchange. An organization that assists in the transfer of wastes from a generating company to another company for use as a feedstock. There are primarily two types of waste exchanges: active and passive. An active exchange intervenes between the generator and the potential user (e.g., by taking possession of the waste or locating wastes for “clients”). A passive exchange involves the exchange of information only. Frequently a passive exchange will maintain a catalog or newsletter identifying generators who can provide wastes, and consumers who can use wastes as feedstock. Generally the type, quantity, and description of the waste available/desired is provided. Interested parties are then responsible for contacting each other directly and the waste exchange plays no additional role.

Waste minimization. The reduction, to the extent feasible, of industrial/hazardous waste that is generated or subsequently, treated, stored, or disposed of. It includes any source reduction or recycling activity undertaken by a generator that results in either (a) the reduction of total volume or quantity of hazardous waste, or (b) the reduction of toxicity of hazardous waste, or both, so long as the reduction is consistent with the goal of minimizing present and future threats to human health and the environment.

Waste oil. Used and/or reprocessed, but not subsequently re-refined, oil that has served its original intended purpose. Such oil includes, but is not limited to, used and/or reprocessed fuel oil, engine oil, gear oil, cutting oil, and transmission fluid.

Waste reduction. Reduction in the volume and toxicity of waste. As used in this manual, it includes all source reduction and recycling practices performed on gaseous, aqueous, or solid hazardous or toxic wastes. Treating or emitting, discharging, or disposing of wastes after they have been generated is not waste reduction. Reducing the federal government regulated hazardous wastes by proportionally increasing water discharges of toxic substances is also not an acceptable form of waste reduction.
Water table. The depth below which the ground is saturated with groundwater.

Zero discharge. No discharge of a selected effluent or combination of several effluents (gaseous effluent, liquid effluent, and/or solid effluent) from a site or installation into the environment. For instance, an industrial plant may have successfully accomplished zero discharge of industrial wastewater effluent, but may still violate air emission standards.

Zero emission. No discharge of any gas from a site or installation into atmospheric circulation.

ACKNOWLEDGMENT

This chapter is a revised, updated, and condensed version of four technical reports [22–25] that were all completed under the financial sponsorship of the United Nations Industrial Development Organization (UNIDO), Vienna, Austria, and when the author was a UNIDO Senior Advisor. The scientific views expressed in this chapter are solely of the author and not necessarily those of the sponsoring organization or the UN member countries. Requests for further information dissemination and technical assistance shall be directed to the author.

REFERENCES

23. Wang, L.K. *Case Studies of Cleaner Production and Site Remediation*; United Nations Industrial Development Organization (UNIDO), Vienna, Austria, 1995; Training Manual No. 5-4-95, 136 p.