FRTR 2005

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Remediation Technologies Screening Matrix and Reference Guide, Version 4.0

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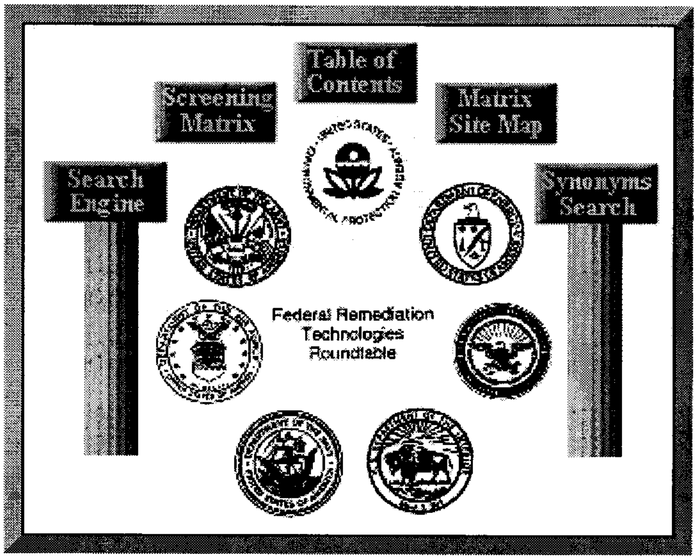

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Section 3 Treatment Perspectives

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Three primary strategies used separately or in conjunction to remediate most sites are:

- Destruction or alteration of contaminants.
- Extraction or separation of contaminants from environmental media.
- Immobilization of contaminants.

Treatment technologies capable of contaminant destruction by altering their chemical structure are thermal, biological, and chemical treatment methods. These destruction technologies can be applied in situ or ex situ to contaminated media.

Treatment technologies commonly used for extraction and separation of contaminants from environmental media include soil treatment by thermal desorption, soil washing, solvent extraction, and soil vapor extraction (SVE) and ground water treatment by either phase separation, carbon adsorption, air stripping, ion exchange, or some combination of these technologies. Selection and integration of technologies should use the most effective contaminant transport mechanisms to arrive at the most effective treatment scheme. For example, more air than water can be moved through soil. Therefore, for a volatile contaminant in soil that is relatively insoluble in water, SVE would be a more efficient separation technology than soil flushing or washing.

Immobilization technologies include stabilization, solidification, and containment technologies, such as placement in a secure landfill or construction of slurry walls. No immobilization technology is permanently effective, so some type of maintenance is desired. Stabilization technologies are often proposed for remediating sites contaminated by metals or other inorganic species.

These concepts about site remediation strategies and representative technologies associated with them are summarized in Figure1: Classification of Remedial Technologies by Function. One feature obvious from the figure is that the choice of applied technologies is not extensive once a strategy is selected.

Generally, no single technology can remediate an entire site. Several treatment technologies are usually combined at a single site to form what is known as a treatment train. SVE can be integrated with ground water pumping and air stripping to simultaneously remove contaminants from both ground water and soil. The emissions from the SVE system and the air stripper can be treated in a single air treatment unit. An added benefit is that the air flow through the soil stimulates or enhances natural biological activity, and some biodegradation of contaminants occurs. In some cases, air is injected into either the saturated or the unsaturated zones to facilitate contaminant transport and to promote biological activity.

For the purpose of this document, the technologies are separated into 14 treatment groups as follows:

- Soil, sediment, and sludge:
  - In situ biological treatment.
  - In situ physical/chemical treatment.
  - In situ thermal treatment.
  - Ex situ biological treatment (assuming excavation).

  - Ex situ physical/chemical treatment (assuming excavation).
  - Ex situ thermal treatment (assuming excavation).
  - Containment.
  - Other treatment processes.
- Ground water, surface water, and leachate:
  - In situ biological treatment.
  - In situ physical/chemical treatment.
  - Ex situ biological treatment (assuming pumping).
  - Ex situ physical/chemical treatment (assuming pumping).
  - Containment.
- Air emissions/off-gas treatment.

These 14 treatment groups correspond to the following 14 subsections (3.1 through 3.14). The discussion of the broad application of each treatment group (e.g., in situ biological treatment for soil, sediment, bedrock and sludge) in this section is followed by a more detailed discussion of each treatment technology (e.g., bioventing) in that treatment group, in Section 4. Information on completed projects in these treatment process areas has been presented in tables extracted from the *Treatment Technologies for Site Cleanup: Annual Status Report Tenth Edition (February 2001)*, and the *Synopses of Federal Demonstrations of Innovative Site Remediation Technologies*, FRTR, 1993.

Tables 3-1 and 3-2 summarize pertinent information for each of the treatment technologies presented in Section 4. Information summarized includes the following:

- Technology Profile Number (refers to Section 4).
- Developmental Status (full scale vs. pilot scale).
- Typical Treatment Train.
- Residuals Produced.
- O&M or Capital Intensive.
- Availability.
- Contaminants Treated.
- System Reliability/Maintainability.
- Cleanup Time.
- Overall Cost.

Additionally, a brief description of each treatment technology is presented at the beginning of each process description.

TABLE 3-1a. DEFINITION OF LEGENDS USED IN THE TREATMENT TECHNOLOGIES SCREENING MATRIX

Factors	**Definitions**			
Development Status Scale status of an available technology.	**F** Full scale: technology has been used in real site remediation.		**P** Pilot Scale: studies conducted in the field or the laboratory to fine-tune the design of the technology.	
Treatment Train Is the technology only effective as part of the treatment train?	**Y** Technology must be used with the combination of other technologies as a treatment train.		**N** Technology can be used as a stand alone one.	
Residuals Produced Residuals need to be treated.	**S** Solid	**L** Liquid	**V** Vapor	**N** None

O&M or Capital Intensive Main cost intensive parts.	**O&M** Operation and Maintenance Intensive	**Cap** Capital Intensive	**B** Both O&M and Capital Intensive	**N** Neither O&M or Capital Intensive

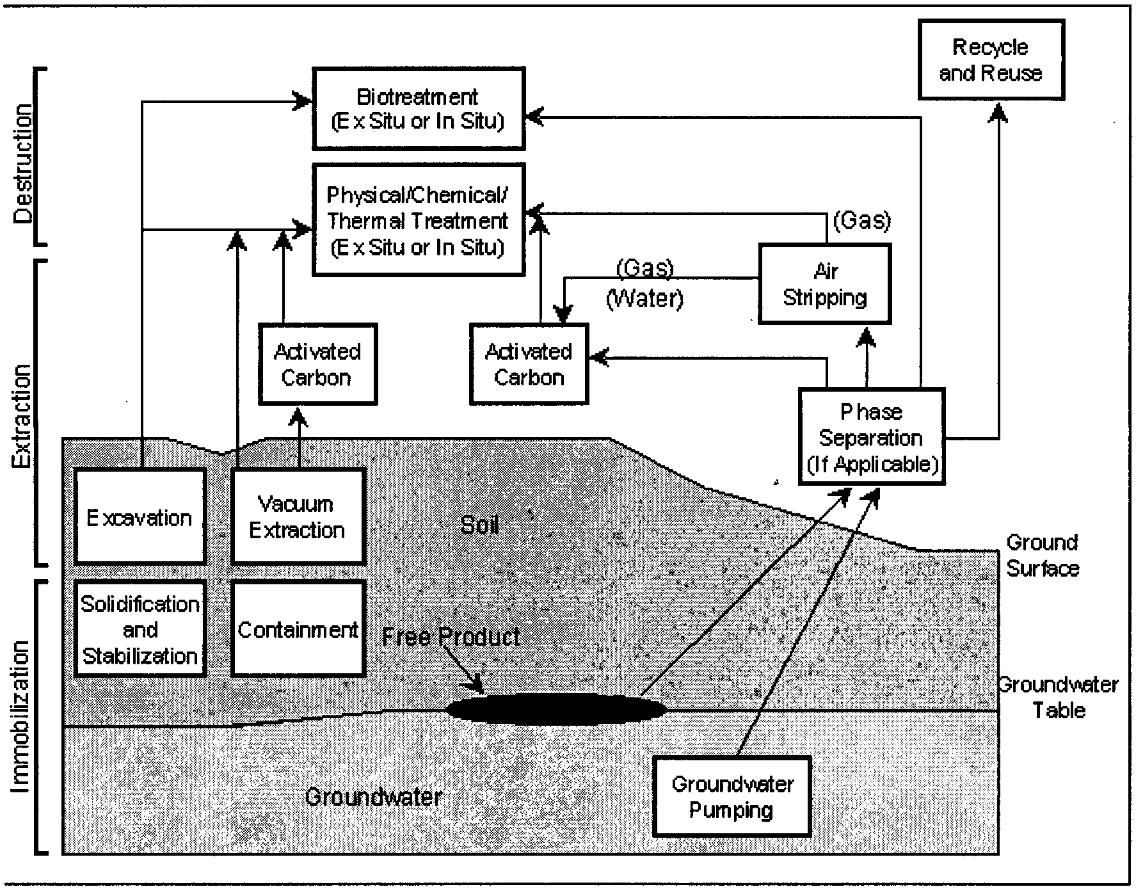
TABLE 3-1b. DEFINITION OF SYMBOLS USED IN THE TREATMENT TECHNOLOGIES SCREENING MATRIX

Factors and Definitions	**Worse** △	**Average** ○	**Better** ■	**Other** ◆
Availability Number of vendors that can design, construct, and maintain the technology.	Fewer than 2 vendors	2-4 vendors	More than 4 vendors	Data Not Available
Contaminants Treated Contaminants are classified into the following eight groups: - Nonhalogenated VOCs; - Halogenated VOCs; - Nonhalogenated SVOCs; - Halogenated SVOCs; - Fuels; - Inorganics; - Radionuclides; - Explosives.	No Demonstrated Effectiveness at Pilot or Full Scale	Limited Effectiveness Demonstrated at Pilot or Full Scale	Effectiveness Demonstrated at Pilot or Full Scale	Level of Effectiveness highly dependent upon specific contaminant and its application/design
System Reliability /Maintainability The expected range of demonstrated reliability and maintenance relative to other effective technologies	Low reliability and high maintenance	Average reliability and average maintenance	High reliability and low maintenance	Not applicable
Cleanup Time provided that this technology is effective for this specific contaminant. Time required to clean up a "standard" site using the technology. The "standard" site is assumed to be 20,000 tons (18,200 metric tons) for soils and 1 million gallons (3,785,000 liters) for ground water.	More than 3 years for in situ soil	1-3 years	Less than 1 year	Contaminant specific
	More than 1 year for ex situ soil	0.5-1 year	Less than 0.5 year	Contaminant specific
	More than 10 years for water	3-10 years	Less than 3 years	Contaminant specific
Overall Cost Design, construction, and operations and maintenance (O&M) costs of the core process that defines each technology, exclusive of mobilization,	More than $330/metric ton ($300/ton) for soils	$110-$330 /metric ton ($100-$300 /ton)	Less than $110/metric ton ($100/ton)	Contaminant specific
	More than	$0.79-	Less than	Contaminant

demobilization, and pre- and post-treatment. For ex situ soil, sediment, and sludge technologies, it is assumed that excavation costs average $55.00/metric ton ($50/ton). For ex situ ground water technologies, it is assumed that pumping costs average $0.07/1,000 liters ($0.25/1,000 gallons).	$2.64/1,000 liters ($10/1,000 gal.) for ground water	$2.64 /1,000 liters ($3.00-$10.00/ 1,000 gallons)	$0.79/1,000 liters ($3.00/1,000 gallons)	specific
	More than $11.33/kg ($25/lb) for air emissions and off-gases	$3.17-$11.33 /kg ($7-$25/lb)	Less than $3.17/kg ($7/lb)	Contaminant specific

Source: Remediation Technologies Screening Matrix and Reference Guide, Version I (EPA, USAF, 1993).

FIGURE 3-1 CLASSIFICATION OF REMEDIAL TECHNOLOGIES BY FUNCTION*



Notice this is an image map and the boxes are linked, except for the "Recycle and Reuse" box.

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3.1 In Situ Biological Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of in situ treatment is that it allows soil to be treated without being excavated and transported, resulting in potentially significant cost savings. However, in situ treatment generally requires longer time periods, and there is less certainty about the uniformity of treatment because of the variability in soil and aquifer characteristics and because the efficacy of the process is more difficult to verify.

Bioremediation techniques are destruction techniques directed toward stimulating the microorganisms to grow and use the contaminants as a food and energy source by creating a favorable environment for the microorganisms. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms adapted for degradation of the specific contaminants are applied to enhance the process.

Biological processes are typically implemented at low cost. Contaminants can be destroyed, and often little to no residual treatment is required. However, the process requires more time, and it is difficult to determine whether contaminants have been destroyed. Biological treatment of PAHs leaves less degradable PAHs (cPAHs) behind. These higher molecular weight cPAHs are classified as carcinogens. Also, an increase in chlorine concentration leads to a decrease in biodegradability. Some compounds, however, may be broken down into more toxic by-products during the bioremediation process (e.g., TCE to vinyl chloride). For in situ applications, these by-products may be mobilized to ground water or contacted directly if no control techniques are used. This type of treatment scheme requires soil, aquifer, and contaminant characterization, and may require extracted ground water treatment. Ground water with low level contamination may sometimes be recirculated through the treatment area to supply water to the treatment area.

Although not all organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate soils, sludges, and ground water contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals. Bioremediation is not applicable for treatment of inorganic contaminants.

The rate at which microorganisms degrade contaminants is influenced by the specific contaminants present and their concentrations, oxygen supply, moisture, temperature, pH, nutrient supply, bioaugmentation, and cometabolism. In situ biological treatment technologies are sensitive to certain soil parameters. For example, the presence of clay or humic materials in soil cause variations in biological treatment process performance. Treatability studies are typically conducted to determine the effectiveness of bioremediation in a given situation. These parameters are discussed briefly in the following paragraphs.

Oxygen level in the soil is increased by avoiding saturation of the soil with water, the presence of sandy and loamy soil as opposed to clay soil, avoiding compaction, avoiding high redox potential, and low concentrations of degradable materials. To ensure that oxygen is supplied at a rate sufficient to maintain aerobic conditions, forced air or hydrogen peroxide injection can be used. The use of hydrogen peroxide is limited because at high concentrations (above 100 ppm, or 1,000 ppm with proper acclimation), it is toxic to microorganisms. Also, hydrogen peroxide tends to decompose into water and oxygen rapidly in the presence of some soil constituents.

Anaerobic conditions may be used to degrade highly chlorinated contaminants, although at a very slow rate. This can be followed by aerobic treatment to complete biodegradation of the partially dechlorinated compounds as well as the other contaminants.

Water serves as the transport medium through which nutrients and organic constituents pass into the microbial cell and metabolic waste products pass out of the cell. Too much water can be detrimental, however, because it may inhibit the passage of oxygen through the soil (unless anaerobic conditions are desired).

Nutrients required for cell growth are nitrogen, phosphorous, potassium, sulfur, magnesium, calcium, manganese, iron, zinc, copper, and trace elements. If nutrients are not available in sufficient amounts, microbial activity will become limited. Nitrogen and phosphorous are the nutrients most likely to be deficient in the contaminated environment. These are usually added to the bioremediation system in a useable form (e.g., as ammonium for nitrogen and as phosphate for phosphorous). Phosphates can cause soil plugging as a result of their reaction with minerals, such as iron and calcium, to form stable precipitates that fill the pores in the soil and aquifer.

pH affects the solubility, and consequently the availability, of many constituents of soil, which can affect biological activity. Many metals that are potentially toxic to microorganisms are insoluble at elevated pH; therefore, elevating the pH of the treatment system can reduce the risk of poisoning the microorganisms.

Temperature affects microbial activity in the environment. The biodegradation rate will slow with decreasing temperature; thus, in northern climates bioremediation may be ineffective during part of the year unless it is carried out in a climate-controlled facility. The microorganisms remain viable at temperatures below freezing and will resume activity when the temperature rises.

Heating the bioremediation site, such as by use of warm air injection, may speed up the remediation process. At Eielson AFB, Alaska, passive solar warming by incubation tanks (ex situ) or the application of heated water below the ground surface to the contaminated vadose zone is being investigated. Too high a temperature can be detrimental to some microorganisms, essentially sterilizing the soil.

Temperature also affects nonbiological losses of contaminants mainly through the increased volatilization of contaminants at high temperatures. The solubility of contaminants typically increases with increasing temperature; however, some hydrocarbons are more soluble at low temperatures than at high temperatures. Additionally, oxygen solubility decreases with increasing temperature.

Bioaugmentation involves the use of microbial cultures that have been specially bred for degradation of specific contaminants or contaminant groups and sometimes for survival under unusually severe environmental conditions. Sometimes microorganisms from the remediation site are collected, separately cultured, and returned to the site as a means of rapidly increasing the microorganism population at the site. Usually an attempt is made to isolate and accelerate the growth of the population of natural microorganisms that preferentially feed on the contaminants at the site. In some situations different microorganisms may be added at different stages of the remediation process because the contaminants in abundance change as the degradation proceeds. USAF research, however, has found no evidence that the use of non-native microorganisms is beneficial in the situations tested.

Cometabolism uses microorganisms growing on one compound to produce an enzyme that chemically transforms another compound on which they cannot grow.

Treatability or feasibility studies are used to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of

Anaerobic conditions may be used to degrade highly chlorinated contaminants, although at a very slow rate. This can be followed by aerobic treatment to complete biodegradation of the partially dechlorinated compounds as well as the other contaminants.

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Heating the bioremediation site, such as by use of warm air injection, may speed up the remediation process. At Eielson AFB, Alaska, passive solar warming by incubation tanks (ex situ) or the application of heated water below the ground surface to the contaminated vadose zone is being investigated. Too high a temperature can be detrimental to some microorganisms, essentially sterilizing the soil.

Temperature also affects nonbiological losses of contaminants mainly through the increased volatilization of contaminants at high temperatures. The solubility of contaminants typically increases with increasing temperature; however, some hydrocarbons are more soluble at low temperatures than at high temperatures. Additionally, oxygen solubility decreases with increasing temperature.

Bioaugmentation involves the use of microbial cultures that have been specially bred for degradation of specific contaminants or contaminant groups and sometimes for survival under unusually severe environmental conditions. Sometimes microorganisms from the remediation site are collected, separately cultured, and returned to the site as a means of rapidly increasing the microorganism population at the site. Usually an attempt is made to isolate and accelerate the growth of the population of natural microorganisms that preferentially feed on the contaminants at the site. In some situations different microorganisms may be added at different stages of the remediation process because the contaminants in abundance change as the degradation proceeds. USAF research, however, has found no evidence that the use of non-native microorganisms is beneficial in the situations tested.

Cometabolism uses microorganisms growing on one compound to produce an enzyme that chemically transforms another compound on which they cannot grow.

Treatability or feasibility studies are used to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. For sites contaminated with common petroleum hydrocarbons (e.g., gasoline and/or other readily degradable compounds), it is usually sufficient to examine representative samples for the presence and level of an indigenous population of microbes, nutrient levels, presence of microbial toxicants, and soil characteristics such as pH, porosity, and moisture.

Statistical characterization techniques should be used to represent "before" and "after" situations to verify biological treatment effectiveness.

Available in situ biological treatment technologies include bioventing, enhanced biodegradation, and phytoremediation. These technologies are discussed in Section 4 . Completed in situ biological treatment projects for soil, sediment, bedrock, and sludge are shown in Table 3-4 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.2 In Situ Physical/Chemical Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of in situ treatment is that it allows soil to be treated without being excavated and transported, resulting in potentially significant cost savings. However, in situ treatment generally requires longer time periods, and there is less certainty about the uniformity of treatment because of the variability in soil and aquifer characteristics and because the efficacy of the process is more difficult to verify.

Physical/chemical treatment uses the physical properties of the contaminants or the contaminated medium to destroy (i.e., chemically convert), separate, or contain the contamination. Soil vapor extraction uses the contaminant's volatility to separate it from the soil. Soil flushing uses the contaminant's solubility in liquid to physically separate it from the soil. Surfactants may be added to the flushing solution to chemically increase the solubility of a contaminant. Solidification/stabilization also uses both physical and chemical means. Solidification encapsulates the contaminant, while stabilization physically alters or binds with the contaminant. Pneumatic fracturing is an enhanced technique that physically alters the contaminated media's permeability by injecting pressurized air to develop cracks in consolidated materials.

Physical/chemical treatment is typically cost effective and can be completed in short time periods (in comparison with biological treatment). Equipment is readily available and is not engineering or energy-intensive. Treatment residuals from separation techniques will require treatment or disposal, which will add to the total project costs and may require permits. Extraction fluids from soil flushing will increase the mobility of the contaminants, so provisions must be made for subsurface recovery.

Available in situ physical/chemical treatment technologies include electrokinetic separation, fracturing (blast-enhanced, pneumatic, and lasagna process), soil flushing, soil vapor extraction, and solidification/stabilization. These treatment technologies are discussed in Section 4. Completed in situ physical/chemical treatment projects for soil, sediment, bedrock and sludge are shown in Table 3-5 and additional information on completed demonstration projects are shown on the FRTR Web Site.

Certain in situ physical/chemical treatment technologies are sensitive to certain soil parameters. For example, the presence of clay or humic materials in soil causes variations in horizontal and vertical hydraulic parameters, which, in turn, cause variations in physical/chemical process performance. Stabilization/solidification technologies are less sensitive to soil parameters than other physical/chemical treatment technologies.

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3.3 In Situ Thermal Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of in situ thermal treatment is that it allows soil to be treated without being excavated and transported, resulting in significant cost savings. However, in situ treatment generally requires longer time periods, and there is less certainty about the uniformity of treatment because of the variability in soil and aquifer characteristics and because the efficacy of the process is more difficult to verify.

Thermal treatment offers quick cleanup times, but it is generally the most costly treatment group. Cost is driven by energy and equipment costs and is both capital and O&M-intensive.

Thermally enhanced SVE is an extraction technique that uses temperature to increase the volatility of the contaminants in the soils. Thermally enhanced SVE may require off-gas and/or residual liquid treatment. In situ vitrification uses heat to melt soil, destroying some organic compounds and encapsulating inorganics.

An available in situ thermal treatment technology is thermally enhanced SVE. This technology is discussed in Section 4. Completed in situ thermal treatment projects for soil, sediment, bedrock and sludge are shown in Table 3-6 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.4 Ex Situ Biological Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of ex situ treatment is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment because of the ability to homogenize, screen, and continuously mix the soil. However, ex situ treatment requires excavation of soils, leading to increased costs and engineering for equipment, possible permitting, and material handling/worker exposure considerations.

Bioremediation techniques are destruction or transformation techniques directed toward stimulating the microorganisms to grow and use the contaminants as a food and energy source by creating a favorable environment for the microorganisms. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms adapted for degradation of the specific contaminants are applied to enhance the process.

Biological processes are typically implemented at low cost. Contaminants can be destroyed or transformed, and little to no residual treatment is required. However, the process requires more time and it is difficult to determine whether contaminants have been destroyed. Biological treatment of PAHs leaves less degradable PAHs (cPAHs) behind. These higher molecular cPAHs are classified as carcinogens. Also, an increase in chlorine concentration leads to a decrease in biodegradability. Some compounds, however, may be broken down into more toxic by-products during the bioremediation process (e.g., TCE to vinyl chloride). An advantage over the in situ applications is that in ex situ applications, these by-products are contained in the treatment unit until nonhazardous end-products are produced.

Although not all organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate soils, sludges, and ground water contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals. Bioremediation is not yet commonly applicable for treatment of inorganic contaminants.

The rate at which microorganisms degrade contaminants is influenced by the specific contaminants present; oxygen supply; moisture; nutrient supply; pH; temperature; the availability of the contaminant to the microorganism (clay soils can adsorb contaminants making them unavailable to the microorganisms); the concentration of the contaminants (high concentrations may be toxic to the microorganism); the presence of substances toxic to the microorganism, e.g., mercury; or inhibitors to the metabolism of the contaminant. These parameters are discussed briefly in the following paragraphs.

Oxygen level in ex situ applications is easier to control than in in situ applications and is typically maintained by mechanical tilling, venting, or sparging.

Anaerobic conditions may be used to degrade highly chlorinated contaminants. This can be followed by aerobic treatment to complete biodegradation of the partially dechlorinated compounds as well as the other contaminants.

Water serves as the transport medium through which nutrients and organic constituents pass into the microbial cell and metabolic waste products pass out of the cell. Moisture levels in the range of 20% to 80% generally allow suitable biodegradation in soils.

Nutrients required for cell growth are nitrogen, phosphorous, potassium, sulfur, magnesium, calcium, manganese, iron, zinc, and copper. If nutrients are not available in sufficient amounts, microbial activity will stop. Nitrogen and phosphorous are the nutrients most likely to be deficient in the contaminated environment and thus are usually added to the bioremediation system in a useable form (e.g., as ammonium for nitrogen and as phosphate for phosphorous).

pH affects the solubility, and consequently the availability, of many constituents of soil, which can affect biological activity. Many metals that are potentially toxic to microorganisms are insoluble at elevated pH; therefore, elevating the pH of the treatment system can reduce the risk of poisoning the microorganisms.

Temperature affects microbial activity in the treatment unit. The biodegradation rate will slow with decreasing temperature; thus, in northern climates bioremediation may be ineffective during part of the year unless it is carried out in a climate-controlled facility. The microorganisms remain viable at temperatures below freezing and will resume activity when the temperature rises. Too high a temperature can be detrimental to some microorganisms, essentially sterilizing the soil. Compost piles require periodic tilling to release self-generated heat.

Temperature also affects nonbiological losses of contaminants mainly through the volatilization of contaminants at high temperatures. The solubility of contaminants typically increases with increasing temperature; however, some hydrocarbons are more soluble at low temperatures than at high temperatures. Additionally, oxygen solubility decreases with increasing temperature. Temperature is more easily controlled ex situ than in situ.

Bioaugmentation involves the use of cultures that have been specially bred for degradation of a variety of contaminants and sometimes for survival under unusually severe environmental conditions. Sometimes microorganisms from the remediation site are collected, separately cultured, and returned to the site as a means of rapidly increasing the microorganism population at the site. Usually an attempt is made to isolate and accelerate the growth of the population of natural microorganisms that preferentially feed on the contaminants at the site. In some situations different microorganisms may be added at different stages of the remediation process because the contaminants in abundance change as the degradation proceeds. USAF research, however, has found no evidence that the use of non-native microorganisms is beneficial in the situations tested.

Cometabolism, in which microorganisms growing on one compound produce an enzyme that chemically transforms another compound on which they cannot grow, has been observed to be useful. In particular, microorganisms that degrade methane (methanotrophic bacteria) have been found to produce enzymes that can initiate the oxidation of a variety of carbon compounds.

Treatability or feasibility studies are used to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. For sites contaminated with common petroleum hydrocarbons (e.g., gasoline and/or other readily degradable compounds), it is usually sufficient to examine representative samples for the presence and level of an indigenous population of microbes, nutrient levels, presence of microbial toxicants, and soil characteristics such as pH, porosity, and moisture.

Available ex situ biological treatment technologies include biopiles, composting, landfarming, and slurry phase biological treatment. These technologies are discussed in Section 4. Completed ex situ biological treatment projects for soil, sediment, bedrock and sludge are shown inTable 3-7 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.5 Ex Situ Physical/Chemical Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of ex situ treatment is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment because of the ability to homogenize, screen, and continuously mix the soil. Ex situ treatment, however, requires excavation of soils, leading to increased costs and engineering for equipment, possible permitting, and material handling/worker exposure conditions.

Physical/chemical treatment uses the physical properties of the contaminants or the contaminated medium to destroy (i.e., chemically convert), separate, or immobilize the contamination. Chemical reduction/oxidation and dehalogenation (APEG, BCD or glycolate) are destruction technologies. Soil washing, SVE, and solvent extraction are separation techniques, and Solidification/Stabilization (S/S) is an immobilization technique.

Physical/chemical treatment is typically cost effective and can be completed in short time periods (in comparison with biological treatment). Equipment is readily available and is not engineering or energy-intensive. Treatment residuals from separation techniques will require treatment or disposal, which will add to the total project costs and may require permits.

Available ex situ physical/chemical treatment technologies include chemical extraction, chemical reduction/oxidation, dehalogenation (APEG, BCD or glycolate), separation, soil washing, and solidification/stabilization. These technologies are discussed in Section 4. Completed ex situ physical/chemical treatment projects for soil, sediment, bedrock and sludge are shown in Table 3-8 and additional information on completed demonstration projects is shown on the FRTR Web Site.

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3.6 Ex Situ Thermal Treatment for Soil, Sediment, Bedrock and Sludge

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The main advantage of ex situ treatments is that they generally require shorter time periods, and there is more certainty about the uniformity of treatment because of the ability to screen, homogenize, and continuously mix the soils. Ex situ processes, however, require excavation of soils leading to increased costs and engineering for equipment, possible permitting, and materials handling worker safety issues.

Thermal treatments offer quick cleanup times but are typically the most costly treatment group. This difference, however, is less in ex situ applications than in in situ applications. Cost is driven by energy and equipment costs and is both capital and O&M-intensive.

Thermal processes use heat to increase the volatility (separation); burn, decompose, or detonate (destruction); or melt (immobilization) the contaminants. Separation technologies include thermal desorption and hot gas decontamination. Destruction technologies include incineration, open burn/open detonation, and pyrolysis. Vitrification immobilizes inorganics and destroys some organics.

Separation technologies will have an off-gas stream requiring treatment. Destruction techniques typically have a solid residue (ash) and possibly a liquid residue (from the air pollution control equipment) that will require treatment or disposal. If the treatment is conducted on-site, the ash may be suitable for use as clean fill, or may be placed in an on-site monofill. If the material is shipped off-site for treatment, it will typically be disposed of in a landfill that may require pretreatment prior to disposal. It should be noted that for separation and destruction techniques, the residual that requires treatment or disposal is a much smaller volume than the original. Vitrification processes usually produce a slag of decreased volume compared to untreated soil because they drive off moisture and eliminate air spaces. A possible exception can occur if large quantities of fluxing agent are required to reduce the melting point of the contaminated soil.

Available ex situ thermal treatment technologies include hot gas decontamination, incineration, open burn/open detonation, pyrolysis, and thermal desorption (high and low). These technologies are discussed in Section4. Completed ex situ thermal treatment projects for soil, sediment, bedrock and sludge are shown in Table 3-9 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.7 Containment for Soil, Sediment, Bedrock and Sludge

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Containment treatments are often performed to prevent, or significantly reduce, the migration of contaminants in soils or ground water. Containment is necessary whenever contaminated materials are to be buried or left in place at a site. In general, containment is performed when extensive subsurface contamination at a site precludes excavation and removal of wastes because of potential hazards, unrealistic cost, or lack of adequate treatment technologies.

Containment treatments offer quick installation times and are typically a low to moderate cost treatment group. Unlike ex situ treatment groups, containment does not require excavation of soils, that lead to increased costs from engineering design of equipment, possible permitting, and material handling. However, these treatments require periodical inspections for settlement, ponding of liquids, erosion, and naturally occurring invasion by deep-rooted vegetation. Additionally, ground water monitoring wells, associated with the treatments, need to be periodically sampled and maintained. Even with these long-term requirements containment treatments usually are considerably more economical than excavation and removal of the wastes.

Containment treatments for soil, sediment, bedrock and sludge include landfill cap and landfill cap enhancements. These treatments are discussed in more detail in Section 4. Completed projects for other treatment technologies for soil, sediment, bedrock and sludge are shown in Table 3-10.

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3.8 Other Treatment Technologies for Soil, Sediment, Bedrock and Sludge

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Other treatment technologies for soil, sediment, bedrock and sludge include excavation, retrieval, and off-site disposal. These treatments are discussed in more detail in Section 4. Completed projects for other treatment technologies for soil, sediment, and sludge are shown in Table 3-11.

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3.9 In Situ Biological Treatment for Ground Water, Surface Water, and Leachate

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The main advantage of in situ treatment is that it allows ground water to be treated without being brought to the surface, resulting in significant cost savings. In situ treatment, however, generally requires longer time periods, and there is less certainty about the uniformity of treatment because of the variability in aquifer characteristics and because the efficacy of the process is more difficult to verify.

Bioremediation techniques are destruction techniques directed toward stimulating the microorganisms to grow and use the contaminants as a food and energy source by creating a favorable environment for the microorganisms. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms adapted for degradation of the specific contaminants are applied to enhance the process.

Biological processes are typically implemented at low cost. Contaminants are destroyed and little to no residual treatment is required. Some compounds, however, may be broken down into more toxic by-products during the bioremediation process (e.g., TCE to vinyl chloride). In in situ applications, these by-products may be mobilized in ground water if no control techniques are used. Typically, to address this issue, bioremediation will be performed above a low permeability soil layer and with ground water monitoring wells downgradient of the remediation area. This type of treatment scheme requires aquifer and contaminant characterization and may still require extracted ground water treatment.

Although not all organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate ground water contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals. Bioremediation has no expected effect on inorganic contaminants.

The rate at which microorganisms degrade contaminants is influenced by the specific contaminants present; temperature; oxygen supply; nutrient supply; pH; the availability of the contaminant to the microorganism (clay soils can adsorb contaminants making them unavailable to the microorganisms); the concentration of the contaminants (high concentrations may be toxic to the microorganism); the presence of substances toxic to the microorganism, e.g., mercury; or inhibitors to the metabolism of the contaminant. These parameters are discussed in the following paragraphs.

To ensure that **oxygen** is supplied at a rate sufficient to maintain aerobic conditions, forced air, liquid oxygen, or hydrogen peroxide injection can be used. The use of hydrogen peroxide is limited because at high concentrations (above 100 ppm, 1,000 ppm with proper acclimation), it is toxic to microorganisms. Also, hydrogen peroxide tends to decompose into water and oxygen rapidly in the presence of some constituents, thus reducing its effectiveness.

Anaerobic conditions may be used to degrade highly chlorinated contaminants. This can be followed by aerobic treatment to complete biodegradation of the partially dechlorinated compounds as well as the other contaminants.

Nutrients required for cell growth are nitrogen, phosphorous, potassium, sulfur, magnesium, calcium, manganese, iron, zinc, and copper. If nutrients are not available in sufficient amounts, microbial activity will stop. Nitrogen and phosphorous are the nutrients most likely to be deficient in the contaminated environment and thus are usually added to the bioremediation system in a useable form (e.g., as ammonium for nitrogen and as phosphate for phosphorous). Phosphates are suspected to cause soil plugging as a result of their reaction with minerals, such as iron and calcium. They form stable precipitates that fill the pores in the soil and aquifer.

pH affects the solubility, and consequently the availability, of many constituents of soil, which can affect biological activity. Many metals that are potentially toxic to microorganisms are insoluble at elevated pH; therefore, elevating the pH of the treatment system can reduce the risk of poisoning the microorganisms.

Temperature affects microbial activity in the environment. The biodegradation rate will slow with decreasing temperature; thus, in northern climates bioremediation may be ineffective during part of the year unless it is carried out in a climate-controlled facility. The microorganisms remain viable at temperatures below freezing and will resume activity when the temperature rises.

Provisions for heating the bioremediation site, such as use of warm air injection, may speed up the remediation process. Too high a temperature, however, can be detrimental to some microorganisms, essentially sterilizing the aquifer.

Temperature also affects nonbiological losses of contaminants mainly through the evaporation of contaminants at high temperatures. The solubility of contaminants typically increases with increasing temperature; however, some hydrocarbons are more soluble at low temperatures than at high temperatures. Additionally, oxygen solubility decreases with increasing temperature.

Bioaugmentation involves the use of cultures that have been specially bred for degradation of a variety of contaminants and sometimes for survival under unusually severe environmental conditions. Sometimes microorganisms from the remediation site are collected, separately cultured, and returned to the site as a means of rapidly increasing the microorganism population at the site. Usually an attempt is made to isolate and accelerate the growth of the population of natural microorganisms that preferentially feed on the contaminants at the site. In some situations different microorganisms may be added at different stages of the remediation process because the contaminants change in abundance as the degradation proceeds. USAF research, however, has found no evidence that the use of non-native microorganisms is beneficial in the situations tested.

Cometabolism, in which microorganisms growing on one compound produce an enzyme that chemically transforms another compound on which they cannot grow, has been observed to be useful. In particular, microorganisms that degrade methane (methanotrophic bacteria) have been found to produce enzymes that can initiate the oxidation of a variety of carbon compounds.

Treatability or feasibility studies may be performed to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. For sites contaminated with common petroleum hydrocarbons (e.g., gasoline and/or other readily degradable compounds), it is usually sufficient to examine representative samples for the presence and level of an indigenous population of microbes, nutrient levels, presence of microbial toxicants, and aquifer characteristics.

Available in situ biological treatment technologies include enhanced biodegradation (nitrate and oxygen enhancement with either air sparging or hydrogen peroxide (H_2O_2)), natural attenuation, and phytoremediation of organics. These technologies are discussed in Section 4. Completed in situ biological treatment projects for ground water, surface water, and leachate are shown in Table 3-12 and additional information on completed demonstration projects are shown on the FRTR Web Site.

Implementation of biological treatment in vadose zone soils differs from that of soils below the water table largely in the mechanism of adding required supplemental materials, such as oxygen and nutrients. For saturated soils, nutrients may be added with and carried by reinjected ground water. Oxygen can be provided by sparging or by adding chemical oxygen sources such as hydrogen peroxide. Surface irrigation may be used for vadose zone soils. Bioventing oxygenates vadose zone soils by drawing air through soils using a network of vertical wells.

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3.10 In Situ Physical/Chemical Treatment for Ground Water, Surface Water and Leachate

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The main advantage of in situ treatments is that they allow ground water to be treated without being brought to the surface, resulting in significant cost savings. In situ processes, however, generally require longer time periods, and there is less certainty about the uniformity of treatment because of the variability in aquifer characteristics and because the efficacy of the process is more difficult to verify.

Physical/chemical treatment uses the physical properties of the contaminants or the contaminated medium to destroy (i.e., chemically convert), or separate the contamination. Passive treatment walls separate and destroy the contaminant from in situ ground water. Air sparging, directional wells, dual phase extraction, fluid/vapor extraction, and hot water or steam flushing/stripping are separation techniques.

Available in situ physical/chemical treatment technologies include air sparging, bioslurping, directional wells, dual phase extraction, thermal treatment, hydrofracturing, in-well air stripping, and passive/reactive treatment walls. These treatment technologies are discussed in Section 4. Completed in situ physical/chemical treatment projects for ground water, surface water, and leachate are shown in Table 3-13 and additional information on completed demonstration projects are shown on the FRTR Web Site. Physical/chemical treatment is typically cost effective and can be completed in short time periods (in comparison with biological treatment). Equipment is readily available and is not engineering or energy-intensive. Treatment residuals from separation techniques will require treatment or disposal, which will add to the total project costs and may require permits.

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3.11 Ex Situ Biological Treatment for Groundwater, Surface Water, and Leachate

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The main advantage of ex situ treatment is that it generally requires shorter time periods, and there is more certainty about the uniformity of treatment because of the ability to monitor and continuously mix the groundwater. However, ex situ treatment requires pumping of groundwater, leading to increased costs and engineering for equipment, possible permitting, and material handling.

Bioremediation techniques are destruction techniques directed toward stimulating the microorganisms to grow and use the contaminants as a food and energy source by creating a favorable environment for the microorganisms. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms adapted for degradation of the specific contaminants are applied to enhance the process.

Biological processes are typically implemented at low cost. Contaminants are destroyed and little to no residual treatment is required; however, some compounds may be broken down into more toxic by-products during the bioremediation process (e.g., TCE to vinyl chloride). An advantage over the in situ applications is that in ex situ applications, these by-products are contained in the treatment unit until nonhazardous end-products are produced.

Although not all organic compounds are amenable to bioremediation, techniques have been successfully used to remediate soils, sludges, and groundwater contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals.

The rate at which microorganisms degrade contaminants is influenced by the specific contaminants present; temperature; oxygen supply; nutrient supply; pH; the availability of the contaminant to the microorganism (clay soils can adsorb contaminants making them unavailable to the microorganisms); the concentration of the contaminants (high concentrations may be toxic to the microorganism); the presence of substances toxic to the microorganism, e.g., mercury; or inhibitors to the metabolism of the contaminant. These parameters are discussed briefly in the following paragraphs.

Oxygen level in ex situ applications is easier to control than in in situ applications and is typically maintained by mechanical mixing or air sparging.

Anaerobic conditions may be used to degrade highly chlorinated contaminants. This can be followed by aerobic treatment to complete biodegradation of the partially dechlorinated compounds as well as the other contaminants.

Nutrients required for cell growth are nitrogen, phosphorous, potassium, sulfur, magnesium, calcium, manganese, iron, zinc, and copper. If nutrients are not available in sufficient amounts, microbial activity will stop. Nitrogen and phosphorous are the nutrients most likely to be deficient in the contaminated environment and thus are usually added to the bioremediation system in a useable form (e.g., as ammonium for nitrogen and as phosphate for phosphorous).

pH affects the solubility, and consequently the availability, of many constituents of soil, which can affect biological activity. Many metals that are potentially toxic to microorganisms are insoluble at elevated pH; therefore, elevating the pH of the treatment system can reduce the risk of poisoning the microorganisms.

Temperature affects microbial activity in the treatment unit. The biodegradation rate will slow with decreasing temperature; thus, in northern climates bioremediation may be ineffective during part of the year unless it is carried out in a climate-controlled facility. The microorganisms remain viable at temperatures below freezing and will resume activity when the temperature rises. Too high a temperature can be detrimental to some microorganisms, essentially sterilizing the soil.

Temperature also affects nonbiological losses of contaminants mainly through the volatilization of contaminants at high temperatures. The solubility of contaminants typically increases with increasing temperature; however, some hydrocarbons are more soluble at low temperatures than at high temperatures. Additionally, oxygen solubility decreases with increasing temperature. Temperature is more easily controlled ex situ than in situ.

Bioaugmentation involves the use of cultures that have been specially bred for degradation of a variety of contaminants and sometimes for survival under unusually severe environmental conditions. Sometimes microorganisms from the remediation site are collected, separately cultured, and returned to the site as a means of rapidly increasing the microorganism population at the site. Usually an attempt is made to isolate and accelerate the growth of the population of natural microorganisms that preferentially feed on the contaminants at the site. In some situations different microorganisms may be added at different stages of the remediation process because the contaminants in abundance change as the degradation proceeds. USAF research, however, has found no evidence that the use of non-native microorganisms is beneficial in the situations tested.

Cometabolism, in which microorganisms growing on one compound produce an enzyme that chemically transforms another compound on which they cannot grow, has been observed to be useful. In particular, microorganisms that degrade methane (methanotrophic bacteria) have been found to produce enzymes that can initiate the oxidation of a variety of carbon compounds.

Treatability or feasibility studies are used to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. For sites contaminated with common petroleum hydrocarbons (e.g., gasoline and/or other readily degradable compounds), it is usually sufficient to examine representative samples for the presence and level of an indigenous population of microbes, nutrient levels, presence of microbial toxicants, and soil characteristics such as pH, porosity, and moisture.

Available ex situ biological treatment technologies are bioreactors and constructed wetlands. These technologies are discussed in Section 4. Completed ex situ biological treatment projects for groundwater, surface water, and leachate are shown in Table 3-14 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.12 Ex Situ Physical/Chemical Treatment for Ground Water, Surface Water, and Leachate

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The main advantage of ex situ treatment is that it generally requires shorter time periods, and there is more certainty about the uniformity of treatment because of the ability to monitor and continuously mix the ground water. Ex situ treatment, however, requires pumping of ground water, leading to increased costs and engineering for equipment, possible permitting, and material handling.

Physical/chemical treatment uses the physical properties of the contaminants or the contaminated medium to destroy (i.e., chemically convert), separate, or contain the contamination. UV oxidation is a destruction technology, and all other technologies included in this subsection are separation technologies.

Physical/chemical treatment is typically cost effective and can be completed in short time periods (in comparison with biological treatment). Equipment is readily available and is not engineering or energy-intensive. Treatment residuals from separation techniques will require treatment or disposal, which will add to the total project costs and may require permits.

Available ex situ physical/chemical treatment technologies include adsorption/absorption, advanced oxidation processes, air stripping, granulated activated carbon (GAC)/liquid phase carbon adsorption, ground water pumping, ion exchange, precipitation/coagulation/ flocculation, separation, sprinkler irrigation. These technologies are discussed in Section 4. Completed ex situ physical/chemical treatment projects for ground water, surface water, and leachate are shown in Table 3-15 and additional information on completed demonstration projects are shown on the FRTR Web Site.

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3.13 Containment for Ground Water, Surface Water, And Leachate

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Containment measures are often performed to prevent, or significantly reduce, the migration of contaminants in soils or ground water. Containment is necessary whenever contaminated materials are to be buried or left in place at a site. In general, containment is performed when extensive subsurface contamination at a site precludes excavation and removal of wastes because of potential hazards and/or unrealistic cost.

The main advantage of containment methods is that they can prevent further migration of contaminant plumes, and allow for contaminant reduction at sites where the source is undetermined, inaccessible, or where long term remedial actions are being developed. Unlike ex situ treatment groups, containment does not require excavation of contaminated soils, which leads to increased costs from engineering design of equipment, possible permitting, and material handling. However, these treatments require periodical inspections for leaks, ponding of liquids, and corrosion. Additionally, ground water monitoring wells, associated with the treatments, need to be periodically sampled and monitored.

Available containment technologies include physical/biological barriers and deep well injection. These processes are discussed in Section4. Completed containment for ground water, surface water, and leachate projects are shown in Table 3-16.

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3.14 Air Emissions/Off-Gas Treatment

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A number of technologies have been widely applied for removal of VOCs from off-gas streams. However, the application of these technologies to off-gases from site remediation may be quite limited. Biofiltration has been widely applied for VOC destruction in Europe and Japan, but it has only recently been used in the United States. Catalytic and thermal oxidation are widely used for the destruction of gas-phase VOCs in U.S. industry, yet have only limited applications to site remediation of off-gases. Vapor phase carbon adsorption has been the VOC removal technology most commonly used for site remediation off-gases. Carbon adsorption, however, does not destroy the VOCs, so that additional destruction or disposal is required. The following factors may affect the effectiveness and cost of the various technologies: VOC concentration, VOC species, presence of halogenated VOCs, presence of catalyst poisons, particulate loading, moisture content, gas flow rate, and ambient temperature.

Available air emissions/off-gas treatment technologies include biofiltration, high energy destruction, membrane separation, nonthermal plasma, oxidation, scrubbers, and vapor phase carbon adsorption. These processes are discussed in Section 4 . Completed air emissions/off-gas treatment projects are shown in Table 3-17.