

## VI.10

# Hazardous waste site remediation technology selection

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### VI.10.1. Introduction

Hazardous materials may exist in air, water or soil media and may require treatment, management or disposal relevant to any one of the media. A spill of hazardous material, for example, may affect all three at one time. This chapter deals with selection of technologies for use in site remediation, either for cleanup of areas contaminated with improperly disposed wastes or materials, or for cleanup of sites which are authorized or permitted to dispose of hazardous wastes and materials commercially.

There are a number of possible techniques that may be used to guide the selection of technology for waste treatment or management. There are tens of thousands of chemical compounds, hundreds of different wastes and hazardous materials and dozens of possible treatment processes and technologies applicable to disposal, treatment and management. If it was necessary to examine all possible permutations and combinations of compounds, wastes and technologies, an assessment of millions of options would be required to develop a plan to successfully cleanup a site. The problem is not nearly that complicated, since we may be guided by the experience of past applications of technology, the likelihood that some technologies may work for organics and others for inorganics, and by the fact that technologies must be applied in given sequences, some acting as pretreatment for others that follow in the sequence.

Nevertheless, even after reducing considerably the number of possibilities using the three simplifying strategies mentioned above, the task may be a formidable one. The approach used herein is based on following a number of steps toward developing a treatment or disposal strategy starting with initial data and information about the problem.

One broadly applicable technique for technology selection can be based on a straightforward logic process incorporating the following:

- a) the characteristics of the various constituents in the waste,
- b) the specific "purpose" of different remediation technologies,
- c) inherent restrictions in the applicability of each technology and
- d) the specific "cleanup objectives" for the site.

Using this approach, available technologies can be viewed in terms of their functional purpose, i.e. whether their operation achieves one of the following:

- separation
- detoxification/destruction or
- immobilization.

In this tripole context therefore, air stripping, chemical precipitation and soil washing each are examples of separation technologies; chemical dehalogenation and incineration are examples of detoxification or destruction technologies; vitrification is an example of an immobilization technology. Separation technologies may be chosen when the need is to separate contaminants from contaminated media or when the need is to separate contaminants, from each other, especially in those cases where one type of contaminant causes interferences in a technology otherwise suitable for the contaminant mix present. Destruction/detoxification techniques are chosen when all requisite separations have been achieved and a treatable stream of contaminants is available for final destruction or detoxification. Immobilization technologies are used when no remaining destruction/detoxification techniques are appropriate and yet some waste constituents remain whose movement from emplacement must be restricted.

One can then initially select candidate technologies aimed at achieving a specific purpose, i.e. separation, destruction/detoxification or immobilization. Then, using the physical characteristics of the waste constituents (e.g. octanol–water partition coefficient, Henry’s law coefficient, water solubility, heat content, etc.), the probable effectiveness of the technology may be estimated. If however, some site characteristic exists, which restricts the use of a specific technology, there is no need to retain such a candidate through the detailed evaluation process. Finally, any candidate technology when evaluated should either meet or move toward the cleanup objectives for the site. Applied remediation strategies will incorporate several technologies in sequence, with following technologies further treating the effluents of earlier technologies until all objectives are met in all media. The technique presented herein follows this logic approach.

## **VI.10.2. Hazardous waste treatment**

### ***VI.10.2.1. Hazardous wastes***

The United States Environmental Protection Agency (EPA) has specifically “listed” wastes as hazardous, based on their toxicity, reactivity, corrosivity and ignitability, as measured against specified criteria identified in the Code of Federal Regulations (CFR). Detailed explanations for these wastes are contained in Listing Background Documents. The listing documents are organized as: (i) the EPA basis for listing the waste or waste stream, (ii) a brief description of the industries generating the listed waste stream, (iii) a description of the manufacturing process or other activity that generates the waste, and identification of waste composition, constituent concentrations and annual quantities generated, (iv) a summary of the adverse health effects of each of the waste constituents of concern and (v) a summary of case histories and damage done by the waste. The listed hazardous wastes consist of wastes from non-specific sources (F code), wastes from specific sources (K code) and commercial products (U and P code).

Some of the most commonly found contaminants at hazardous waste sites include *organics* (e.g. VOCs, SVOCs, fuels, etc.), *inorganics* and *explosives*. Organic compounds comprise many classes, including chlorinated solvents, e.g. trichloroethylene (TCE), 1,1,1-trichloroethane (TCA), carbon tetrachloride, dichloroethylene (DCE), methylene chloride, perchloroethylene (PCE), chloroform; fuel constituents such as BTEXs (benzene, toluene, ethyl benzene and xylenes), *n*-alkanes, and substituted alkanes, alkenes and aromatics; polychlorinated biphenyls (PCBs); phenol; pentachlorophenol (PCP); polycyclic aromatic hydrocarbons (PAHs); and pesticides and herbicides (e.g. DDT, chlordane, lindane and dieldrin). Inorganics include toxic metals (e.g. arsenic, cadmium, chromium, copper, lead and zinc), radionuclides and other contaminants, such as asbestos and cyanide. Explosives follow treatment techniques typically applicable to SVOCs and include di- and trinitrotoluene (DNT and TNT), and RDX. Choice of treatment technology for wastes containing one or more of these classes of compounds or other hazardous waste constituents depends on the media (soil, groundwater, surface water, leachate, liquid, air, industrial stream) and other relevant properties (physical, chemical, biological) of the waste media. In the absence of established techniques or historical experience, treatability studies are carried out to determine (i) whether the waste is amenable to the treatment process(es); (ii) what pretreatment, if any, is required; (iii) the optimal process conditions needed to achieve the desired treatment; (iv) the efficiency of a treatment process and (v) the characteristics and volumes of residuals from a particular treatment process.

In this section, a brief overview of some of the commonly used techniques for hazardous waste treatment, and their applications are provided.

The hazardous waste treatment processes can be classified in the following categories:

1. Separation including physical and chemical,
2. Destruction/detoxification including chemical, biological, thermal,
3. Immobilization including chemical or thermal, solidification/stabilization (S/S).

#### **VI.10.2.2. Physical separation processes**

In these techniques, physical characteristics are used as means to *separate* or *concentrate* waste constituents. Separation or concentration of target species can be accomplished by affecting or utilizing the changes in *phase* (evaporation, distillation, steam or air stripping), *density* (sedimentation, centrifugation, flocculation, dissolved air floatation), *solubility* (extraction, soil washing, chelation), *adsorptivity* (granulated or powdered activated carbon adsorption), *size* (filtration, reverse osmosis) or *ionic characteristics* (ion exchange, electrodialysis). Some of the commonly used physical processes are briefly described below.

- *Air stripping*: In a typical gas absorption unit, used for air stripping or scrubbing operations, air and water are contacted in a countercurrent fashion in a packed or plate column, as shown in Figure VI.10.1. Water is sprayed through liquid distributors from the top of the tower, while the air is pumped from the bottom. The inert packing, randomly distributed in the tower, provides a large surface area for air–water contact necessary for the mass transfer. The packing material is plastic, ceramic or porcelain, and the typical shapes are rashig rings, berl saddles, intalox and pall rings. The packing must be

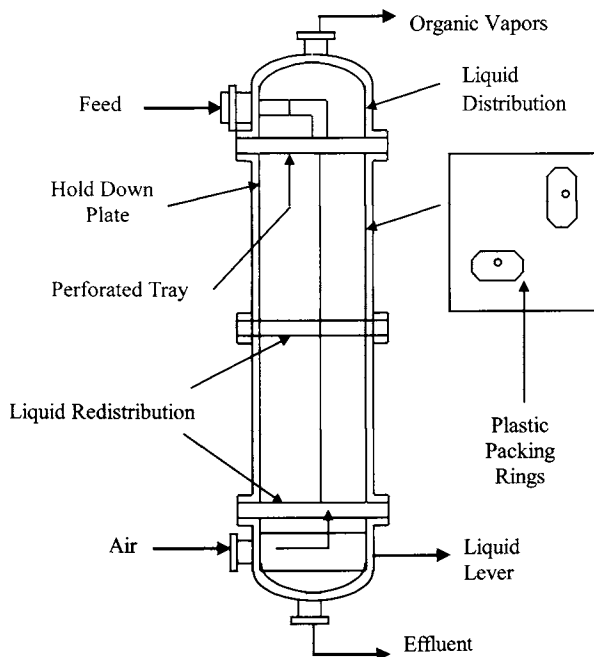


Figure VI.10.1. Schematics of air stripping/scrubbing in a typical gas absorption unit.

chemically inert, strong, lightweight, open to flow, have large surface area and inexpensive. For a given water flow rate and tower packing, there is an upper limit to the air flow rate, flooding velocity, at which the pressure drop is excessive and the column stops to operate. The tower is generally operated at about 50–60% of this flooding velocity. The water stream, leaving the tower is leaner in contaminants, while the air stream is richer in contaminants. The contaminants in the exit air can be further removed by incineration or vapor phase carbon adsorption. Over a sustained operating period of time, the packing and tower internals get clogged because of scale formation due to inorganic impurities in water and suspended solids. Scaling reduces the stripping efficiency by reducing the flow rates and mass transfer surface area, and increasing the pressure drop. Shutdown period for cleaning with appropriate solvents is included in the process design. Air stripping is applicable for low contaminant concentrations, typically less than 100 ppm (mg/kg).

The capital costs for air stripping towers are moderate, compared with other technologies. The operating costs are typically low and include packing material and electricity for pumps and blowers. Since this is a separation/removal technology, off-gases need to be treated in a later step, incurring further treatment costs.

- *Steam stripping*: This is a form of continuous fractional distillation process, in which steam is used to provide the heat instead of reboiler bottoms. The process is similar to air stripping, in the way the column is operated. Liquid feed is introduced from the top in a plate column, while steam is blown from the bottom, as shown in Figure VI.10.2. As the hot steam moves up, it picks up volatile contaminants from the downcoming water

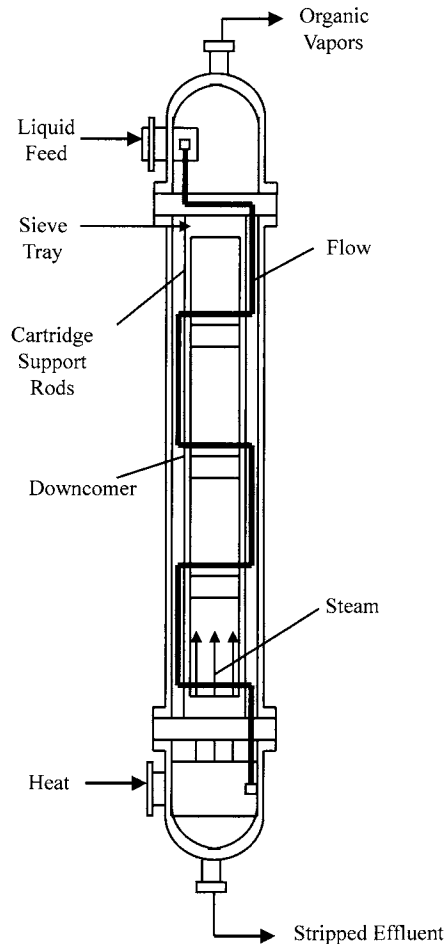


Figure VI.10.2. Steam stripping column – perforated tray type.

stream, in a countercurrent fashion. Some of the steam condenses to provide heat for the contaminant volatilization. The organic vapors in the steam effluent leave the top of the column, while the stripped effluent leaves from the bottom. Steam stripping is applicable to a wider range of organics (less volatile with b.p.  $< 150^{\circ}\text{C}$ , and more soluble) than air stripping, because of higher operating temperature. Aqueous wastes contaminated with chlorinated solvents (e.g. TCE, TCA) and aromatics (e.g. PCP), fuel aromatics (e.g. BTEXs) and alcohols (e.g. methanol) can be treated by steam stripping, over a wide concentration range, from 100 ppm (mg/kg) to 10%.

- *Carbon adsorption:* Adsorption is a surface-based process as opposed to absorption, which encounters changes at the molecular level. The contaminant transfers from the liquid or vapor phase to the surface of the solid adsorbent (e.g. activated carbon). The ratio of the concentration of the solute on the solid phase to that in the fluid phase, at equilibrium, is known as the partition coefficient and is represented as adsorption

isotherms. Organics from air and water streams are adsorbed on the external and internal surfaces of the porous particles of carbon, which provides high surface area. A typical adsorption design includes two packed adsorption columns – one on line and one being regenerated – pipes and flow control schemes for introducing liquid/gas feed, steam or inert gas inlet for spent carbon regeneration and an effluent port for treated fluid stream (Fig. VI.10.3). The flow arrangement provides for cyclic switching (operation and regeneration) between the two columns. The bed depths and flow rates are generally chosen for an adsorption cycle of 2–24 h. As the bed depth increases, the removal rates increase along with an increase in the adsorption cycle, column length, pressure drop and the cost. On the other hand, a decrease in the bed depth will lower the pressure drop and the cost, but the shallow beds (less than 1 ft = 30.48 cm) do not provide good separation and require more energy for regeneration.

Carbon adsorption may be used to treat single-phase aqueous organic phase, and gas streams contaminated with high molecular weight and boiling point organics with low solubility and polarity. A wide range of contaminants (e.g. chlorinated solvents, trihalomethanes, PCBs, PCP, pesticides, inorganics and metals) is amenable to adsorption. The suggested concentration ranges are: organics < 10,000 ppm (mg/kg); suspended solids < 50 ppm (mg/kg); dissolved inorganics, and oil and grease < 10 ppm (mg/kg) and removal rates of > 95% can typically be accomplished.

- *Distillation:* It is a process of separating by vaporization, a mixture of components into individual components or groups of components. The distillation process can be carried out in a batch mode in which feed is partially vaporized into a vapor stream, rich in

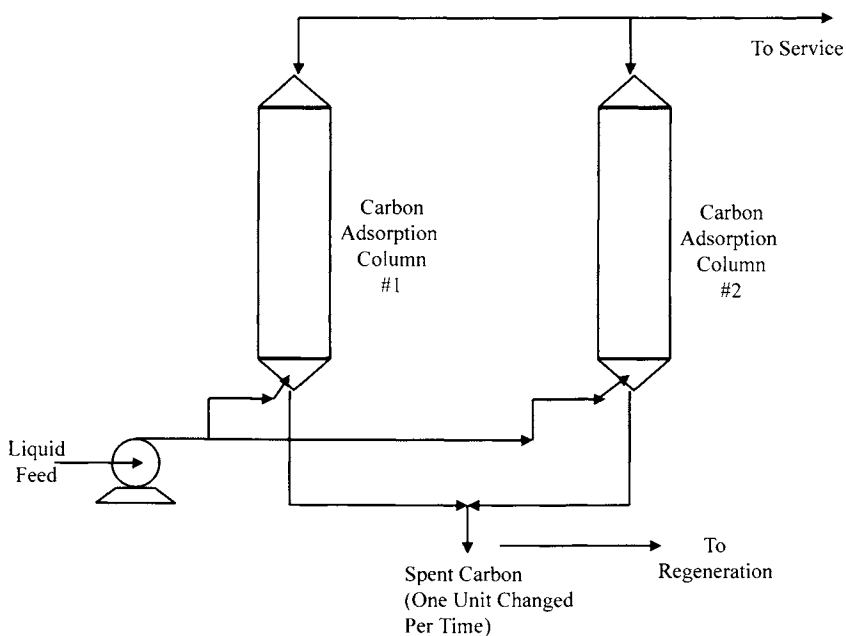


Figure VI.10.3. A typical granular activated carbon adsorption design.

more volatile component and a liquid stream, rich in the lesser volatile components. In the continuous mode, a part of the condensate from the top of the column is returned back to the top of the column where it contacts the upcoming vapor stream. Similarly, a portion of the bottoms stream is vaporized in the reboiler and sent back to the distillation column, as the upflowing vapor stream. This establishes a countercurrent system of liquid and vapor streams contacting throughout the column, establishing equilibrium at the plates, and transferring more volatile components from liquid stream to the vapor stream and lesser volatile components from the vapor stream to the liquid stream. As the vapor moves up, it gets richer and richer in the more volatile components, and the liquid, moving down, gets richer and richer in the lesser volatile components. Figure VI.10.4 shows schematics of batch (A) and continuous distillation (B) processes. Flash distillation is a process in which a portion of the liquid feed is vaporized at a reduced pressure. This results in two streams – a vapor and a liquid – in equilibrium with each other.

Distillation can be used to separate miscible organic liquids for solvent reclamation and waste volume reduction. Most organics with different volatilities can be separated from aqueous streams. Design procedures for distillation processes are outlined in detail in many chemical engineering unit operations textbooks.

- *Soil washing/flushing*: This process is aimed at extracting contaminants from soils and sludges using a liquid medium as the washing solution. The washing solution may be water, surfactants, organic solvents, chelating agents, acids or bases, depending on the type of contaminants to be removed. The process can be operated *in situ* or *ex situ*. The goal of the process is to transfer the contaminants from the solid to the liquid phase. In the post-treatment step, which may be carried out in conjunction, or separately, the contaminants are treated or removed by a chemical, biological or thermal technique.

Soil washing has been successfully applied to various organics, inorganics and heavy metals.

### VI.10.2.3. Chemical separation processes

These techniques are usually only appropriate in the liquid phase and involve the addition of specific reagents to change the oxidation state of the target contaminants, followed by pH adjustment to a condition of lower solubility for the target contaminant so that a precipitate forms. Chemical separation is usually accompanied by a physical separation process such as sedimentation or filtration.

### VI.10.2.4. Chemical detoxification/destruction processes

In these processes, molecular or structural changes are made on the target waste constituents so that the result is a detoxified form of the original molecule (e.g. dehalogenation) or the target contaminant is completely oxidized to innocuous products (e.g. oxidation of hydrocarbons to CO<sub>2</sub> and H<sub>2</sub>O). Chemical destruction/detoxification processes include *chemical hydrolysis* or *ozonolysis*, *redox reactions* (reduction or oxidation of the contaminant by various chemical agents) and *electrolytic oxidation*.

- *Precipitation/flocculation/sedimentation*: Precipitation is a physio-chemical process, based on the reduction of solubilities of inorganic species, resulting in change of phase of the species to solid. Metals can be precipitated as hydroxides or sulfides by

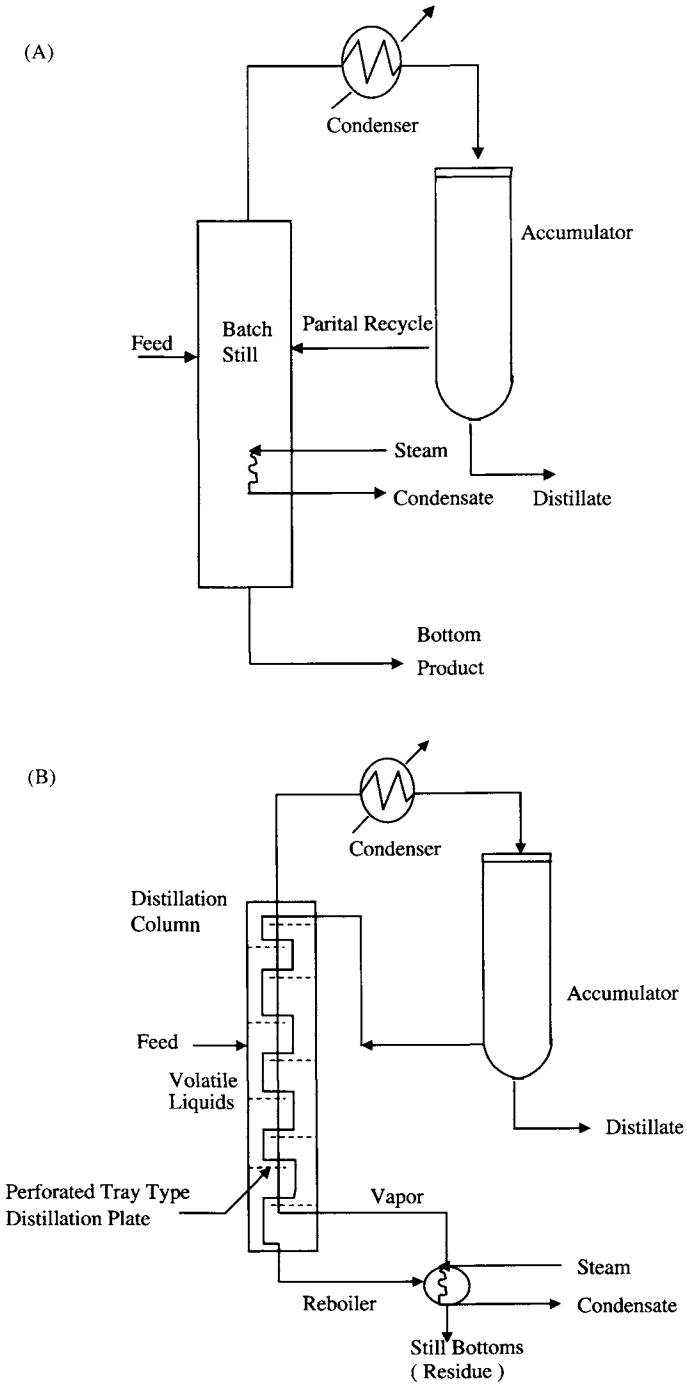


Figure VI.10.4. Schematics of batch (A) and continuous fractional distillation (B) processes.

changing pH, as shown in Figure VI.10.5. For instance, lead can be precipitated as PbS by changing the pH from 4 to 11.5; the solubility drops by seven orders of magnitude, precipitating Pb as lead sulfide. Addition of flocculating agents causes the precipitated particles to agglomerate. Agglomerated particles are separated from the liquid phase by sedimentation or filtration. Figure VI.10.6 shows a typical configuration of precipitation/flocculation/sedimentation process.

- **Neutralization:** Neutralization is the process of adjusting pH by the addition of acid or base to a mixture. It can be a treatment technology in itself, or a pretreatment step for chemical or biological treatment processes. Sulfuric acid or hydrochloric acid is generally used as acidic agents, while sodium hydroxide or limes are used as alkaline agents. The neutralization system is a simple mixing unit, with feed controls, and chemical storage units. Simultaneous neutralization of acid and caustic waste is shown in Figure VI.10.7. Acidification of certain hazardous wastes produces heat and toxic off-gases, and should be handled with caution.

- **Ion exchange:** The process is carried out in packed towers, filled with ion exchange resins (Fig. VI.10.8). The target ions from the aqueous phase are removed and substituted by the harmless ions from the resin. The resins are temperature and pH tolerant, and can be tailored specifically for particular waste applications. Ion exchange can remove a wide variety of organics, inorganics and metals. Some of the design challenges are similar to traditional packed tower mass transfer processes, e.g. absorption and adsorption, and the resin has to be regenerated periodically. Plugging and scaling problems, because of suspended solids and mineral scaling, need to be resolved in regular cleaning operations.

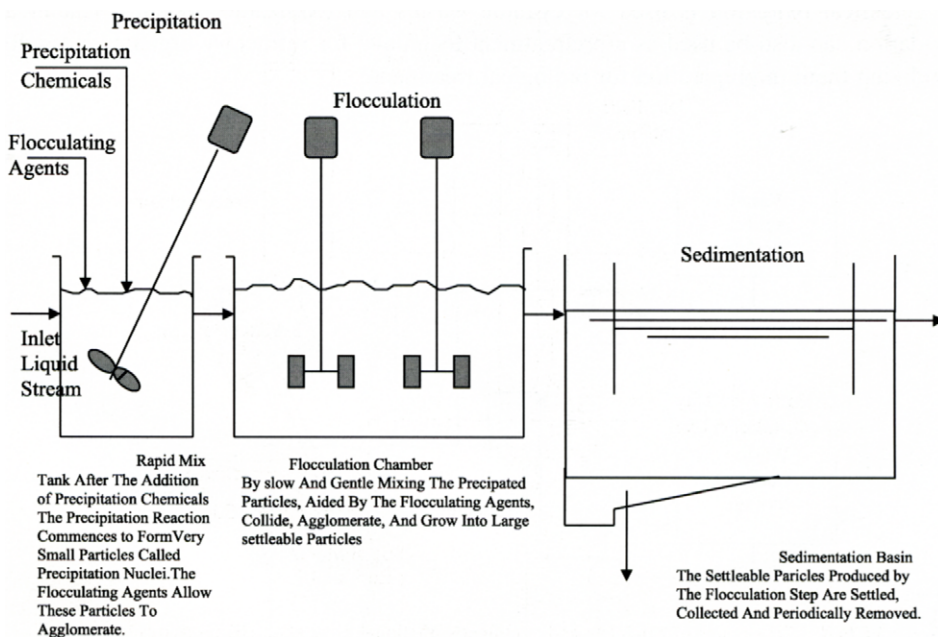


Figure VI.10.5. Schematics of chemical precipitation/flocculation/sedimentation process.

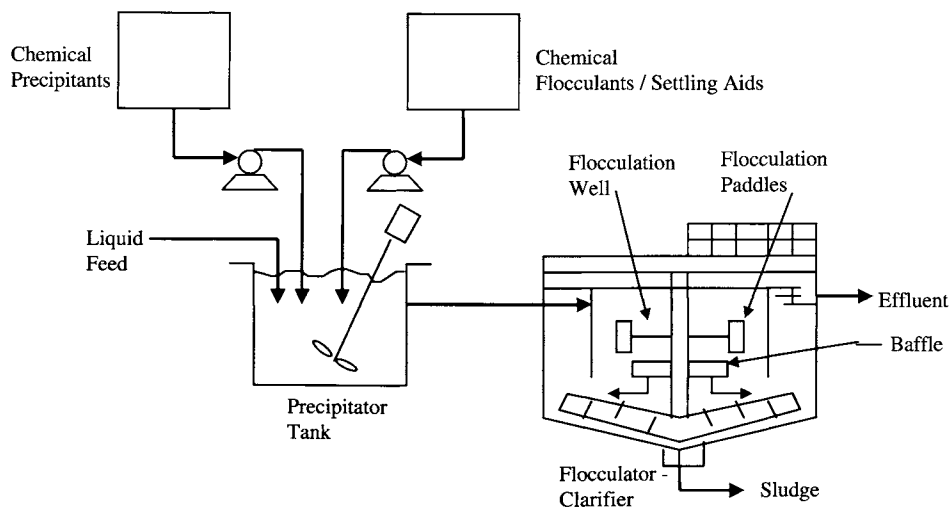


Figure VI.10.6. Typical configuration of chemical precipitation and associated flocculation/sedimentation process steps.

- **Reduction–oxidation reactions:** In redox reactions, one of the reactants is reduced while the other is oxidized. In chemical oxidation, the waste is oxidized to a higher oxidation state, a less hazardous or toxic form. Oxidation power of some common oxidants is included in Table VI.10.1.

Chemical oxidation is used for cyanide wastes and oxidizable organics. Chemical oxidation can also be used as a pretreatment technique for refractory organics, partially oxidizing them in preparation for biological treatment.

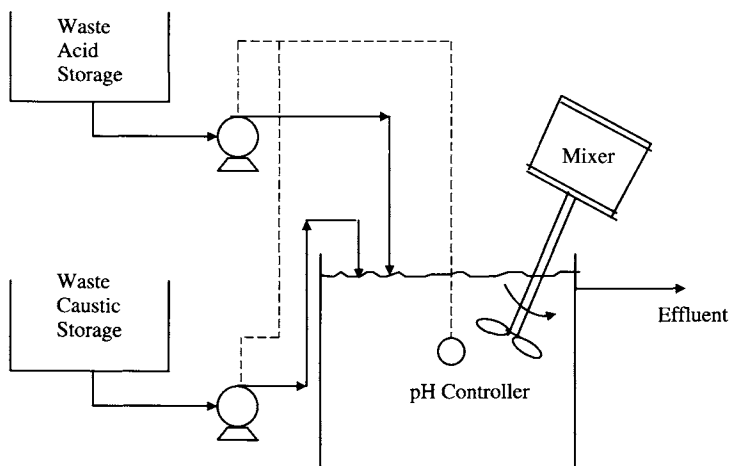


Figure VI.10.7. Simultaneous neutralization of acid and caustic waste.

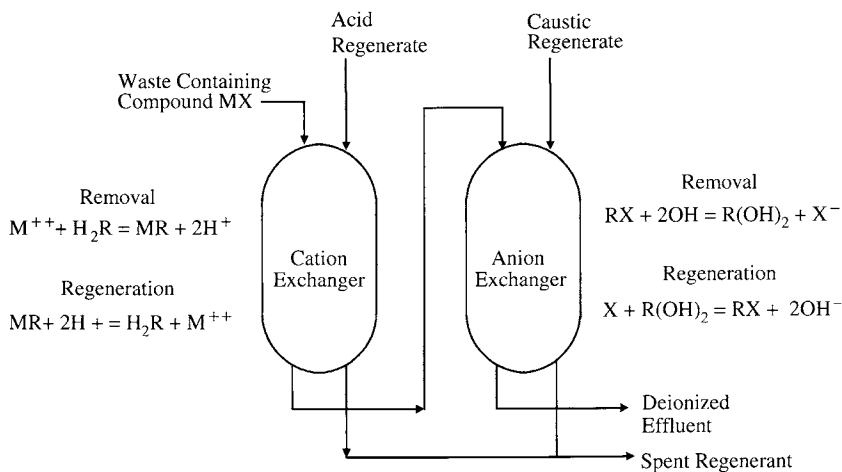
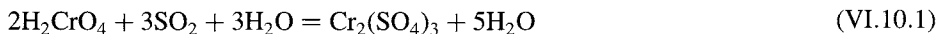


Figure VI.10.8. Schematics of the ion exchange processes.

Chemical reduction is the opposite process to chemical oxidation. Reducing agents are added to lower the oxidation state of a waste compound, e.g. addition of sulfur dioxide converts toxic  $Cr^{+6}$  to the less toxic  $Cr^{+3}$  form, as shown below:



Some common reducing agents include sulfite salts, sulfur dioxide and base metals, Fe, Al and Zn.

Table VI.10.1. Oxidation power of some oxidants.

Oxidants	Oxidation power
Fluorine	2.23
Hydroxyl radical	2.06
Atomic oxygen	1.78
Hydrogen peroxide	1.31
Perhydroxyl radical	1.25
Permanganate	1.24
Hypobromous acid	1.17
Chlorine dioxide	1.15
Hypochlorous acid	1.10
Hypoiodous acid	1.07
Chlorine (reference)	1.00
Bromine	0.80
Iodine	0.54

#### **VI.10.2.5. Biological destruction/detoxification processes**

These techniques utilize microorganisms to break down organic wastes into products such as CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> and others. Depending on the type of electron acceptor used, biological processes are classified as *aerobic* (oxygen as terminal electron acceptor) or *anaerobic* (sulfate or nitrate as terminal electron acceptor). Indigenous microorganisms, as well as specially adapted or genetically manipulated microorganisms can degrade a wide range of compounds under proper conditions of nutrients and electron acceptor concentrations.

Bioremediation techniques involve the use of naturally occurring microorganisms for contaminant degradation by providing favorable conditions for the growth of microorganisms, which in turn use contaminants as a source of food and energy. The favorable conditions for the growth of microorganisms include appropriate values of oxygen, nutrients, moisture, temperature and pH. Bioremediation can be used to remediate soils, sludges, sediments, groundwater, leachate and surface water. Biotreatment is generally applicable to a wide variety of organics – VOCs, SVOCs, fuels and explosives. A large number of sites contaminated with petroleum hydrocarbons, halogenated and non-halogenated solvents, pesticides, wood preservatives and other organic chemicals have been studied for the application of biological techniques for the destruction of hazardous wastes. Inorganics are generally not amenable to biological treatment.

#### **VI.10.2.6. Thermal destruction/detoxification processes**

These methods use high temperature under controlled conditions to change the physical, chemical or biological character or composition of the waste. An incinerator is any enclosed device using controlled flame combustion. Figure VI.10.9 shows a schematic of a rotary kiln incineration device. Thermal oxidation degrades wastes into products such as CO<sub>2</sub>, H<sub>2</sub>O, SO<sub>2</sub>, NO<sub>x</sub>, HCl, products of incomplete combustion (PICs) and ash. In general, air pollution control devices (APCDs) are required to control the release of air contaminants into the atmosphere. Thermal techniques can be used to destroy organic contaminants in all three phases (liquids, solids and gases) and various waste media – water and leachate, soils and sediments and air and off-gases. Other forms of thermal treatment include pyrolysis, microwave discharge, wet air oxidation and molten salt processes.

EPA RCRA regulations use destruction and removal efficiency (DRE) as a measure of a hazardous waste incinerator performance. Destruction applies to the waste combustion, while removal applies to the cleansing of the combustion gases in APCDs, before release to the atmosphere. Because of the complexities and potentially large number of constituents involved in a waste stream, representative hazardous compounds, called the principal organic hazardous constituents (POHCs) are selected as surrogates to determine the DRE performance of the incinerator during testing for a RCRA permit. POHCs are selected based on their high concentration in the waste feed and their high resistance to destruction compared to other waste constituents. The logic is that if the required DRE is achieved for the POHCs during testing, then the other compounds in the feed should perform at the same or better DRE values.

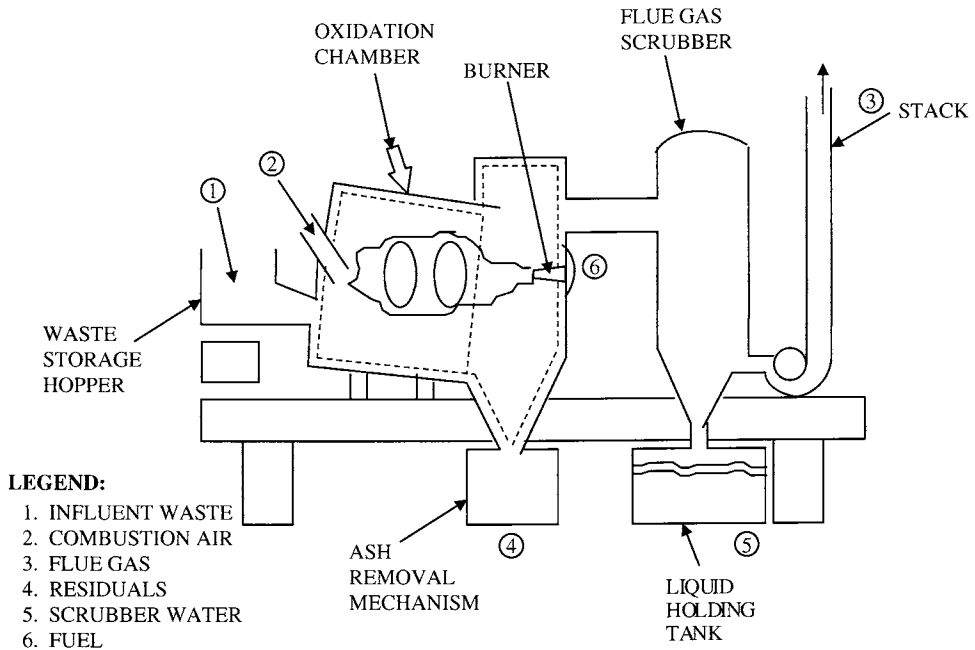


Figure VI.10.9. Schematics of a rotary kiln incineration device.

### VI.10.2.7. Immobilization

Immobilization, or more commonly S/S is a technique to immobilize hazardous contaminants within a matrix (e.g. soil, sand, glasses, building materials). Immobilization can be achieved by physical, chemical or thermal means. Contaminants are physically bound or enclosed within a solid mass of high compressive strength and low permeability (solidification); or immobilized via chemical reactions between the contaminants and stabilizing agents (stabilization). The major factors contributing to the success of a good S/S application include: (i) pH, (ii) redox potential, (iii) permeability, (iv) diffusion coefficients, (v) solubility characteristics and (vi) chemical interactions between the wastes and the binding agents. A criterion used for measuring the success of S/S is leachability testing. S/S techniques can be used alone or in conjunction with other treatment and disposal methods to yield a product for some beneficial use. This technology is typically used for inorganics and has limited effectiveness in the case of SVOCs and pesticides. Some S/S processes cause large increases, up to 100%, in the volume of the waste matrix. VOCs do not respond favorably to S/S technology. S/S methods can be categorized as follows:

- *Cement-based solidification*: The waste is directly mixed with Portland cement and incorporated into the hard cement matrix. The bonds may be physical or chemical. Over a period of time, with erosion, physical bonds may weaken, causing the leaching of contaminants. Metals are good candidates for this process, because they form insoluble

hydroxides or carbonates. However, the insolubility is highly pH dependent, and even a slightly acidic condition could cause solubility to increase, resulting in the leaching of metals. A major disadvantage of this process is that the cement–waste matrix often weighs twice as much and occupies twice as much volume as the waste itself, making it more expensive for transportation. Certain wastes (organics, some salts of Na, Mg, Sn, Cu, Pb and Zn) can cause problems with the setting, curing or stability process of cement, and are not suitable for cement-based solidification.

- *Silicate-based solidification*: These processes use siliceous material along with additives, such as lime, cement, gypsum and other settling agents. Silicate material reacts with polyvalent metal ions, and the technique is applicable to a wide range of metals and organics (waste oils and solvents). The silicate material is fly ash, blast furnace slag or soluble silicates of Na or K.
- *Thermoplastic solidification*: The waste is dried, heated and incorporated in a heated plastic matrix. The mixture is then cooled to a rigid, deformable solid. Compared to cement solidification, the rates of leaching and increase in weight and volume are significantly lower. The effects of water and microbial attack are not present. Major disadvantages include high energy usage, high equipment and processing costs, and the need for specialty equipment and highly trained labor. Some wastes are not compatible with thermoplastic solidification. They include oxidizers such as perchlorates or nitrates, which can react with the solidification materials to cause an explosion, and some solvents and greases can cause asphalt materials to soften and never become rigid.
- *Encapsulation*: Waste material is mixed and churned with polymeric materials, physically encapsulating waste by sealing them in an organic binder or resin. An advantage of this approach is that the waste is completely isolated from leaching solutions. Depending on the size of the resulting particles, these are called, micro-encapsulated or macro-encapsulated. Organic as well as inorganic wastes can be encapsulated. Some disadvantages of the process include high cost, skilled labor needs and high energy requirements.
- *Vitrification*: Wastes are combined with molten glass at temperatures above 1350°C, and the melt is then cooled into a stable, non-crystalline solid. This can be a very expensive process and therefore limited to the worst wastes – radioactive and highly toxic.

#### **VI.10.2.8. Site remediation**

Hazardous waste site remediation can be very complex and involves treatment of contaminants in various media. These media include groundwater or aqueous phase, soil, gaseous phase in the unsaturated zone and immiscible phase. For instance, VOCs can dissolve in groundwater in both saturated zone and unsaturated zone, and exist as soluble organic contaminants up to their solubility limits. VOCs can also adsorb as liquid, on the soil particles in both saturated and unsaturated zones. In the unsaturated zone, VOCs can also exist as vapors at concentrations which are dependent on the Henry's law coefficient and the vapor pressure of the particular VOC. Additionally, due to the capillary action in the porous media of the unsaturated zone and the up and down movement of the water table, organic contaminants can exist as isolated blobs or globules in the pore space, and

not as a continuous phase. In this form, organic phase exists as non-aqueous phase liquids (NAPLs). If the organic phase has a specific gravity greater than unity (denser than water), it is known as DNAPL, and conversely, if it is lighter than water, it is called LNAPL. Once they are released from the interfacial forces of soil pores, NAPLs move downwards toward the groundwater or aquifers. NAPLs dissolve in water up to the solubility limit and the excess DNAPLs sink to the bottom while LNAPLs float on the surface. These “sinker” DNAPLs and “floater” LNAPLs stay in the water and cause a long-term continuous source of contamination in the groundwater. Continuous leaching or desorption of organics from the soil particles and dissolution of DNAPLs and LNAPLs in the groundwater cause most “pump and treat” techniques for groundwater to fail and/or require years of continuous or intermittent action. Inorganics and SVOCs may not exist in the vapor phase to the same extent as VOCs.

An overview of various options in media, mode, remedial action and types of contaminants encountered at a hazardous waste site is presented in Figure VI.10.10.

**VI.10.2.9. Permitting – treatment goals and criteria**

There are goals and criteria that determine the selection of a treatment technology for a particular application. The basic question one must ask is “how clean is clean”. The answer may vary depending on the perspective of the stakeholder – principal responsible parties (PRPs) for cleanup, regulators, community and other interested parties such as insurance companies, banks and environmental organizations. For a typical CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act, commonly

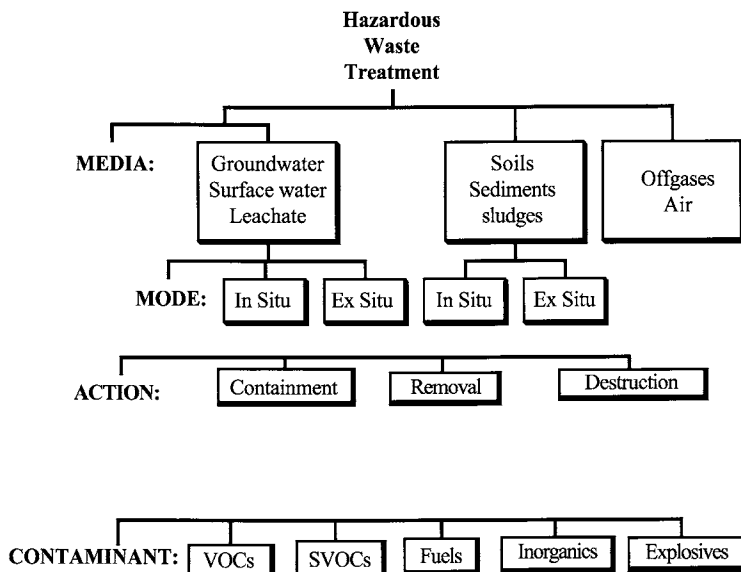


Figure VI.10.10. Hazardous waste treatment: an overview of mode and kind of remedial action and types of contaminants encountered at a hazardous waste site in different media.

known as Superfund), site remediation process, a Preliminary Assessment/Site Investigation (PA/SI) is undertaken to identify areas needing further investigation. A subsequent Remedial Investigation/Feasibility Study (RI/FS) is carried out to determine the nature and extent of contamination, and evaluate and select a remedy. After negotiations, based on technical and economic feasibility, and other factors, permits are issued and Record of Decision (ROD) signed between the PRPs and the regulating agencies for cleanup of the contaminated media. A Remedial Design/Remedial Action (RD/RA) is instituted to design and implement the chosen remedy. A similar corrective action process for RCRA (Resource Conservation and Recovery Act) facilities also exists.

EPA's general operating requirements for the treatment technique and units require that they must be located, designed, constructed, operated, maintained and closed in a manner that will ensure protection of human health and the environment. Conditions must be included for appropriate design and operating requirements, detection and monitoring requirements and requirements for responses to release of hazardous waste or constituents from the unit. To meet the performance standards, the principal hazardous substance migration pathways (groundwater, surface water, wetlands, air and soil) must be protected.

*Factors for the protection of groundwater and subsurface pathways:*

1. Physical and chemical characteristics, and volume of the waste.
2. Patterns for land use in the region.
3. Hydrogeological characteristics of the site.
4. Potential for damage to food-chain crops, wildlife, vegetation, physical structures and domestic animals.

*Factors for the protection of surface water, wetlands and surface soil pathways:*

1. Physical and chemical characteristics, and volume of the waste.
2. Existing quality of surface water and soil.
3. Current and potential surface water and land use in the nearby area.
4. Hydrology and surrounding topography of the site.
5. Proximity to surface water.
6. Operating characteristics, and effectiveness and reliability of systems and structures that contain, confine and collect migrating substances.
7. Potential for damage to food-chain crops, wildlife, vegetation, physical structures and domestic animals.

*Factors for the protection of the air pathway:*

1. Physical and chemical characteristics, and volume of the waste, including its potential to emit gases, aerosols and particulates.
2. Existing quality of air.
3. Atmospheric, meteorological and topographic characteristics of the surrounding area.
4. Operating characteristics including the effectiveness and reliability of systems and structures to reduce or prevent emissions of hazardous wastes or constituents to the air.
5. Potential for damage to food-chain crops, wildlife, vegetation, physical structures and domestic animals.

### VI.10.2.10. Mode of treatment

Hazardous waste site remediation can be attempted either *in situ* (in place, without excavation) or *ex situ*. The mode of treatment is very site specific and depends on the site characteristics and the extent of contamination, contaminant type and concentrations, level of cleanup desired and future use, treatment technology and costs.

#### VI.10.2.10.1. *In situ* treatment

The main advantage of *in situ* treatment is that it can save the time, effort and money required for excavation and transport of soil both before and after treatment. Additional expense of site reparation is also avoided in the *in situ* treatment. The negative side of this treatment mode is that it generally requires longer time periods than *ex situ* treatment. Because of the variability in the soil and aquifer characteristics, and development of preferential fluid flow, the treatment is non-uniform and pockets of high contaminant concentration may remain in the subsurface soil.

Physical/chemical separation techniques use the physical or chemical properties of the soil-contaminant-aquifer system, such as volatility in the soil vapor extraction (SVE) or solubility in the soil washing/flushing operations. Physical operations combined with chemical reactions or biological degradation may also be used to enhance the contaminant destruction by either increasing the reaction rates (chemical) or making the contaminant more bioavailable (biological), as in surfactant-enhanced bioremediation applications.

In the case of *in situ* biological processes, organic contaminants are either targeted directly for biological treatment or mobilized to groundwater or collection wells for *in situ* treatment. In some cases, groundwater may be extracted aboveground and treated on-site.

To provide an aerobic environment, oxygen concentration in the soil can be increased by injecting air or hydrogen peroxide. Care must be taken to avoid saturating the soil with water (thus inhibit the movement of oxygen through the soil), compaction of the soil (thus lowering the mass transfer rates) and diluting the contaminant (thus decreasing the rate of biodegradation). The use of hydrogen peroxide is limited, because at concentrations above 100 ppm, it can be toxic to microorganisms. Anaerobic conditions, which are prevalent in the subsurface soil, are amenable, although at a very slow rate, to degrade highly chlorinated contaminants such as PCBs. This can be followed by the aerobic treatment to complete biodegradation of the partially degraded compounds.

Nutrients, especially nitrogen and phosphorus, are likely to be deficient in the contaminated environment, and can be added in a useable form (as ammonium and phosphate). Care must be taken as phosphates can react with soil minerals, iron and calcium, and form stable precipitates that can cause soil plugging. Temperature and pH can affect the biological activity and must be maintained at certain values, depending on the microorganisms, contaminants and site characteristics. Temperature can be increased in colder climates by warm air injection to maintain microbial activity at a high level, but the technology is in experimental stages. On the other hand, too high a temperature can be detrimental to the microorganisms and may increase the volatility of contaminants. Alkaline conditions ( $\text{pH} > 7$ ) are generally more favorable to microbial activity than acidic conditions ( $\text{pH} < 7$ ). Many metals that are potentially toxic to microorganisms are

generally insoluble at high pH values. Therefore, generally a higher pH value would favor an increased degradation.

Sometimes, indigenous microorganisms collected from the contaminated targeted site, or other similar microorganisms, are cultured and grown for the degradation of specific contaminants, or for survival under unusually severe environmental conditions. Addition of these microbial cultures to the contaminated site is known as bioaugmentation. In some cases, the contaminants cannot be utilized directly by the microorganisms for growth or energy, without the presence of a specific enzyme. In some of those cases, a primary substrate is used to produce that enzyme, which aids the subsequent utilization of the contaminant (secondary substrate) by the microorganisms for energy. An example of a co-metabolic process is the aerobic biodegradation of TCE in the presence of methane or gasoline constituents as co-substrates.

Bioventing is another biological technique for *in situ* soil remediation that achieves the biodegradation of VOCs and adsorbed fuel residuals, by providing oxygen via low air flow rates, just enough to sustain microbial activity. Saturated soils, especially in the vicinity of water table or low permeability soils may limit bioventing performance.

*In situ* application of a solidification technique can be achieved via thermally enhanced SVE or vitrification, which uses electrically generated heat to melt the soil. The vitrification process destroys some organics by oxidation due to extremely high temperatures (1300–2000°C) and encapsulates inorganics in the vitrified glass and crystalline mass.

Solidification/stabilization processes use both physical and chemical changes by encapsulating the contaminant (solidification), or altering or binding (stabilization) with the contaminant.

#### VI.10.2.10.2. *Ex situ* treatment

The advantages of *ex situ* process are that the contaminated media (soil, sediments and groundwater) can be thoroughly mixed and homogenized for more uniform treatment, degradation rates are higher and therefore it takes less time for remediation than *in situ* treatment. The major disadvantage is that there are a number of problems associated with the excavation of soil, such as, increased cost, additional equipment, material handling, worker exposure, extra permitting and space considerations. *Ex situ* treatment can be carried out on- or off-site. Off-site treatment further adds transportation costs for contaminated and fill soils, and has the potential to expose a larger population.

The treatment techniques for *ex situ* processing are less limited than *in situ* processing. Additionally, the delivery of chemicals and materials to the contaminated medium is much easier, and can be better targeted than for *in situ* treatment. Operating conditions, such as temperature, pH, mixing, oxygen level, nutrients, chemical additives, binders, surfactants and other parameters can also be optimally controlled in *ex situ* situations.

Treatment technologies for *ex situ* remediation of hazardous wastes include soil washing, solvent extraction, SVE, redox reactions, dehalogenation, biodegradation, composting, landfarming, solid and slurry phase biological treatment, thermal desorption, incineration, pyrolysis and vitrification.

In *ex situ* thermal treatment, waste gases, ash and slag may be generated during the destruction process, which may require additional disposal/treatment.

### VI.10.3. Decision steps in technology selection

Selecting corrective measures objectively is a challenge for several reasons. The individual evaluator is usually biased toward one or a group of technologies with which he/she has had experience. Personal experience often generates more confidence than a broader experience would justify. Similarly, a more conventional technology such as landfill or incineration, usually exhibits more background experience and operational data and information, than a newer technology. On the other hand, there may be “pressure” to select alternative or innovative technologies over more conventional applications on the basis that “newer is better”, or that conventional technology is flawed to the extent of “having brought us to where we are now”. In certain cases, innovative technology may, in fact, be more suitable and/or more cost effective but design may be more uncertain because of lack of data.

This section is meant therefore, to provide guidelines for selecting any technology, but because of the information offered, to provide additional assurance for selecting emerging technology for application to site remediation. A series of decision steps are provided to serve as a basis for a regularized approach to selection of appropriate technology for application at a given site. The eight decision steps are as follows (Williams et al., 1992):

1. Identify contaminants present in each medium.
2. Identify candidate technologies.
3. Screen candidates by evaluating the probable effect(s) of application on target contaminants.
4. Estimate effect on non-target contaminants of technically acceptable candidate technologies.
5. Repeat steps 1–4 until each contaminated medium is assessed and all contaminants are addressed in each medium.
6. Compare acceptable processes for similar treatment steps applied to different media.
7. Compare all acceptable treatment process concepts.
8. Select corrective measure(s) for implementation.

A discussion of each of the steps is given below.

1. *Identify contaminants present in each medium.* Often there appear to be too many compounds represented in each medium to allow a reasonable analysis to proceed. Several contaminants may be selected from the full array on the basis of toxicity, mobility and amount present, and listed in the category of “target contaminants”. It may be useful to categorize contaminants into “families”, representatives of each of those that may be used to evaluate potential technology applicability. The three criteria, toxicity, mobility and amount must be jointly considered and care must be taken to avoid selecting contaminants on the basis of a single criterion, such as amount present or concentration. Toxicity of individual compounds may vary by orders of magnitude. Thus, contaminants present in low concentrations may be included in the preliminary array of high priority compounds on which decisions are based.

2. *Identify candidate technologies.* Table VI.10.2 is provided to guide the collection of contaminant and site related data. During early site investigations and feasibility studies in the United States, the tendency was to gather all possible data on the contaminants and the site. This resulted in significant expenditures for collection of data and information that



Contaminant profile	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Contaminant isopleth (major contaminants)	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Physical chemical constants for each target														
Water solubility	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Vapor pressure	•													
Boiling point	•													
Density				•										
Viscosity (liquids)				•										
Henry's coefficient	•	•	•	•	•									
$K_{ow}$		•	•	•	•									
$K_{oc}$		•	•	•	•									
Biorefractory index								•						
Heat content									•	•				
Ignition temperature	•									•			•	
Measured characteristics														
BOD5								•				•		
COD								•	•			•	•	
TOC								•	•			•	•	
Biodegradation rate								•				•		
Freundlich isotherms					•								•	•
Particle size distribution									•				•	•

were often not needed to guide the performance of remediation actions. On the other hand, the dilemma associated with the amount and scope of data collection is not easily resolved at many sites because the selection of possible technologies is intimately tied to the contaminants present and their form(s). If the general character of the contaminants present is known, then Table VI.10.2 is useful in limiting the scope of data collection.

The contaminant-related selection criteria for technologies include: organic/inorganic contaminants or both; media or phase(s) in which contaminants are present; solid, liquid, gas; a real extent of the contamination; "as-found" matrix in the field, i.e. the chemical and physical context in which the waste is found at a given site. Perhaps the most important set of criteria related to the contaminants are the cleanup objectives.

Cleanup objectives are numerical values for the required maximum concentration(s) of contaminants remaining in the treated media after full implementation of the remediation strategy. These values comprise the end point of the system effectiveness, but may be considered as the beginning step for the system component selection. The final treatment process in the system array must be capable of achieving the stated cleanup objective(s) as an output. Similarly, the next-to-last process must be capable of achieving as output, the required input for the final process. The selection process proceeds *backwards* to the point where the whole system can accept both the site contamination levels and the media involved (also refer to Step 6).

3. *Screen candidates by evaluating the probable effect(s) of application on target contaminants.* After the contaminants have been grouped into chemical families, Table VI.10.3 may be used as a first cut to screen technologies for potential applicability. This screening step may be based on rejection rather than potential applicability (i.e. by rejecting those which potentially fail). At the screening step, technologies should be kept in the analysis as long as possible rather than eliminated if applicability is questionable. Eliminating technologies too soon in the analysis may negatively impact the effectiveness of cleanup actions. Other than those with an open circle in Table VI.10.3, the technologies may have applicability.

Alternatively, carrying processes through the analysis that have limited applicability may expand the analysis unnecessarily. For example, S/S does not work well on organic compounds (especially volatiles) unless special steps are taken, such as using specially treated clays or chemical additives, and/or pretreatment. Therefore, S/S should not be used in situations that contain largely organic contamination. Treatability studies will almost certainly be required for applications showing a diamond shape ("potential effectiveness") in Table VI.10.3. Treatability studies may even be required for those applications showing a filled square ("demonstrated effectiveness") in Table VI.10.3. Biological treatment applications will probably require treatability studies in all cases. A complete assessment of removal and/or destruction effectiveness is given by Martin and Johnson (1987). The procedure, though developed long ago, is still valid nowadays.

The chief basis of the analysis in Step 3 is treatability. Considerable data are available about treatability but often not specifically relevant to the "as-found" matrix at a given site. Therefore, criteria for screening should be developed and used for the analysis. Treatability consists of many subcategories of more specific "-ability" characteristics, some of which are discussed below.

Biodegradability is clearly important for applicability of biological processes. "Biodegradability" can often be an amorphous term when applied to specific cases.

Table VI.10.3. Selection matrix for hazardous – solid waste technologies.

Contaminant	Technology																Other
	Fluidized bed incineration	Rotary kiln incineration	Infrared thermal treatment	Pyrolysis–incineration	Vitrification	Chemical extraction	<i>In situ</i> chemical treatment	Soil washing	<i>In situ</i> soil flushing	Dechlorination	Low temperature thermal stripping	<i>In situ</i> vacuum stream extraction	Stabilization/solidification	<i>In situ</i> vitrification	Biodegradation	<i>In situ</i> biodegradation	
Organic																	
Halogenated volatiles	◆	■	■	◆	◆	◆	○	◆	◆	◆	◆	■	○	○	◆	◆	
Halogenated semivolatiles	◆	■	■	◆	◆	◆	○	◆	◆	◆	◆	■	◆	◆	◆	◆	
Non-halogenated volatiles	◆	■	■	◆	◆	◆	○	◆	◆	○	◆	■	○	○	◆	◆	
Non-halogenated semivolatiles	◆	■	■	◆	◆	◆	○	◆	◆	○	◆	■	◆	◆	◆	◆	
PCBs	◆	■	■	◆	◆	◆	○	◆	◆	◆	○	■	◆	◆	◆	◆	
Pesticides	◆	■	◆	◆	◆	◆	○	◆	◆	◆	○	◆	◆	◆	◆	◆	
Organic cyanides	◆	■	◆	◆	◆	◆	◆	◆	○	○	○	◆	◆	◆	◆	◆	
Organic corrosives	◆	■	◆	◆	◆	◆	◆	◆	○	○	○	○	◆	◆	×	×	
Inorganic																	
Volatile metals	◆	◆	◆	○	×	◆	◆	◆	◆	○	◆	◆	■	○	×	×	
Non-volatile metals	◆	◆	◆	○	◆	◆	◆	◆	◆	○	○	○	■	◆	×	×	
Asbestos	○	○	○	◆	■	○	○	○	○	○	○	○	■	◆	×	×	
Radioactive materials	○	○	○	○	■	◆	◆	◆	◆	○	○	○	■	◆	×	×	
Inorganic corrosives	○	○	○	◆	◆	◆	◆	◆	◆	○	○	○	■	◆	×	×	
Inorganic cyanides	◆	◆	◆	◆	◆	◆	◆	◆	○	○	○	○	■	◆	×	×	
Reactive																	
Oxidizers	■	■	■	■	◆	◆	◆	◆	◆	○	○	○	◆	◆	×	×	
Reducers	■	■	■	■	◆	◆	◆	◆	◆	○	○	○	◆	◆	×	×	

Demonstrated effectiveness ■; Potential effectiveness ◆; No effectiveness ○; Potential adverse impacts to the process ×.

There are, however, much data on the use of biological processes for removal of toxic and hazardous compounds. For example, for most organic compounds, significantly high (>90%) removability data can be found for wastewaters. Similarly, most metals in the compound state(s) found in municipal wastewaters are removable by biological processes (Martin and Johnson, 1987), again to a significant extent (often between 50 and 90%; sometimes even higher removals are possible).

Special considerations may be necessary for certain screening evaluations. For example, strippability and solubility can have variable definitions. Strippability has been defined as compounds having a Henry's law coefficient  $H_L > 3 \times 10^{-3}$  atm m<sup>3</sup>/mol at 20°C. Henry's law coefficients, however, are often difficult to find, although software is now common for determining values. Acceptable values for solubility may vary depending on the treatment strategy; a solubility cutoff value for carbon adsorption may be different from one applicable to soil washing (depending on the solvent). One definition may be, solubility in water at 20°C > 200 mg/l. In this case, 200 mg/l is felt to be a reasonable cutoff for the treatment strategy being considered. Octanol-water partition coefficient ( $K_{ow}$ ) values >10<sup>4</sup> may be considered a good range for high efficiency depending on the solvent being used.

4. *Estimate effect on non-target contaminants of technically acceptable candidate technologies.* Some strategies for remedial investigations and site evaluations suggest that a short list of compounds representing the most ubiquitous, most toxic or hazardous, and those present in the greatest quantities be developed and used for the screening evaluations. Some of the compounds not being carried completely through the evaluation process may not be efficiently removed and/or managed by the selected strategies. Indeed, some compounds may have negative impacts on the treatment process(es) being considered. Table VI.10.3 contains information on "no effectiveness" and "potential adverse impacts on the process".

At this point in the analysis, it is necessary to revisit compounds that may not have been included in the short list array. Sometimes the list can be quite extensive but it is necessary to determine potential adverse impacts on the treatment strategy. Two examples are: volatile organic compounds are likely to escape during *in situ* vitrification and thus may not be effectively controlled; corrosives (both high and low pH) will probably be deleterious in a biodegradation strategy (see Table VI.10.3).

5. *Repeat steps 1–4 until each contaminated medium is assessed and all contaminants are addressed in each medium.*

6. *Compare acceptable processes for similar treatment steps applied to different media.* The approaches to different media may be combined when appropriate to build multimedia treatment trains.

Technologies that may be included in a corrective measure fall into three categories: separation technologies, detoxification–destruction technologies and immobilization technologies. Treatment processes that achieve removal but not destruction will generally require additional management and may be implemented in a separate system. Thus, both separation and detox–destruct technologies may be required in the same system.

General considerations for media are presented in Tables VI.10.4–VI.10.7. Table VI.10.4 presents *in situ* strategies for various major contaminant families and Tables VI.10.5–VI.10.7 do the same for *ex situ* strategies.

Table VI.10.4. Technologies and suitability for *in situ* application.

Technology	Chemical families potentially treatable
Technologies for <i>in situ</i> application in the vadose zone	
Air stripping	All volatile and semivolatile organics
Steam stripping	All volatile and semivolatile organics
Vacuum extraction	All volatile and semivolatile organics
Soil flushing	All water-soluble organics and inorganic salts
Radio frequency heating	Simple aromatics, paraffins, olefins and PAHs
Biological oxidation	Many organics and some inorganics
Chemical oxidation	Most organics and some inorganics to a degree
Dechlorination	Haloaromatics and persistent pesticides
Solidification (injected cement)	Inorganics
Vitrification	Inorganics and up to 10% organics
Excavation	All contaminants
Technologies for <i>in situ</i> application in saturated soils	
Air stripping	All volatile and semivolatile organics
Soil flushing	All water-soluble contaminants
Radio frequency heating	Simple aromatics, paraffins, olefins and PAHs
Biological oxidation	Many organics and some inorganics
Chemical oxidation	Most organics and some inorganics to a degree
Solidification (injected cement)	Inorganics
Technologies for <i>in situ</i> application in groundwater	
Biological oxidation	Many organics and some inorganics
Steam stripping	All volatiles
Radio frequency heating	Simple aromatics, paraffins, olefins and PAHs
Chemical oxidation	Most organics and some inorganics
Pumping	All contaminants
Technologies for application to surface water and sludges ( <i>in situ</i> )	
Biological oxidation	Many organics and some inorganics
Air stripping	All volatiles
Steam stripping	All volatiles
Chemical oxidation	Most organics and some inorganics
Pumping	All contaminants
Dredging	All contaminants

It is desirable to combine treatment process applications where possible, e.g. treating sludge residue from a liquid process sequence along with contaminated soil in the same process(es), if both sludge and soil contain similar or the same contaminants.

Every treatment process will generate a residue; sludge, brine, ash, dust, etc. All but the simplest treatment systems will therefore likely generate an array of residues, which considered as a group, will provide combination treatment possibilities. Comparison

Table VI.10.5. Separation technologies and suitability for *ex situ* application.

Technology	Chemical families potentially treatable
Separation technologies for use in contaminated waters	
Air stripping	All volatile organics
Steam stripping	Volatile and semivolatile organics
Distillation	All organics
Solvent extraction	All organics soluble in the selected solvent
Centrifugation/sedimentation	All insoluble contaminants with densities different from water
Dissolved air flotation	All insoluble contaminants with densities less than water
Carbon adsorption	All insoluble contaminants and many non-volatile, soluble organics
Oil/water separation	All insoluble organics with densities different from water
Ion exchange	Most metals and exchangeable anions
Precipitation/pH adjustment	Most metals
Freezing	Most organics and inorganics
Separation technologies for use in excavated soils	
Air stripping	All volatile contaminants
Soil washing	All contaminants soluble in the selected solvent
Solvent extraction	All organics soluble in the selected solvent
Low temperature thermal desorption	All organics
Separation technologies for use in aboveground sludge streams	
Oil sludge separation – acid cracking	All insoluble organics with densities different than water
Air stripping	All volatile organics
Soil washing	All contaminants soluble in the selected solvent
Solvent extraction	All organics soluble in the selected solvent
Sedimentation	All insoluble contaminants with densities different than water
Filtration	All insoluble contaminants
Dissolved air flotation	All insoluble contaminants with densities less than water
Precipitation/pH adjustment	Most metals
Ion exchange	Most metals and exchangeable anions
Separation technologies for use in air streams	
Condensation	All organics and volatile inorganics
Carbon adsorption	All insoluble contaminants and most non-volatile, soluble organics

Table VI.10.6. Detoxification/destruction technologies and suitability for *ex situ* application.

Technology	Chemical families potentially treatable
Chemical oxidation	Sludges and aboveground waters
Biological oxidation	Excavated soils, sludges and aboveground waters
Catalyzed chemical oxidation	Sludges and aboveground waters
Incineration	Sludges, excavated soils and sludges
Chemical reduction	Aboveground waters, sludges and excavated soils
Catalyzed chemical reduction	Aboveground waters, excavated soils and sludges
Anaerobic bio-reduction	Aboveground waters and sludges

criteria for this step will therefore include treatment combinations that make best use of treatment process applications to mixed media, e.g. soils and sludges.

7. *Compare all acceptable treatment process concepts.* The basis for comparison may include many factors but at least the following should be addressed: (1) the cleanup level achieved compared to cleanup objectives, (2) elapsed time to complete the remediation, (3) cost of remediation and (4) short- and long-term effectiveness.

Comparisons should be drawn only among carefully selected systems that achieve the same or similar outputs. For example, a landfill achieves storage of organic contaminants while incineration is a destruction process for organics. Direct comparisons between these two technologies are often made and are usually inappropriate. It is important to consider all four of the factors listed above, *together*. A joint comparison of the factors will require, for example, matching achieved cleanup levels with cost. Thus, a choice of a less costly landfill will become more clearly unacceptable against incineration, when considering also cleanup levels and long-term effectiveness. A simple comparison of the two technologies for managing organics is given in Table VI.10.8.

8. *Select corrective measure(s) for implementation.* There often is an attempt made to reduce the number of selection criteria because of the difficulty of quantifying values of the various criteria. Shortening the list of selection criteria should be avoided.

Table VI.10.7. Immobilization technologies for use in corrective measures.

Technology	Contaminant streams potentially treatable
<i>In situ</i> vitrification	Vadose zones containing hazardous inorganics and <5% organics
Vitrification furnace	Soils and sludges containing hazardous inorganics and <3% organics
Cement Pozzolan immobilization	Metal bearing wastes (solids, liquids or sludges) with <1% organics
Lime-based immobilization	Waters containing dissolved heavy metals and <1% organics

Table VI.10.8. Example comparison of the two treatment process concepts for organic waste.

Treatment process	Cleanup level	Elapsed time	Cost	Effectiveness
Incineration	High	Same	Higher	Permanent
Landfill	Low or zero	Same	Lower	Landfill life

A rigorous selection analysis need not be based on quantifiable or quantified selection criteria. Therefore, the list of selection criteria should be made as long as needed in order to satisfy all parties involved in the process. Indeed, the selection will be more acceptable to all and therefore more implementable, the more extensive the list of criteria. The plus (+), zero (0), minus (-) approach has been used successfully in many cases to evaluate the overall impact of both quantifiable and non-quantifiable selection criteria. Table VI.10.9 was constructed using this approach for a simplistic landfill-incineration case. In many cases, it is unnecessary to provide any quantification. Usually, however, participants in the analysis will want to know costs.

Based on the analysis in the table alone, incineration should be chosen. Zeros (0) count neither plus nor minus in the summation, since the determination of a zero for a criterion suggests neither benefit nor deficit in the evaluation. The list may be extended to include other criteria, e.g. emission of combustion by-products in the case of incineration and cost of re-landfilling in the case of landfill, thus making the evaluation more complex.

#### VI.10.4. General economics

This section deals with the generalized costs of hazardous waste site remediation in the United States. A later section of this chapter presents costs for several processes for which experience provides more recent costs. Typical soil remediation projects involve excavation, treatment of processing waste streams, measurement and monitoring and site restoration. EPA's SITE (Superfund Innovative Technology Evaluation) Program evaluates and publishes Technology Evaluation and Applications Analysis Reports for new or innovative technologies, after they are being demonstrated in the field (see Chapter VI.11). These reports include economic analysis of the particular technique by breaking down the costs, typically, into 12 categories. The costs are site and contaminant specific,

Table VI.10.9. Example selection analysis of the treatment process using the plus (+), zero (0), minus (-) approach.

Treatment process	Cleanup level	Elapsed time	Cost	Effectiveness
Incineration	High	Same	Higher	Permanent
Landfill	Low or zero	Same	Lower	Landfill life

and can only provide general comparisons and guidance. However, the total cost based on these 12 cost categories can be widely applied for comparison of different remediation techniques for the same site, and help in the selection of the candidate technologies. The 12 cost categories are given below:

1. Site preparation costs
2. Permitting and regulatory costs
3. Equipment costs
4. Startup and fixed costs
5. Labor costs
6. Supply costs
7. Supply and consumables cost
8. Effluent treatment and disposal costs
9. Residuals and waste shipping, handling and transportation costs
10. Analytical costs
11. Facility modification, repair and replacement costs
12. Site demobilization costs.

These cost estimates are highly site dependent, and should be used with caution, only for qualitative comparisons. A summary of processes, their status and their estimated cost (\$/ton) in 1994 are included in Table VI.10.10 to be used for the comparative analysis. The subject of current remediation economics is discussed in the following section.

#### **VI.10.5. Detailed selection criteria and considerations**

The contaminant destruction and removal strategies for groundwater and surface water, soil, and gas treatment are tabulated in detailed remediation technology selection matrices: Tables VI.10.11–VI.10.13. The tables list remediation strategy, media, remediation technology, conditions favorable and unfavorable and economic factors including unit cost ranges and major cost drivers.

Additional remarks are provided that are specific to particular contaminant technology applications.

#### **VI.10.6. Costs of remediation technologies**

A number of technologies have been developed and applied for hazardous waste management in the past few years (McCabe et al., 2001, see also Chapter VI.10). For these technologies, cost data have been determined based on the experience at the sites. This section contains recent available cost data for the following: bioremediation, thermal desorption, SVE, on-site incineration, groundwater pump and treat (P&T) systems, and permeable reactive barriers. A cost plot was not prepared for permeable reactive barriers because of the difficulty and uncertainty of determining the quantity treated by barriers placed within the underground context of the site being remediated. Therefore, unit costs could not be determined.

Table VI.10.10. Summary of some processes for hazardous waste site remediation (status and estimated costs in 1994).

Process	Status in 1994	Estimated cost (\$/ton)
<i>Chemical extraction</i>		
CF Systems	Full-scale	80–450
BEST	Full-scale	75–175
Carver–Greenfield Process	Pilot-scale	100–220
Low-energy solvent extraction process (LEEP) Acurex	Pilot-scale	70–150
OHM Corp. Methanol Extraction Process	Field-tested	75–230
<i>Soil washing</i>		
OHM Corp. Soil Washing	Full-scale	50–125
BioGenesis Soil Cleaning Process	Full-scale	40–140
BioTrol Soil Washing System	Full-scale	100–125
Westinghouse Soil Washing System	Full-scale	150–250
Canonie Environmental Services Soil Washing	Full-scale	50–100
Bergmann USA Particle Separation Process	Full-scale	75–125
Divesco, Inc. SRS-10	Full-scale	50–65
Alternative Remedial Technologies, Inc. Soil Washing	Full-scale	85–225
<i>Thermal extraction</i>		
X* TRAX	Full-scale	100–200
Anaerobic Thermal Processor (ATP) or Taciuk Process	Full-scale	120–300
Williams Thermal Desorption System	Full-scale	125–250
Canonie Environmental Services LTTA System	Full-scale	60–150
Roy F. Weston, Inc. LT	Full-scale	100–150
Maxymillian Mobile Thermal Desorption	Full-scale	40–300
Westinghouse Thermal Desorption	Full-scale	150–300
Advanced Soil Technologies Thermal Desorption	Full-scale	35–150
<i>Physical extraction</i>		
Hydrocyclones	Full-scale	
Sedimentation	Full-scale	
Centrifugation	Full-scale	
Flocculation	Full-scale	
Oil/water separation	Full-scale	
Mechanical screening	Full-scale	
<i>Chemical destruction</i>		
SDTX KPEG Dechlorination	Full-scale	100–300
Base-catalyzed decomposition (dechlorination) process	Full-scale	150–250
G. E. M., Inc. Oxidation	Bench-scale	150–500

(continued)

Table VI.10.10. (Continued)

Process	Status in 1994	Estimated cost (\$/ton)
Agent 313	Bench-scale	100–175
APEG Dechlorination	Full-scale	200–500
ETUS, Inc. TR-DETOX	Full-scale	20–50
Eco Logic Reduction	Full-scale	400–500
<i>Radiant energy</i>		
Light activated reduction of chemicals (LARC)	Pilot-scale	90
Perox-Pure	Full-scale	
Ultrax UV Radiation and Oxidation	Full-scale	
Laser-induced photochemical oxidative destruction (excimer laser)	Lab-scale	
Titanium Dioxide Photocatalytic Oxidation System/Nulite Technology	Bench-scale	
Photothermal detoxification unit (PDU)	Lab-scale	
<i>Thermal destruction</i>		
Eco Logic Thermal Gas	Full-scale	300–400
Phase Reduction Process		
Molten salt oxidation (MSO) process	Pilot-scale	
<i>Biological destruction</i>		
Cognis Bioremediation Technology	Full-scale	40–80
Envirogen	Full-scale	40–170
BIOFAST	Full-scale	35–75
Petroclean Bioremediation System	Full-scale	25–50
Remediation Technologies, Inc.	Full-scale	15–100
Earthfax Engineering, Inc.	Pilot-scale	200
CNP-PLUS	Full-scale	15–30
<i>Solidification</i>		
Geo-Con, Inc. Solidification Process	Full-scale	30–100
Wastech, Inc. Solidification Process	Full-scale	70–250
Advanced Remediation Mixing, Inc.	Full-scale	35–100

The selection of these six technologies by site cleanup managers is a major indication of the status of the technologies for application at other sites. Even in those cases referred to as “demonstration scale” in the reference material, the applications are at sufficiently large scale to set these apart from technologies mentioned earlier in this chapter for which smaller scale data are available. In previous sections, a wide array of technologies, indeed almost the full assortment has been presented along with generalized descriptive and cost information in order to provide a platform for a full technical assessment of possibilities.

Cost data were obtained from US federal agency sources, including case studies and reports prepared by the Federal Remediation Technologies Roundtable (FRTR), the US

Table VI.10.11. Remediation technology selection matrix I.

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range (US \$)	Major cost drivers	Additional comments
<ul style="list-style-type: none"> <li>A strategy should be developed prior to technology selection</li> <li>A strategy may include any combination of these options</li> <li>No containment measure should be considered permanent</li> <li>Removal and destruction are often used together</li> </ul>	<ul style="list-style-type: none"> <li>Each medium affected by a completed risk exposure pathway should be remediated</li> <li>The majority of contaminant mass is likely to be located in soil</li> <li>Groundwater remediation should be coordinated with source remediation in the unsaturated zone</li> </ul>	<p>These technologies may be considered to be proven technologies; innovative technologies are not included</p> <p>Technology selection can be guided by performance of nearby remediation projects at similar sites. IRPIMS may be used to locate sites having similar media stratigraphy and contaminants concern</p>	<ul style="list-style-type: none"> <li>These generalizations are based on projects demonstrating acceptable performance and cost effectiveness; they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>These generalizations are based on projects demonstrating acceptable performance and cost effectiveness; they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>These costs are typical of successful projects conducted by the Air Force and private industry</li> <li>These costs may be used for budget planning and as a rough check of contractor proposals</li> <li>These costs are typical of those charged by companies specialized in each technology</li> <li>A useful measure of merit for evaluating costs is to compute the project cost per pound of contaminant                             <ul style="list-style-type: none"> <li>Cost effective projects typically run &lt;\$200/lb</li> <li>Projects where the costs are orders of magnitude higher</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>Reviews of project cost estimates can focus on these areas to expedite the reviews</li> <li>Regulatory requirements for monitoring and preparing project documentation can be major cost drivers for any project, and they are not addressed in this guide because of the wide range of variability in regulatory requirements among state and local agencies</li> </ul>	<ul style="list-style-type: none"> <li>These comments and performance estimates are provided as helpful hints and observations based on successful projects</li> </ul>
Contaminant	Groundwater	<p>Groundwater pumping</p> <p>Solidification</p>	<p>Receptors actually or immediately at risk</p> <p>Inorganic contaminants present</p> <p>Non-volatile organics &lt; 1%</p>	<p>Active source of contamination remains because soil and free product sources not isolated or removed such as pooled DNAPLs in the saturated zone</p> <p>Volatile organic present</p> <p>High-clay soils</p> <p>High debris content</p>	<p>\$40–\$80/ft of well for installation</p> <p>\$4000–\$9000/well for pumping system</p> <p>Water treatment systems costed below</p> <p>\$30–\$150/ton of soil treated (<i>ex situ</i>)</p> <p>\$60–\$200/ton of soil treated (<i>in situ</i>)</p>	<p>Power</p> <p>Effluent treatment (options listed below)</p> <p>Reagents and transportation materials handling (large volume increase)</p>	<p>Not a cost-effective method for remediating contaminant mass</p> <p>Site-specific treatability testing mandatory</p> <p>Very long-term stability difficult to predict</p>

Contaminant		Stabilization	Inorganic contaminants present Non-volatile organics < 1%	Volatile organic present High-clay soils High debris content	\$30–\$150/ton of soil treated	Reagents and transportation materials handling	Site-specific treatability testing mandatory Very long-term stability difficult to predict
		Asphalt blending (“soil recycling”)	Petroleum product contamination	Volatile organic present High-clay soils High debris content Halogenated organic present	\$55–\$100/ton of soil treated	Feed material preparation (crushing, screening, aggregate addition)	
		Slurry walls Sheet piling HDPE walls	Groundwater levels < 20 ft Receptors imminently at risk Availability of aquitard within 40 ft of ground surface to anchor walls	Corrosive contaminants and strong electrolytes High expensive soils High climate moisture variation (extreme wet–dry cycles) Complex terrain	\$7–\$10/sq. ft of wall	Trenching depth Soil additives (cements, aggregate)	Site-specific compatibility testing recommended Wall may degrade over time
	Soil	Capping	Rainfall > 10 in./year Large contaminated soil volume Relatively low hazard Use as an interim measure	Presence of material that will settle in landfill Dry climates	\$25–\$30/sq. yd for RCRA cap \$10–\$15/sq. yd for clay cap	Long-term monitoring and maintenance requirements Regulatory specifications for cap construction Gas collection and treatment	Construction quality assurance to ensure low conductivity of the cap is critical Gas collector may be necessary Cap can enhance soil vapor extraction efficiency
		Off-site landfilling	Quick remediation required	Concern about long-term liability	\$200–\$500/ton tipping fee \$0.40–\$0.90/ton-mile for transportation	Disposal fee Transportation	Costs provided for hazardous material landfilling
	Dust control	Short-term control of exposure pathway Dry climate	High soil moisture content	* \$0.02–\$0.04/sq. ft for sending or one chemical spray application \$0.30–\$0.40/sq. ft for one foam application \$0.25–\$0.60/sq. ft for synthetic cover	Labor	Foam application and synthetic cover can also inhibit contaminant volatilization	

Note: US units used: 1 in. = 2.54 cm; 1 ft = 0.3048 m; 1 sq. ft = 0.0929 m<sup>2</sup>; 1 sq. yd = 0.8361 m<sup>2</sup>; 1 lb = 0.45359 kg.

Table VI.10.12. Remediation technology selection matrix II.

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range	Major cost drivers	Additional comments
<ul style="list-style-type: none"> <li>• A strategy should be developed prior to technology selection</li> <li>• A strategy may include any combination of these options</li> <li>• No containment measure should be considered permanent</li> <li>• Removal and destruction are often used together</li> </ul>	<ul style="list-style-type: none"> <li>• Each medium affected by a completed risk exposure pathway should be remediated</li> <li>• The majority of contaminant mass is likely to be located in soil</li> <li>• Groundwater remediation should be coordinated with source remediation in the unsaturated zone</li> </ul>	<p>These technologies may be considered to be proven technologies; innovative technologies are not included</p> <p>Technology selection can be guided by performance of nearby remediation projects at similar sites. IRPIMS may be used to locate sites having similar media stratigraphy and contaminants concern</p>	<ul style="list-style-type: none"> <li>• These generalizations are based on projects demonstrating acceptable performance and cost effectiveness; they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>• These generalizations are based on projects demonstrating acceptable performance and cost effectiveness; they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>• These costs are typical of successful projects conducted by the Air Force and private industry</li> <li>• These costs may be used for budget planning and as a rough check of contractor proposals</li> <li>• These costs are typical of those charged by companies specialized in each technology</li> <li>• A useful measure of merit for evaluating costs is to compute the project cost per pound of contaminant <ul style="list-style-type: none"> <li>– Cost effective projects typically run &lt;\$200/lb</li> <li>– Projects where the costs are orders of magnitude higher</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Reviews of project cost estimates can focus on these areas to expedite the reviews</li> <li>• Regulatory requirements for monitoring and preparing project documentation can be major cost drivers for any project, and they are not addressed in this guide because of the wide range of variability in regulatory requirements among state and local agencies</li> </ul>	<ul style="list-style-type: none"> <li>• These comments and performance estimates are provided as helpful hints and observations based on successful projects</li> </ul>

	Liquid phase carbon adsorption	<p>Contamination &lt; 10 ppm</p> <p>Presence of semivolatile halogenated and on-halogenated contaminants</p> <p>Flow rate &lt; 10 gpm id</p> <p>Contamination &gt; 10 ppm</p>	<p>Suspended solids &gt; 50 ppm</p> <p>Oil, grease content &gt; 10 ppm</p> <p>High volatile organic content</p> <p>Presence of humic and fulvic acids</p>	<p>Capital cost:</p> <p>10–30 gpm: \$200/gpm</p> <p>30–500 gpm: \$130/gpm</p> <p>Operating cost: \$20–\$50/lb of contaminant removed</p>	Carbon regeneration	<p>Best suited for low volume, low concentration applications such as effluent polishing</p> <p>Removal efficiencies of 100% can be attained</p> <p>On-site regeneration usually not cost effective</p>
Groundwater or surface water	Air stripping	<p>Volatile organic contaminants &gt; 10 ppm</p>	<p>Presence of non-volatile organics</p> <p>Iron content &gt; 10 ppm</p> <p>Hardness &gt; 800</p>	<p>Capital cost: \$250–\$400/gpm throughput up to 100 gpm</p> <p>Operating cost: \$20–\$50/lb of contaminant removed</p>	<p>Instrumentation for automated operation</p> <p>Power consumption</p> <p>Air reheat</p> <p>Offgas treatment (options listed below)</p>	<p>Tray strippers have less visual impact than packed towers and tray strippers may be less prone to fouling</p> <p>Units designed for removal efficiencies around 99%</p>

(continued)

Table VI.10.12. (Continued)

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range	Major cost drivers	Additional comments
		Free product removal by pumping	Measured thickness of organic layer > 6 in. Water depth < 50 ft below ground surface	Viscous free product that is difficult to pump Thin free product layers Water table depth > 100 ft below ground surface	\$3000–\$5000 for a single well \$1500/well for additional wells in multi-well systems	Product treatment or disposal (excluding recovery credits)	Should be initiated immediately upon discovery of free product layer Single phase pumping less costly than two phase pumping which requires water treatment
Contaminant		Phase separation (oil–water)	Contamination > 200 ppm Flow rate > 100 gpm	Presence of emulsions	\$10–\$20/gpm capacity of separator	Equipment	Effluent concentration seldom < 10 ppm
		Air sparging	Volatile contaminants present	Low permeability aquifer Presence of free product > 6 in. thick	Capital cost: \$75/ft for injection wells \$5000–\$25,000 for air injection pumps	Trial test Implementation	Small scale (1 or 2 wells) pilot test recommended Sparging may spread contamination to clean areas, such as basements or utility lines May be used with SVE

Removal	Soil	Soil vapor extraction	Volatile contaminant concentrations > 1000 ppmv in soil gas Presence of low permeability surface cap Presence of contamination > 30 ft below ground surface Structures or utilities present that would hinder excavation	Water table < 10 ft below ground surface Clay content > 20%	Capital cost: \$15–\$25/scfm capacity for extraction skid with no emission controls (see contaminant destruction by thermal treatment for emission control costs) \$40–\$75/ft for extraction wells	Equipment Process monitoring Trial test if no nearby SVE applications	Emission control equipment probably necessary: contaminant destruction by thermal treatment is the preferred alternative Operation is generally not cost effective at removal rates < 10 lb/day Air flow promotes biodegradation Can be used with air sparging
		Excavation	<i>Ex situ</i> treatment planned, such as thermal, soil washing or biological treatment Off-site treatment available Contamination < 20 ft below ground surface	Presence of structures and utilities Very volatile or toxic contaminants Noise sensitive environments	\$2–\$25/cu. yd for excavating and loading \$1–\$3/cu. yd for backfilling and compacting Treatment costs additional	Field implementation Treatment or disposal of contaminated material	
		Soil washing	Thermal treatment prohibited Soil cannot be disposed of off-site	Presence of > 30% silt and clay Presence of a sensitive aquifer that may be affected by residual washing chemicals	\$100–\$500/ton of soil treated	Number of extraction stages required Waste stream management or decontamination	Due to the complexity of this technology, a compelling reason for use should exist Treatment of numerous waste streams required

(continued)

Table VI.10.12. (Continued)

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range	Major cost drivers	Additional comments
	Gas SVE exhaust Air Stripper exhaust	Condensation	Gas flow rate < 200 scfm High contaminant concentrations Collection efficiencies > 80–90% are not required	Gas flow rate > 200 scfm Dense or viscous condensate	\$15,000–\$20,000 for a 200 scfm unit	Equipment Compressor power	Both contaminants and water will condense, water will require treatment prior to discharge Recovered product may be partially oxidized, unfit for reuse, and may plug the condenser
		Vapor phase carbon adsorption	Application on trial test SVE units Short term (< 1 month) emission control required Contaminant concentrations < 100 ppmv	Application on air strippers Flow rates > 200 scfm Application to water-saturated gas streams	Capital cost: < \$1000 for units 200 scfm or less \$3–\$4/scfm capacity for larger units Operating cost \$40–\$100/lb of contaminant removed	Equipment Carbon replacement	On-site carbon reactivation is generally not cost effective: vendors provide carbon replacement service Removal efficiencies of 100% can be attained but saturated gases impede performance

Note: US units used: 1 in. = 2.54 cm; 1 ft = 0.3048 m; 1 sq. ft = 0.0929 m<sup>2</sup>; 1 sq. yd = 0.8361 m<sup>2</sup>; 1 cu. ft = 28.317 dm<sup>3</sup>; 1 cu. yd = 0.7646 m<sup>3</sup>; 1 lb = 0.45359 kg; 1 US ton (short) = 0.90718 ton; 1 US gal = 3.78533 l; 1°F = 5/9°C; ppm, parts per million; gpm, gallons per minute; scfm, standard cubic feet per minute.

Table VI.10.13. Remediation technology selection matrix III.

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range	Major cost drivers	Additional comments
<ul style="list-style-type: none"> <li>• A strategy should be developed prior to technology selection</li> <li>• A strategy may include any combination of these options</li> <li>• No containment measure should be considered permanent</li> <li>• Removal and destruction are often used together</li> </ul>	<ul style="list-style-type: none"> <li>• Each medium affected by a completed risk exposure pathway should be remediated</li> <li>• The majority of contaminant mass is likely to be located in soil</li> <li>• Groundwater remediation should be coordinated with source remediation in the unsaturated zone</li> </ul>	<p>These technologies may be considered to be proven technologies: innovative technologies are not included</p> <p>Technology selection can be guided by performance of nearby remediation projects at similar sites. IRPIMS may be used to locate sites having similar media stratigraphy and contaminants concern</p>	<ul style="list-style-type: none"> <li>• These generalizations are based on projects demonstrating acceptable performance and cost effectiveness: they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>• These generalizations are based on projects demonstrating acceptable performance and cost effectiveness: they are not presented as rigid guidelines because each project needs to be evaluated individually</li> </ul>	<ul style="list-style-type: none"> <li>• These costs are typical of successful projects conducted by the Air Force and private industry</li> <li>• These costs may be used for budget planning and as a rough check of contractor proposals</li> <li>• These costs are typical of those charged by companies specialized in each technology</li> <li>• A useful measure of merit for evaluating costs is to compute the project cost per pound of contaminant                             <ul style="list-style-type: none"> <li>– Cost effective projects typically run &lt;\$200/lb</li> <li>– Projects where the costs are orders of magnitude higher</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Reviews of project cost estimates can focus on these areas to expedite the reviews</li> <li>• Regulatory requirements for monitoring and preparing project documentation can be major cost drivers for any project, and they are not addressed in this guide because of the wide range of variability in regulatory requirements among state and local agencies</li> </ul>	<ul style="list-style-type: none"> <li>• These comments and performance estimates are provided as helpful hints and observations based on successful projects</li> </ul>
Contaminant	Groundwater	Intrinsic remediation or natural attenuation	Contaminant mass < 2000 lb No receptors at risk	Presence of halogenated organics or heavy metals Presence of free product	No capital or O&M costs	Monitoring	Halogenated organics degrade slowly
	Soil	Biotreatment: <i>In situ</i> <i>Ex situ</i>	Presence of water-soluble organic contaminants For <i>in situ</i> treatment, aquifer must have permeability > 10 <sup>2</sup> ft/day	Presence of halogenated organics Presence of free product Presence of inorganic contaminants	\$13–\$50/cu. yd for <i>in situ</i> \$40–\$175/cu. yd for <i>ex situ</i>	Trial test Monitoring	Trial test is recommended to determine performance

(continued)

Table VI.10.13. (Continued)

Remediation strategy	Media	Remediation technology	Conditions favorable to use	Conditions unfavorable to use	Unit cost range	Major cost drivers	Additional comments
			Contaminant mass ranging from 1000 to 8000 lb				
		Biotreatment: <i>In situ</i> <i>Ex situ</i> (composting) Bioventing	Moist, permeable soil, neutral to basic pH Temperature > 40°F	Presence of free product Presence of halogenated organics or inorganics Saturated soil or water content >50% Rapid remediation required	\$15–\$50/cu. yd	Trial test Field implementation	Trial test is recommended, especially if microorganisms are added to soil Nutrient requirement need to be determined Performance depends on soil pore structure, low ppm levels may not be attained
		Thermal treatment: Low temperature High temperature	High contaminant concentrations and presence of free product Water content < 20% Contaminant mass > 2000 lb for on-site treatment Rapid remediation required	High clay content	\$15–\$150/ton for POL only (low temperature treatment) \$300–\$600/ton for halogenated organics (high temperature treatment) \$700–\$1500/ton if PCBs present \$6000/ton if process-related dioxins are present in soil	Contaminant type determining whether high or low temperature treatment is required On-site or off-site location of treatment unit Need for air emission controls	Off-site treatment at high range of costs, on site at low range of costs Soils with water content > 25% require drying High temperature treatment units achieve DREs > 99.99% and often require acid gas scrubbing and pollution control systems

Destruction	Gas SVE exhaust Air stripper exhaust Air sparging emissions	Thermal treatment: Catalytic Flame Reactive bed	Emission control stipulated by regulatory agencies Contaminant concentrations > 1000 ppmv favors use of flame units Concentrations from 100–5000 ppmv can be treated in catalytic oxidizers	High particulate or water droplet loading requires filtering or separation	Capital cost: \$65–\$100/scfm throughput for thermal equipment cost \$60–\$90/scfm throughput for acid gas emission control equipment Operating cost: – \$50/scfm throughput annual O&M cost for thermal unit – \$250–\$400/scfm throughput annual O&M cost for thermal unit with scrubber	Gas flow rate Presence of halogens requiring acid gas cleaning	Performance > 95% DRE usually attained Base metal catalysts may be more cost effective than precious metal catalysts if halogens are present Units available that convert from flame to catalytic operation as concentrations decrease Influent concentration generally kept < 25% of lower explosive limit by dilution
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Note: US units used: 1 in. = 2.54 cm; 1 ft = 0.3048 m; 1 sq. ft = 0.0929 m<sup>2</sup>; 1 sq. yd = 0.8361 m<sup>2</sup>; 1 cu. ft = 28.317 dm<sup>3</sup>; 1 cu. yd = 0.7646 m<sup>3</sup>; 1 lb = 0.45359 kg; 1 US ton (short) = 0.90718 ton; 1 US gal = 3.78533 l; ppm, parts per million; gpm, gallons per minute; scfm, standard cubic feet per minute.

Department of Energy's (DOE) Los Alamos National Laboratory (LANL); the US Army Corps of Engineers (USACE) Hazardous, Toxic, and Radioactive Waste Center for Expertise; and the US Air Force Center for Environmental Excellence (AFCEE). Those sources provided cost data for approximately 150 projects. The data were sufficient to begin identifying patterns in costs of several technologies. However, additional cost data for remediation technologies, collected through the use of standard procedure will help to further increase understanding of the factors affecting the cost of technology applications in the future.

#### **VI.10.6.1. Sources of cost data**

The FRTR gathers data on costs and regularly adds those data to its web site at <http://www.frtr.com>.

Additional information about the FRTR and its recommended procedures for documenting case studies is included in the FRTR's *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (the guide), EPA 542-B-98-007, October 1998, which is available through the FRTR web site. FRTR case studies present information from more than 200 reports about remedial technology projects, including cost data for the six remediation technologies of interest herein. Each case study provides information about the site background, technology design and performance, cost and lessons learned. Cost data generally were reported in the format provided in the FRTR's *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects*, with the level of detail of the cost data varying by case study (FRTR, 1995, 1997, 1998, 2000). Case studies are available at the FRTR web site at <http://www.frtr.gov/cost>.

Many USEPA reports are available at <http://www.epa.gov> in downloadable formats.

A major source of data used for the cost of bioventing technology was the report *Bioventing Performance and Cost Results from Multiple Air Force Test Sites, Technology Demonstration, Final Technical Memorandum*, prepared by the AFCEE (1996). This Air Force report presents cost data on 45 bioventing projects that were performed at Air Force bases throughout the United States. For each project, information is provided about site name, location, total cost of bioventing and volume of soil treated. A standard protocol was used in collecting the cost data. This report was the major source of data on bioventing in this document. The data from the Air Force report are considered unique in the field because they represent a comprehensive effort to collect costs through use of standard procedures. The report is available at <http://www.afcee.brooks.af.mil/er/ert/costperf.htm> web site.

The report *A Compendium of Cost Data for Environmental Remediation Technologies*, Los Alamos National Laboratory (LANL), LA-UR-96-2205, August 1996 presents summary information about 250 commercial or pilot-scale remedial projects, including actual costs, site characteristics and comments about the project. Cost data were provided by a variety of sources (including FRTR case studies) and vary in level of detail. The report is available at <http://www.lanl.gov/orgs/d/d4/enviro/etcap>.

Bioremediation in the Field Search System (BFSS), Version 2.1 is a USEPA database of information about waste sites in the United States and Canada where bioremediation is being tested or implemented or has been completed. The database contains information

about 450 full-scale bioremediation efforts and treatability and feasibility studies. BFSS is available at <http://www.clu-in.org/PRODUCTS/MOREINFO/Bfss.htm>.

The report *Cost Data for Innovative Treatment Technologies*, Internal Draft USACE, July 1997 by the US Army Corps of Engineers, presents information about the cost of selected technology applications, drawn from data available in public sources and from personal communications with site managers.

The costs for technology applications in this section were standardized for both time (to 1999 US\$), and location. The inflation factor was applied to most data (except bioventing) using the Engineering News Record (1999) information, available at <http://www.enr.com/cost/costcci.asp>.

In addition to the sources listed, individual case study reports are available at the USEPA site.

#### **VI.10.6.2. Cautions for use of the data**

The cost data throughout this chapter are for use by site managers, engineers, decision makers and other parties interested in assessing remedies on a relative basis, and should not be used for predicting the costs for application because of the significant effects of site-specific factors. The plots in this section may be useful early in the planning process when an analysis of technology costs is performed for general comparative purposes. The plots were prepared from data in the sources indicated on each of the figures. The detailed cost data and descriptive factors are included in each of the sources and the user should refer to them before using the data for more detailed analyses.

#### **VI.10.6.3. Costs affected by site-specific factors**

The data arrays can be seen to exhibit large variations in the coefficient of determination ( $R^2$ ) values. Examples of site-specific factors include: the contaminants being treated and properties of each; characteristics of the as-found matrix for the wastes; concentration of contaminants; distribution of contaminants in the matrix; type and properties of the soil; hydrogeology of the site.

In the case of bioremediation (Fig. VI.10.11), very little correlation of cost with amount treated is observed. Most of the data are gathered between 1000 and 10,000 yd<sup>3</sup> (i.e. 765 and 7650 m<sup>3</sup>). In this case, there are significant differences between *in situ* and *ex situ* applications. Applications included for the data were for BTEX, VOCs, PAHs and chlorinated VOCs contaminants.

The unit costs for bioventing (Fig. VI.10.12), decrease from about \$10 to \$20/cu. yd for 10,000 yd<sup>3</sup> of soils treated to less than \$5/yd<sup>3</sup> for large quantities (i.e. from about US \$13 to US \$27/m<sup>3</sup> for 7650 m<sup>3</sup> of soils treated to less than US \$6.5/m<sup>3</sup> for large quantities; 1 yd<sup>3</sup> = 9.7646 m<sup>3</sup>).

In Figure VI.10.13, thermal desorption shows an economy of scale from about \$200/\$300 per ton at 10,000–20,000 ton treated to less than \$50 per ton at the higher amounts, but the  $R^2$  value is only about 5%.

The  $R^2$  value for SVE projects is about 70% (see Figure VI.10.14). In this case, the cost per pound of contaminant removed is very telling. Cost per pound removed for several projects range from several hundred dollars for a few thousand pounds removed to about

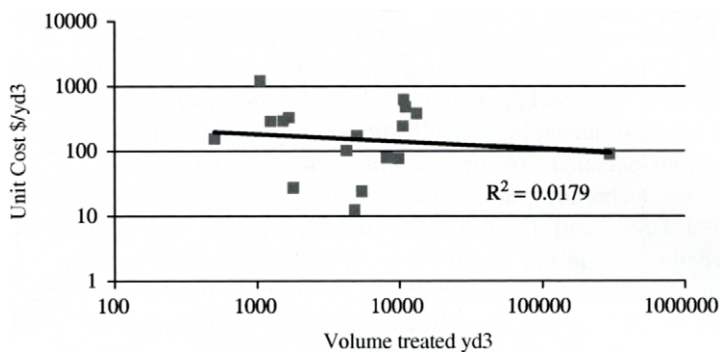


Figure VI.10.11. Costs for bioremediation projects. Sources: (1) FRTR – Federal Remediation Technology Roundtable case studies (Vol. 1 (1995), Vol. 5 (1997) and Vol. 7 (1998b) and CDROM (2000)). Available at: <http://www.frtr.gov/cost>. (2) US Army Corps of Engineers (USACE): *Cost Data for Innovative Treatment Technologies*, Internal Draft, July 1997. Note: US units used;  $1 \text{ yd}^3 = 1 \text{ cu. yd} = 0.7646 \text{ m}^3$ .

\$20,000/lb when the amount removed is less than 100 lb (i.e. to about US \$44,000/kg when the amount removed is less than 45 kg;  $1 \text{ lb} = 0.45359 \text{ kg}$ ). The cost per pound  $R^2$  value is over 90%.

Five of the on-site incineration projects involved soil, sludge, sediment and debris and two involved liquids and fumes. All were included in the analysis for Figure VI.10.15. There are too few data points for a definitive assessment, but they are useful for a general range determination of cost ranges.

There are many pump and treat applications in existence. Clearly, the unit cost for operations over the life of the system cannot be determined because many, if not most, are

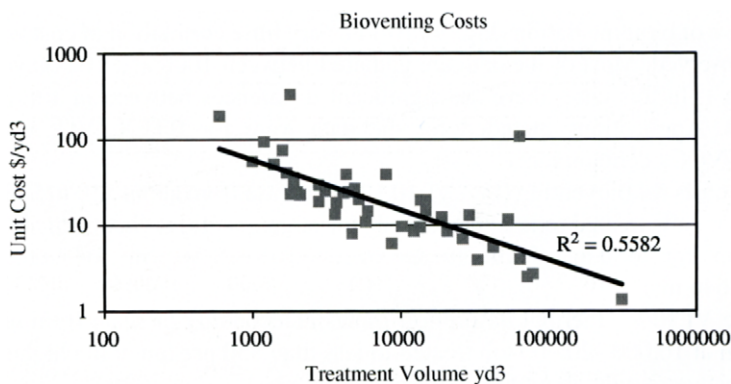


Figure VI.10.12. Cost summary for 47 bioventing projects. Source: AFCEE Technology Transfer Division: *Bioventing Performance and Cost Results from Multiple Air Force Test Sites, Technology Demonstration*, Final Technical Memorandum, June 1966. Note: US units used:  $1 \text{ yd}^3 = 1 \text{ cu. yd} = 0.7646 \text{ m}^3$ .

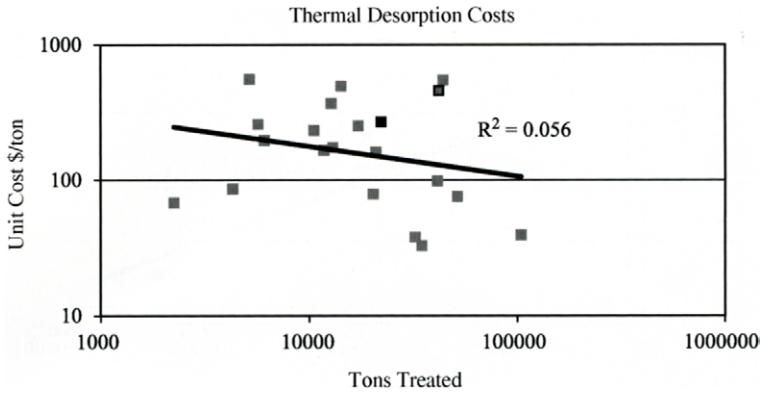


Figure VI.10.13. Cost summary for 21 thermal desorption projects. Sources: (1) FRTR case studies (Vol. 1 (1995), Vol. 5 (1997) and Vol. 7 (1998b) and CDROM (2000)). Available at: <http://www.frtr.gov/cost>. (2) LANL: *A Compendium of Cost Data for Environmental Remediation Technologies*. LA-UR-96-2205, August 1996. Available at: <http://www.lanl.gov/orgs/d/d4/enviro/etcap>. (3) USACE: *Cost Data for Innovative Treatment Technologies*, Internal draft, July 1997. Note: US units used; 1 US ton (short) = 0.90718 ton.

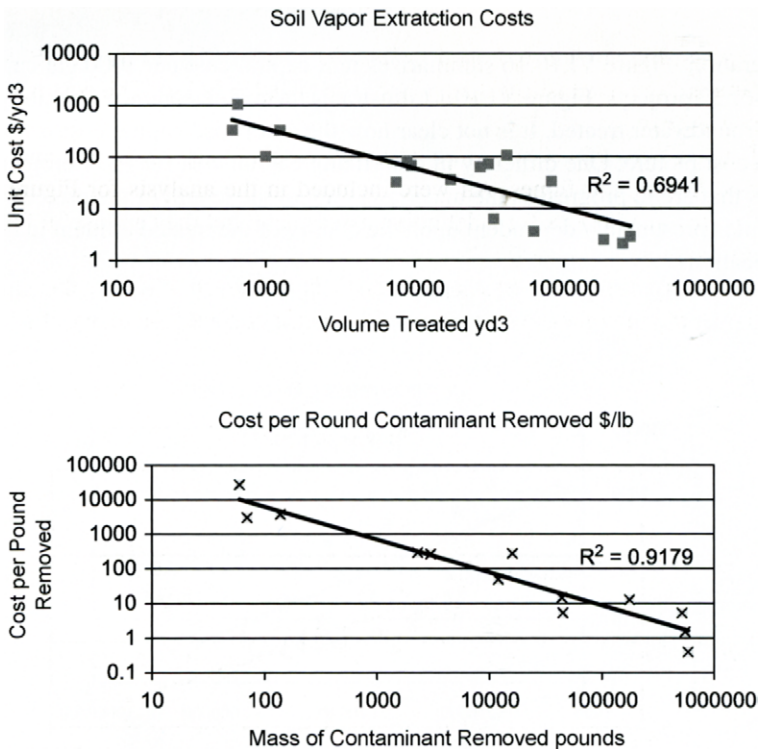


Figure VI.10.14. Cost summary for 22 SVE projects. Sources: (1) FRTR case studies (Vol. 1 (1995), Vol. 5 (1997) and Vol. 7 (1998b) and CDROM (2000)). Available at: <http://www.frtr.gov/cost>. (2) LANL: *A Compendium of Cost Data for Environmental Remediation Technologies*. LA-UR-96-2205, August 1996. Available at: <http://www.lanl.gov/orgs/d/d4/enviro/etcap>. (3) USACE: *Cost Data for Innovative Treatment Technologies*. Internal draft, July 1997. Note: US units used: 1 yd<sup>3</sup> = 1 cu. yd = 0.7646 m<sup>3</sup>; 1 lb = 0.45359 kg.

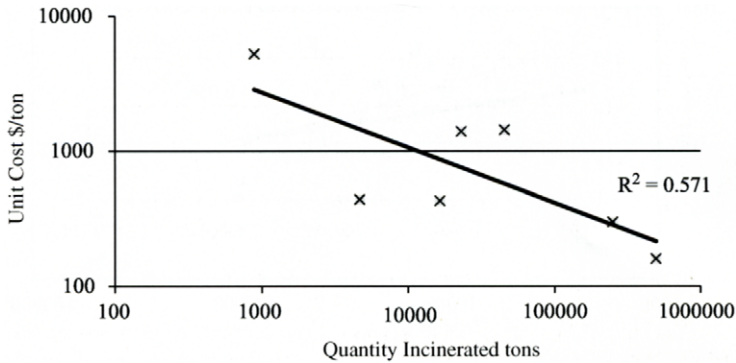


Figure VI.10.15. Cost summary for on-site incineration. Source: FRTR – Federal Remedial Technology Roundtable case studies (Vol. 12 (1998c) and CDROM (2000)). Available at: <http://www.frtr.gov/cost>. Note: US units used; 1 US ton (short) = 0.90718 ton.

still in operation. Figure VI.10.16 summarizes unit capital cost per 1000 gal capacity per year data for 32 projects. Figure VI.10.17 illustrates the average annual operating cost per 1000 gal groundwater treated. It is not clear how the amortized capital cost is managed in the annual cost picture. One difficulty in amortizing capital cost for P&T projects and for all projects that are in progress is the uncertainty about the length of the project. Duration of treatment is presumably dependent upon the quality of the treated effluent in the case of P&T applications.

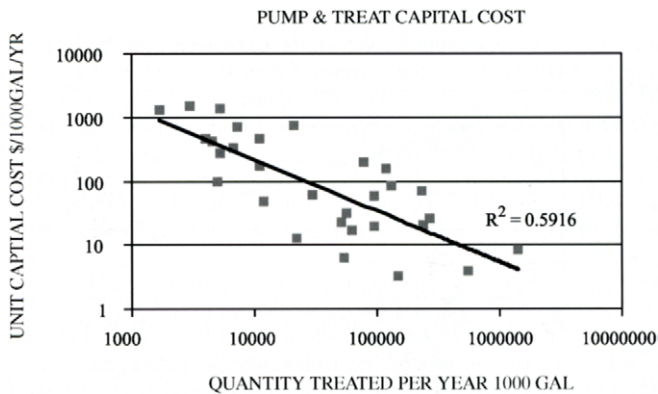


Figure VI.10.16. Summary of Pump and Treat (P&T) capital costs for 32 projects. Source: USEPA Office of Solid Waste and Emergency Response, *Cost Analysis for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, EPA 542-R-00-013. December 2000. Note: US units used; 1 US gal = 3.78533 l.

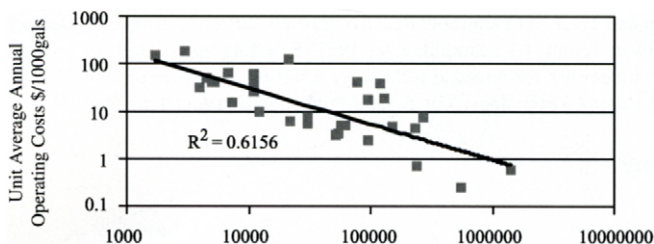


Figure VI.10.17. Summary of Pump and Treat (P&T) operating costs for 32 projects. Source: USEPA Office of Solid Waste and Emergency Response, *Cost Analysis for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, EPA 542-R-00-013. December 2000. Note: US units used; 1 US gal = 3.78533 l.

### VI.10.7. Concluding remark

A simplified logic approach to step-by-step selection of the most appropriate remediation strategies aimed at efficient and possibly cost-effective meeting the cleanup objectives for the contaminated sites is considered to be an important tool in the optimal implementation of a vast number of routine and innovative technologies, which are available for hazardous waste site remediation. Though comparative cost analysis of proper hazardous waste management vs. remediation has not been carried out here, from the discussed data on remediation costs based on several tenths case studies, it is clear that the costs of cleaning up past mistakes are much higher than the costs of adequate waste management controls.

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**Further reading*****Web sites***

- AFCEE – Air Force CEE: <http://www.afcee.brooks.af.mil>.
- ENR – Engineering News Record: <http://www.enr.com>.
- FRTR – Federal Remediation Technology Roundtable (FRTR): <http://www.frtr.gov>.
- LANL – Los Alamos National Laboratory: <http://www.lanl.gov>.
- US EPA: <http://www.epa.gov>.