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Engineering Forum Issue

Considerations in Deciding to Treat Contaminated Unsaturated Soils In Situ

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1.0 Introduction

This Issue Paper was developed for the EPA national Engineering Forum. This group of EPA professionals, representing EPA's Regional Offices, is committed to identifying and resolving the engineering issues related to the remediation of Superfund and RCRA sites. The Forum operates under the auspices of and advises EPA's Technical Support Project.

The purpose of this Issue Paper is to assist the user in deciding if in situ treatment of contaminated soil is a potentially feasible remedial alternative and to assist in the process of reviewing and screening in situ technologies. The definition of an in situ technology is a technology applied to treat the hazardous constituents of a waste or contaminated environmental medium where they are located. Central to the definition of in situ technology is the concept that the contaminated material is not excavated. The technology must be capable of reducing the risk posed by these contaminants to an acceptable level (U.S. EPA, 1990, EPA/540/2-90/002, p. 1).

Many biological, chemical, and physical mechanisms are available to treat contaminants in soils. These mechanisms can be either applied to excavated soil or used in situ. The costs, logistical concerns, and regulatory requirements associated with excavation, ex situ treatment, and disposal can make in situ treatment an attractive alternative. In situ treatment entails the use of chemical or biological agents or physical manipulations to degrade, remove, or immobilize contaminants without requiring bulk soil removal. Containment technologies, such as capping, liners, and grout walls, are not considered in this Issue Paper.

This Issue Paper is intended to assist in the identification of applicable alternatives early in the technology screening process. The Issue Paper discusses and lists important

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considerations for in situ technologies. More detailed information is available on each technology from a variety of reference sources. These references should be consulted for all of the technologies that are likely to be useful at a specific site. In addition to the in situ technologies discussed in this Issue Paper, technology screening also would consider potentially useful ex situ technologies. Final technology selection typically will be based on site-specific evaluation and treatability testing (U.S. EPA, 1992, EPA/540/R-92/071a).

Applying the treatment agents to the largely undisturbed in situ geology gives in situ treatment unique advantages and challenges. The obvious advantage is that no bulk excavation is required for in situ treatment. Preventing excavation eliminates the cost and environmental consequences of moving the contaminated material. The conditions of the subsurface will never be as controlled as in an ex situ reactor, however. As a result, in situ treatment requires more extensive site characterization both before and after treatment, is harder to simulate in the laboratory, and must be designed and operated to minimize the spread of contamination.

The principal feature of in situ treatment is controlled delivery and recovery of energy, fluids, or other treatment agents to the subsurface. The treatment agent usually is water, air, or steam but may be energy input by conduction or radiation. For both physical- and energy-based in situ treatment agents, controlled application is a key to success. Systems must be available to apply treatment agents and to control the spread of contaminants and treatment agents beyond the treatment zone.

Several in situ technologies also rely on the ability to recover the treatment agent and contained contaminants from the subsurface. For example, recovery of flushing fluid containing contaminants is an integral part of soil flushing, and the collection and treatment of steam and condensate are essential to steam/hot air injection and extraction treatment.

Assessing the feasibility of in situ treatment and selecting appropriate in situ technologies requires an understanding of the characteristics of the contaminants, the site, and the technologies, and of how these factors and conditions interact to allow effective delivery, control, and recovery of treatment agents and/or the contaminants.

This Issue Paper discusses established and innovative in situ treatment technologies that are available or should be available for full-scale application by 1996. Emerging technologies that are still being tested in the laboratory and are not available for full-scale implementation are not discussed. Examples of emerging technologies include: in situ oxidation or reduction, electrokinetics, hot brine injection, polymer injection, and soil freezing.

2.0 Critical Factors in Technology Selection

This section describes critical factors to consider in the selection of in situ treatment methods and during evaluation of in situ technologies. Factors to be discussed include the general technology capabilities and generic critical factors that influence the general suitability of in situ treatment when compared to ex situ treatment. Section 3.0 provides more detailed technology descriptions and the technology-specific critical factors.

The process for screening and selecting technologies is described in *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA – Interim Final* (U.S. EPA, 1988, EPA/540/G-89/004). The guidance document describes preliminary screening of technologies based on effectiveness, implementability, and cost. The effectiveness evaluation considers the protection of human health and the environment and reductions in mobility, toxicity, and volume of contaminant achieved by an alternative. The implementability evaluation considers the technical and administrative feasibility of constructing, operating, and maintaining a remedial action alternative. The cost evaluation considers the relative cost of alternatives.

This Issue Paper will assist the user in prescreening in situ technologies for contaminated soil by determining whether the technologies are technically feasible for a particular site. This paper is not meant to replace Feasibility Study Guidance. Consideration and selection of remedial technologies is based on criteria that are defined by the National Contingency Plan. This Issue Paper describes the potential effectiveness of in situ technologies for treating the various types of chemical groups, and reviews both the general and the technology-specific factors to consider during preliminary evaluations of the effectiveness, implementability, and cost of in situ approaches to treatment. Although this Issue Paper describes only in situ treatment, the user should keep in mind that selection of in situ technology candidates will not necessarily eliminate consideration of the ex situ options. At many sites, both in situ and ex situ technologies may be competing candidates late in the technology selection process.

Selecting a technology often requires several iterations with increasingly well-defined data to refine the selection. As the project progresses, technology-specific and site-specific information becomes available. This information must be used to better define which technologies are suitable for waste materials and conditions at the site. As the decision maker obtains more information about site conditions, waste characteristics, and treatability study results, this Issue Paper can be used to help further refine selection of candidate technologies. However, as the list of candidates is narrowed, additional published sources and expert opinion should be sought to obtain more detailed information about the candidate technologies.

2.1 Technology Characteristics

The applicability of the technology to the contaminants present, the technology maturity, and the ability of the technology to operate in the unsaturated and/or saturated zones should be considered in technology selection. The applicability of the technology to general types of contaminants is summarized in Table 2-1. The characteristics of the technologies are summarized in Table 2-2. Preliminary selection of technology candidates can be based on the capabilities of in situ technologies to treat chemical groups present at the site.

The chemical contaminant groups considered are divided into three general groups: organics, inorganics, and reactives. The types of organics considered are halogenated and nonhalogenated volatile organic compounds (VOCs), halogenated and nonhalogenated semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), pesticides, dioxins and furans, organic cyanides, and organic corrosives. Inorganics are subdivided into volatile metals (and metalloids), nonvolatile metals, asbestos, radioactive materials, inorganic corrosives, and inorganic cyanides. Reactive species may be either oxidizers or reducers. The types of materials in these subgroups are outlined below. More detailed lists of constituents within each contaminant group are given in *Technology Screening Guide for Treatment of CERCLA Soils and Sludges* (U.S. EPA, 1988, EPA/540/2-88/004, pp. 10-12).

VOCs are carbon compounds with boiling points lower than 200°C as analyzed by EPA SW-846 method 8240. SVOCs are carbon compounds, other than those covered in the more specific subdivisions, analyzed by EPA SW-846 method 8270. PCBs are any of several compounds produced by replacing hydrogen atoms in a biphenyl group with chlorine. Pesticides are compounds other than PCBs analyzed by EPA SW-846 methods 8080 or 8150. Dioxins and furans are environmentally persistent, toxic, heterocyclic hydrocarbons. Organic cyanides are carbon compounds with a CN group attached. Organic corrosives are carbon compounds that in aqueous solution have a pH less than or equal to 2 or greater than or equal to 12.5, or that exhibit a strong tendency to dissolve materials.

Volatile metals are metals or metalloids where the stable species in an oxidizing atmosphere (metal or oxide) has a boiling point less than 630°C. Nonvolatile metals are metals where the stable species in an oxidizing atmosphere (metal or oxide) has a boiling point equal to or greater than 630°C. Asbestos is any of several minerals that readily separate into long, flexible fibers. Radioactive materials are isotopes that decay by particle or energy release from the nucleus. Inorganic cyanides are compounds with a CN group attached. Inorganic corrosives are compounds that in aqueous solution have a pH less than or equal to 2 or greater than or equal to 12.5, or that exhibit a strong tendency to dissolve materials.

Substances with a strong affinity to acquire electrons are called oxidizers, whereas substances with a strong tendency to donate electrons are called reducers.

Treatment often requires a sequence of operations to deal with a combination of wastes. When evaluating wastes containing contaminants from more than one chemical constituent group, each waste group initially should be considered separately to develop a list of potentially applicable treatment technologies for each chemical group present in the soil. The technology lists can be compared to determine if some candidate technologies are able to treat all of the groups present.

If one technology is unable to treat all of the groups, development of a treatment train may be required. For example at a site with a combination of VOCs and metal contaminants, soil vapor extraction (SVE) can be used to remove the VOCs followed by in situ solidification/stabilization to reduce the mobility of the metals. The selected treatment train also must be reviewed for potential interferences or adverse effects. For example, SVE may increase the proportion of hexavalent chromium, increasing the mobility and toxicity of the chromium.

One of the following three characteristics is indicated for each in situ technology in Table 2-1:

1. Demonstrated Effectiveness – The technology has been shown to treat some contaminants in the chemical group to acceptable levels when applied to contaminated soil. Treatment may involve removal, destruction, immobilization, or toxicity reduction. The demonstration may have been at the laboratory, pilot, or production scale.
2. Potential Effectiveness – Literature reports indicate there is or is not a mechanistic basis for the technology to remove, destroy, immobilize, or otherwise treat some of the chemicals in the group when used to treat soil.
3. Possible Adverse Effects – The contaminant is likely to interfere with the treatment technology or to adversely affect safety, health, or the environment. Adverse effects may occur only when the contaminant concentration is above a threshold level. In many cases, the adverse effect may be alleviated by pretreatment to reduce the concentration of the adverse contaminant.

Table 2-2 indicates the maturity of the technology and its applicability for saturated and unsaturated media. The maturity is indicated by the ranking shown below (U.S. EPA, 1992, EPA/542/R-92/011, p. 1). Technology maturity is an important factor in the cost and timeliness of technology implementation.

1. Established Technology – The technology has been used on a commercial scale and has been established for use in full-scale remediations (e.g., incineration, capping, solidification/stabilization).
2. Innovative Technology – The technology is an alternative treatment technology (i.e., "alternative" to land disposal) for which use at Superfund-type sites is inhibited by lack of data on cost and performance.

To further assist in the review of technology candidates, Table 2-2 indicates the media typically treated, typical treatment agents or amendments, and delivery and recovery methods. Figure 2-1 shows the approximate range of in situ

Table 2-1. Effectiveness of In Situ Treatment on General Contaminant Groups for Soil

Contaminant Groups		In Situ Solidification/ Stabilization (a) (b)	Soil Vapor Extraction (b) (c)	In Situ Bioremediation (d)	Bioventing (e)	In Situ Vitrification (d) (f)	Radio-Frequency Heating (f)	Soil Flushing (b) (g)	Steam Injection	
									Stationary System (b) (f) (h)	Mobile System (b) (f) (h)
Organic	Halogenated Volatiles	X(1)	■	▼	❑	▼	▼	■	■	■
	Halogenated Semivolatiles	▼(2)	▼	▼	▼(4)	▼	▼	▼	▼	▼
	Nonhalogenated Volatiles	X(1)	■	▼	■	▼	■	▼	■	■
	Nonhalogenated Semivolatiles	▼(2)	■	▼	■	▼	■	■	▼	▼
	PCBs	▼	❑	▼	❑	▼	▼	▼	▼	❑
	Pesticides	▼	❑	▼	❑	▼	▼	▼	▼	❑
	Dioxins/Furans	▼	❑	▼	❑	▼	❑	▼	▼	❑
	Organic Cyanides	▼	❑	▼	❑	▼	❑	▼	▼	❑
	Organic Corrosives	▼	❑	X	X	▼	❑	▼	▼	❑
Inorganic	Volatile Metals	■(3)	❑	X(5)	X(5)	▼	❑	▼	▼(6)	❑
	Nonvolatile Metals	■	❑	X(5)	X(5)	▼	❑	■	▼(6)	❑
	Asbestos	■	❑	❑	❑	▼	❑	❑	❑	❑
	Radioactive Materials	■	❑	X	X	■	❑	▼	▼(6)	❑
	Inorganic Cyanides	■	❑	X	X	▼	❑	▼	▼(6)	❑
	Inorganic Corrosives	■	❑	X	X	▼	❑	▼	▼(6)	❑
Reactive	Oxidizers	▼	❑	X	X	▼	❑	▼	▼(6)	❑
	Reducers	▼	▼	X	X	▼	❑	▼	▼(6)	❑

■ Demonstrated Effectiveness: Successful treatability test at some scale completed.
▼ Potential Effectiveness: Mechanistic basis indicating that technology will work.
❑ No Expected Effectiveness: No mechanistic basis indicating that technology will work.
X Potential Adverse Effects.

(1) Vaporization and emission of volatile organic compounds may pose a hazard during mixing.
(2) Semivolatile organics are difficult to treat, but low concentrations of some compounds can be treated.
(3) Arsenic and mercury are difficult to immobilize with cement-based binder formulations.
(4) Possible to treat by cometabolism techniques.
(5) Metals can interfere with bioremediation or bioventing of organics; however, bioremediation methods for low concentrations of metals are being developed.
(6) Potential effectiveness only for water-soluble compounds.

Adapted from the following sources:
(a) U.S. EPA, 1993, EPA/530/R-93/012.
(b) Donehey et al., 1992, pp. 104-105.
(c) U.S. EPA, 1991, EPA/540/2-91/006, p. 2.
(d) U.S. EPA, 1988, EPA/540/2-88/004, p. 13.
(e) U. S. Air Force, 1992, pp. 5-10.
(f) Houthoofd et al., 1991, EPA/600/9-91/002, pp. 190-203.
(g) U.S. EPA, 1991, EPA/540/2-91/021, p. 2.
(h) U.S. EPA, 1991, EPA/540/2-91/005, p. 2.

Table 2-2. Summary of In Situ Technology Characteristics

Technology/Maturity	Media Typically Treated	Typical Agents or Amendments	Delivery Methods (see Section 3.1)	Recovery Methods (see Section 3.1)
Solidification/ stabilization (a)(b) (See Section 3.2) Established	Saturated or unsaturated soil, sediment, or sludge Approximate depth limits: 30 feet for auger system, several feet for in-place mixing, and not a major constraint for grout injection	Cement, fly ash, blast furnace slag, lime, or bitumen	Auger mixing, in-place mixing, or injection	None required
Soil vapor extraction (b)(c) (See Section 3.3) Innovative	Unsaturated soil	Air	Passive air inlet or injection wells	Air extraction wells (off-gas treatment may be required)
In situ bioremediation (d) (See Section 3.4) Innovative	Saturated or unsaturated soil, sediment, or sludge	Aqueous solution containing an electron acceptor (typically oxygen), nutrients, pH modifiers, or additives	Surface infiltration, tilling, or water injection wells	None required
Bioventing (e) (See Section 3.5) Innovative	Unsaturated soil, sediment, or sludge	Air	Passive air inlet or injection wells	Air extraction wells may be used (off-gas treatment may be required)
In situ vitrification (d)(f) (See Section 3.6) Innovative	Saturated or unsaturated soil, sediment, or sludge Approximate depth limit 20 feet with possible extension to 30 feet	Electrical energy by conduction	Electrodes	Off-gas collection and treatment
Radiofrequency heating (f) (See Section 3.7) Innovative	Unsaturated soil, sediment, or sludge	Electrical energy by radiation	Radiofrequency antennae system	Off-gas collection and treatment
Soil flushing (b)(g) (See Section 3.8) Innovative	Unsaturated or saturated soil	Water, acidic solutions, basic solutions, chelating agents, or surfactants	Extraction fluid injection wells	Extraction fluid recovery wells
Steam/hot air injection stationary system (b)(f)(h) (See Section 3.9) Innovative	Saturated or unsaturated soil	Steam and/or hot air	Steam injection wells	Condensate recovery wells and off-gas collection and treatment
Steam/hot air injection mobile (auger) system (b)(f)(h) (See Section 3.9) Innovative	Saturated or unsaturated soil Approximate depth limit: 30 feet for auger system	Steam and/or hot air	Auger mixing	Off-gas collection and treatment

Adapted from the following sources:

(a) U.S. EPA, 1993, EPA/530/R-93/012.
(b) Donehey et al., 1992, pp. 104, 105.
(c) U.S. EPA, 1991, EPA/540/2-91/006, p. 2.
(d) U.S. EPA, 1988, EPA/540/2-88/004, p. 13.
(e) U.S. Air Force, 1992, pp. 5-10.
(f) Houthoofd et al., 1991, EPA/600/9-91/002, pp. 190-203.
(g) U.S. EPA, 1991, EPA/540/2-91/021, p. 2.
(h) U.S. EPA, 1991, EPA/540/2-91/005, p. 2.

remediation costs. The costs shown are based on limited data reported in the literature. The sources rarely give full characterization of elements included in the cost estimates. The ranges should be viewed as preliminary indications of approximate comparative costs of the various technologies.

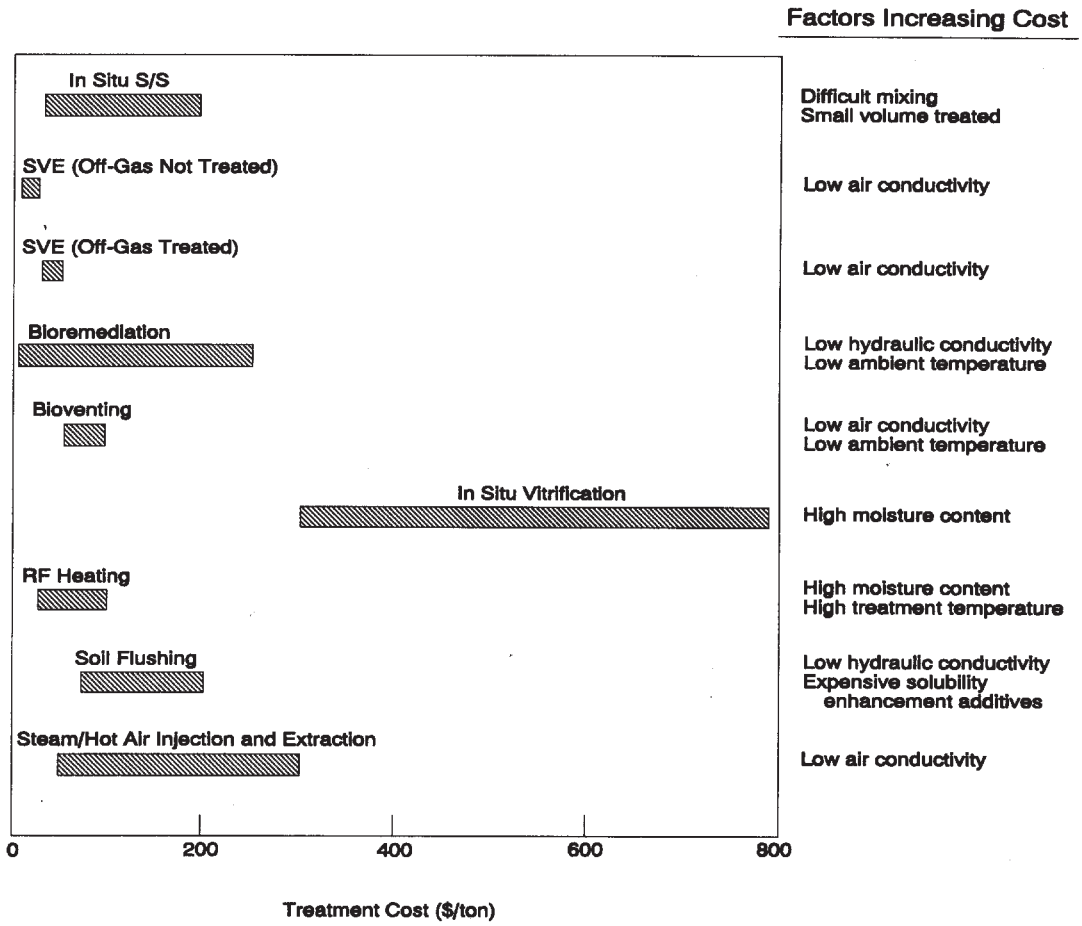

Figure 2-1. Estimated Cost Ranges of In Situ Remediation Technologies

2.2 Generic Critical Factors for Feasibility Screening of In Situ Treatment

Several critical factors apply to the evaluation of in situ treatment at most sites. These generic critical factors have broad application regardless of the specific technology. Five categories have been identified to assist in organizing consideration of the potential feasibility of the in situ treatment for a particular site. This evaluation relates to the three screening criteria named in the National Contingency Plan (NCP) instituted by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and described in the *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA – Interim Final* (U.S. EPA, 1988, EPA/540/G-89/004): effectiveness, implementability, and cost. The five categories are described in Table 2-3.

These generic factors give an overall framework for evaluating the potential for using in situ technologies. Site conditions that give a poor ranking in one or even several factors do not necessarily indicate that in situ approaches are unlikely to succeed. All of the generic and technology-specific factors (see Section 3.0) of in situ and competing ex situ technologies should be considered to indicate the general trend of applicability of in situ treatment and to help identify possible candidate treatment technologies.

The generic critical factors are geologic and in situ waste material characteristics that are significant in controlling or affecting the effectiveness or implementability of in situ technologies. Although these factors generally are of interest at all sites, some have more effect on the performance of specific technologies. The user must not draw a conclusion that in situ treatment is inappropriate based on one or two unfavorable factors. The design features of a particular technology may be able to eliminate or avoid some of the limitations inherent with most in situ treatment technologies. For example, in situ solidification/stabilization (S/S) technologies using mechanical mixing are less affected by the initial

Table 2-3. Generic Factors Influencing Selection of In Situ Treatment

Factor Influencing Selection of In Situ Treatment	Conditions Favoring Selection of In Situ Treatment	Basis
Hydrogeologic flow regime (See Section 2.2.1)	High or moderate conductivity uniformly distributed in formation or Low-conductivity regions surrounded by regions of high or moderate horizontal conductivity (a)	Treatment reagents must reach contaminated matrix by advective or diffusional flow
	Deep water table and/or competent aquitard below contaminated volume	Delivery and recovery of treatment agents must be controlled
Regulatory standards (See Section 2.2.2)	Wastes that are difficult to treat in accordance with Land Disposal Restriction (LDR) requirements	LDRs apply to excavated material, unless the material is excavated and treated within a Corrective Action Management Unit (CAMU)
Time available for remediation (See Section 2.2.3)	Completion time not critical	In situ treatment requires more time to complete than ex situ treatment
Removal logistics (See Section 2.2.4)	Large volume of waste Waste not accessible due to existing structures Excavation difficult due to matrix characteristics or depth Poor transportation infrastructure	In situ treatment does not require excavation
Waste conditions (See Section 2.2.5)	Large volume of waste Low contaminant concentrations	It is not economical to excavate large volumes for treatment of low concentrations In situ treatment may reduce the need for capital-intensive treatment equipment

(a) The low-conductivity regions must be "thin" with respect to diffusion path length, which can be feet or inches for gas-phase diffusion in dry soils and inches or less for water-phase diffusion. (See Table 2-2 for information on type of treatment agent.)

soil conductivity than are technologies that require delivery of fluid flow (see Table 2-2). Moreover, technologies such as steam injection, in situ vitrification, and radiofrequency heating, although generally slower than conventional ex situ methods, can proceed more quickly than in situ bioremediation or soil vapor extraction.

2.2.1 Hydrogeologic Flow Regime

The hydrogeologic flow regime characterizes the gas and liquid flow in the subsurface. Examination of flow regime characteristics is directed at answering questions such as the following:

- Will contaminant removal be achieved at an acceptable rate?
- Will contaminant removal be complete and uniform?
- Will contaminants or treatment agents escape from the treatment area?

The flow regime factor is controlled mainly by the amount of available primary and secondary fluid flow routes, the magnitude and homogeneity of hydraulic conductivity, fluid levels and pressures, and the proximity to a discharge location. Information needed to define the hydrogeologic flow regime includes a complete understanding of the geologic strata and how they were deposited, full characterization of the fluids and deposits for fluid transmission properties, and monitoring of soil moisture and water levels through at least three seasons of one year.

Geologic, hydraulic, and fluid-behavior data are needed to evaluate the flow regime. Geologic data include, in part, primary and secondary effective conductivity, history of geologic strata formation, and the stratigraphic and structural characteristics of the deposit. Hydrologic data include both surface water and groundwater flow, level, and pressure characteristics. Surface water data, such as stream/lake hydrographs and precipitation, infiltration, and recharge measurements, are needed to understand the general water balance of the system, whereas groundwater data, including pressure graphs, well hydrographs, and hydraulic conductivity and dispersion measurements, are needed to calculate water and mass flux through the system.

Understanding the spatial variation of conductivity also is essential to evaluate candidate in situ treatment technologies. Preferred flow pathways develop in the subsurface

due either to inhomogeneities in the conductivity or to geologic facies. Most soils have preferential flowpaths that are responsible for much of the conductivity. The preferential paths can arise from a number of causes such as root intrusions, shrink/swell or wet/dry cycling, or uneven settling (U.S. EPA, 1990, EPA/600/2-90/011, p. 39). These preferred pathways result in high hydraulic conductivity contrasts that can diminish the reliability and efficiency of in situ treatment methods. Geologic deposits with little or no vertical fracturing or with no highly developed bedding planes and those containing hydraulic conductivity contrasts of less than an order of magnitude will be conducive to in situ methods. Implementation time will be less and removal will be more complete when the system tends toward homogeneity.

A geology with uniformly distributed high conductivity is most conducive to application of in situ treatment. Hydraulic conductivity of more than 10^{-3} cm/sec is most favorable to technologies that require flow of water solutions (see Table 2-2). For technologies that require air or vapor flow (see Table 2-2), an air conductivity of more than 10^{-4} cm/sec is most favorable (U.S. EPA, 1990, EPA/600/2-90/011, pp. 40 and 54). In situ treatment still can be applied in geologies with much lower conductivities. However, contaminant transport in the lower conductivity regions will occur by slower diffusion processes rather than by bulk material flow. Feasibility depends on the type of treatment agent, the contaminant transport mechanisms, and the details of the distribution of the primary and secondary flowpaths.

Many in situ treatment technologies require injection of treatment agents such as steam, chemicals, or nutrients. Often the treatment agents must then be collected from the subsurface for further processing. The subsurface geology should be amenable to containment of the treatment agents in the contaminated area. Containment will be maximized when vertical and horizontal hydraulic gradients are low or if the treatment zone is bounded geologically by deposits with low hydraulic conductivity. Close proximity to groundwater discharge areas such as streams, lakes, and seeps can jeopardize containment of in situ treatment agents.

2.2.2 Regulatory Standards

The regulatory standards factor characterizes the overall regulatory climate at the site based on federal, state, and local regulations. Examination of regulatory standards is directed at answering questions such as these:

- What contaminant cleanup levels are required?
- Are land-use restrictions consistent with the candidate technologies?
- Will in situ treatment cause unacceptable alteration of soil conditions?
- Is injection of treatment chemicals consistent with Land Disposal Restrictions (LDRs) and other regulations, as required?

If the site is a CERCLA site, 40 CFR 300.400(g) requires that any remedial alternative must satisfy (or provide a waiver of) all Applicable or Relevant and Appropriate Requirements (ARARs). Applicable requirements include federal and state environmental standards, cleanup standards, and control standards that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site. Relevant and appropriate requirements are standards that are not "applicable" but that specifically address a problem or situation sufficiently similar to those encountered at a CERCLA site (i.e., their use is well suited to the particular site).

If the site is not a CERCLA site, it will not need to satisfy a formal list of ARARs; however, it is probable that certain regulatory requirements must still be met in the cleanup. In either case, these requirements will be specific to the site where treatment will occur and may vary from site to site.

Cleanup levels are one of the most important of the regulatory requirements that will determine whether in situ treatment is potentially acceptable. Treatability studies will help to determine if an in situ treatment method can meet the required performance levels. For extraction technologies, the total residual contaminant levels must be determined to demonstrate remediation. For technologies that reduce contaminant mobility, such as S/S or in situ vitrification, the cleanup levels will be stated in terms of leaching resistance. Leaching data such as results from the Toxicity Characteristic Leaching Procedure (TCLP) or other leaching tests will be needed to demonstrate that the method immobilizes the contaminants. The ability to demonstrate that an in situ treatment method meets the regulatory performance requirements will determine the acceptability of that type of treatment method. Thus, regulatory requirements should be considered at the screening level to the extent that they are known. Although the requirements may not have been finalized at the time screening is conducted, the most current list available should be used.

In situ treatment may require more extensive sampling than ex situ treatment to demonstrate that required treatment performance levels have been achieved. With in situ treatment, the variation in natural conditions and the distribution of the contaminant must be determined. This often requires extensive sampling to build a statistical basis for evaluating whether or not analytical results represent in situ conditions. In contrast, in a typical ex situ treatment system, waste material is excavated, prepared, and homogenized as part of the treatment operation. These homogenized batches can be represented with a smaller number of samples than corresponding in situ materials.

In the past, regulatory requirements favored in situ treatment in some cases because excavation of contaminated material would have caused it to be treated as a RCRA waste subject to the treatment standards and Best Demonstrated Available Technologies (BDATs) under the LDRs. Recently, however, the EPA published a final rule allowing the use of Corrective Action Management Units (CAMUs) at RCRA sites (58 FR 8658, February 16, 1993), which can eliminate this advantage for in situ treatment. Although these regulations were developed for corrective actions at RCRA facilities, the regulations also may be

applied as ARARs to CERCLA sites, particularly where CERCLA remediation involves management of RCRA hazardous wastes. A CAMU is defined as:

> "an area within a facility that is designated by the Regional Administrator under part 264 subpart S, for the purpose of implementing corrective action requirements under section 264.101 and RCRA section 3008(h). A CAMU shall only be used for the management of remediation wastes pursuant to implementing such corrective action requirements at the facility" (40 CFR 260.10).

CAMUs were designed to provide more flexibility in treatment of waste generated during corrective actions. An important provision of the new regulations is the specification in 40 CFR 264.552(a)(1) and (2) that:

> "(1) Placement of remediation wastes into or within a CAMU does not constitute land disposal of hazardous wastes; and
> (2) Consolidation or placement of remediation wastes into or within a CAMU does not constitute creation of a unit subject to MTRs (minimum technology requirements)."

As a result, an area or several areas at a RCRA facility (or CERCLA site) can be designated as a CAMU and the wastes can be removed from the ground, treated, and replaced within the boundaries of that CAMU without being required to comply with the LDR treatment standards. EPA's goal in issuing these regulations is to encourage the use of more effective treatment technologies at a specific site. In situ treatment could still be the favored option at sites where the Regional Administrator does not establish a CAMU and where the ex situ treatment is subject to treatment standards and BDAT under the LDRs.

Technologies that accomplish the treatment in situ may reduce or eliminate point source air emissions or other discharges. Many in situ treatment technologies, however, do have aboveground components. For example, materials are injected; groundwater is extracted, treated, and reinjected; or vapors are captured and treated. The aboveground portion still may be subject to appropriate environmental regulations. Technologies that require injection of fluids may need to follow Underground Injection Control regulations.

2.2.3 Time Available for Remediation

The available time factor characterizes the amount of time allowed to set up, operate, and remove the treatment technology. Determining the time available to complete remediation is directed at answering questions such as:

- Can the cleanup be completed in a time frame consistent with health, safety, and environmental protection?
- Can the cleanup be completed in a time frame consistent with end-use requirements?

The time available for remediation is controlled first by the need to protect human safety and health and the environment. Remediation must proceed quickly if a toxic contaminant is present, the contaminant concentration is high, or the contaminant is mobile and near a critical ecosystem. Time available may be controlled also by the value or intended end use for the site. It is undesirable to hold a high-value site out of productive use for a long period.

In situ remediation typically requires more treatment time than the analogous ex situ treatment technology. In situ bioremediation, for example, typically requires about 4 to 6 years (U.S. EPA and U.S. Air Force, 1993, p. 60). Excavation allows essentially immediate remediation of the site. However, the excavated material often must be shipped and stored before treatment. Rapid remediation is needed if the contaminant presents an imminent danger due to hazard level, mobility, or other factors. Rapid remediation of an imminent hazard generally favors an ex situ remediation approach.

The importance of the length of remediation time may be lessened if the time constraint is driven by economic or end-use requirements. Many in situ technologies can be applied concurrently with other site operations. For example, well and injection/extraction equipment for bioventing, soil vapor extraction, or fixed-system steam injection do not occupy the full surface area of a site. Depending on the technology and the site use, it may be possible to continue routine site operations during an in situ remediation. However, the need for rapid remediation still generally increases the favorability of ex situ treatment technologies.

2.2.4 Removal Logistics

The removal logistics factor characterizes the feasibility of excavating, handling, and transporting the contaminated soil. Examination of removal logistics is directed at answering questions such as:

- Is the material accessible for excavation?
- Can the contaminated soil or water be moved efficiently by conventional bulk material-handling equipment and techniques?
- Will on-site (and if needed off-site) infrastructure support transport of waste materials?

Removal logistics are determined by access to the contaminated site for excavation, the ability to handle excavated materials, space for placement of ex situ treatment equipment, and the road and rail system on and around the site.

Data needed to evaluate the removal logistics include a map of the site showing the general arrangement of structures and infrastructure and an approximate assessment of the subsurface conditions such as the location of contamination and the location of major geologic and hydrogeologic features such as surface water and aquifers.

Poor removal logistics favor in situ treatment. In situ treatment generally is favored by conditions such as contamination located under a building that is to remain after remediation; presence of buried piping or utility lines in the area; contamination located at great depth or under a rock formation; poor road or rail access; nearby businesses, schools, or heavy traffic areas; or site location in a remote area distant from treatment facilities or sources of backfill. Contamination located deeper than 5 feet or occupying a volume of more than 1,000 m^3 increases both the cost and the complexity of excavation (U.S. EPA, 1990, EPA/600/2-90/011, p. 60). Specialized delivery and recovery systems may be necessary to overcome poor site logistics.

2.2.5 Waste Conditions

The waste conditions factor characterizes the chemical and physical form of the waste with respect to the ability to effectively treat or remove the contaminant. Examination of waste conditions is directed at answering questions such as:

- Are the concentration and distribution of contaminants consistent with effective in situ treatment?
- Does the waste distribution or condition allow effective delivery of treatment agents to the contaminant?

The waste conditions factor is controlled by the in situ conditions of the contaminant and matrix. The conditions requiring characterization include the concentration and distribution of the contaminant, the chemical form and speciation of the contaminant and matrix, and physical properties of the waste and matrix.

Data needed to characterize the waste conditions include a survey of the location, concentration measurements, and a description of the form of contaminant, matrix, and debris in the remediation site. Some soil sampling data may be available, but assessment of the waste condition at the preliminary evaluation stage typically will be based largely on historical records.

The understanding of waste conditions must be constantly reevaluated as additional data are obtained. In addition to estimating the areal extent and concentration of contamination, the assessment must address the possibility of the contaminant being contained in drums or tanks and the potential presence of noncontaminant debris that could make excavation difficult or obstruct the flow of in situ treatment agents.

In general, contaminants that are either highly concentrated or spread over a relatively small area are best treated by ex situ methods. In particular, contaminants contained in drums or underground tanks are difficult to treat with in situ methods. Dilute or widely distributed contaminants tend to favor in situ treatment. When the contaminant is present at low concentration, ex situ processing requires excavation, handling, and, processing of a high proportion of matrix materials relative to a small amount of contaminant.

3.0 Technology-Specific Factors

This section outlines the characteristics of in situ technologies and describes factors identified by current testing programs as influencing the effectiveness, implementability, and cost of specific in situ treatment technologies. Reviewing these technology-specific critical factors will help guide planning of site characterization activities and identification of technology candidates. Where possible, specific values are given to indicate what level of a factor is favorable for application of in situ treatment.

The user must consider all of the generic factors (see Table 2-3) and technology-specific factors during evaluation of technology alternatives. The more important factors are indicated in Tables 3-1 to 3-8 by an asterisk (*) to assist in the evaluation. However, the evaluation must not focus on only one factor or one technology. All of the factors should be evaluated for all technologies that are potentially effective for the contaminants present at the site. After full consideration of all the factors, the decision maker can examine the overall indications for favorable and unfavorable trends to identify technologies with a high probability of being effective and implementable. The generic factors will help indicate if in situ approaches are generally favored for the site and contaminants in question. If an in situ technology seems attractive, the technology-specific factors can help guide selection of a group of candidates for more detailed testing and evaluation.

The success or failure of an applied technology often depends on site-specific conditions or design features. Selection of technology candidates should be based on site-specific knowledge and requirements, tempered by the overall effect of all of the critical factors. Treatability testing typically will be required to support final technology selection prior to completion of the feasibility study (FS) or preparation of the Record of Decision (ROD) (U.S. EPA, 1992, EPA/540/R-92/071a).

Action levels are provided where possible to give a starting basis for considering technology alternatives. The action levels give an approximate "yardstick" to use when considering technology candidates. However, these single-value indications cannot characterize or summarize all of the complex situations that occur in practice. There is no substitute for experience, site-specific knowledge, and treatability testing. The user must be aware of the limitations of giving a single value to characterize complex interactions.

Site-specific conditions can cause the action levels to be different at a particular site or with a particular combination of contaminant and matrix. Design or operating features may be applied to overcome technology limitations. For example, at a site where in situ bioremediation is ideal except for the condition of low soil temperature, a number of methods are available to improve the soil energy balance. Many of the technology-specific critical factors show threshold effects. The factor may have an important effect at some level but have no effect below the cutoff level. For example, metals such as zinc are trace nutrients at low levels but toxic to biological systems at higher levels.

3.1 Delivery and Recovery Systems

Efficient delivery and recovery methods control the effectiveness, implementability, and cost of in situ treatment. An array of delivery techniques are available to apply or inject treatment fluids into the subsurface. The types of delivery systems for in situ treatment can be classed generally as gravity driven, pressure driven, auger mixing, and energy coupling. Recovery systems typically fall in the gravity-driven or pressure-driven classification (U.S. EPA, 1990, EPA/600/2-89/066, p. 2).

With the exception of radiofrequency heating and in situ vitrification, the in situ treatment methods discussed below require delivery and control of liquid, slurry, gas, vapor, or a combination in the soil. For some technologies (see Table 2-2), the fluids also must be recovered after passing through the contaminated in situ volume. Fluid delivery may be accomplished by conventional gravity infiltration through surface or trench application or by pressure injection through wells. Conventional recovery methods include trenches or wells. The conventional methods rely on flow patterns determined by the design and placement of the drains or wells and the subsurface stratigraphy. As described below, innovative techniques are available to modify the subsurface conditions to improve flow rates or flow control.

In situ treatment agents, summarized in Table 2-2, include fluids delivered to the contaminated volume. Possible treatment fluids include hot gasses or vapors; water; or water-containing nutrients, surfactants, anions, cations, bacteria, S/S binder, or other treatment agents. For a technology to be effective, implementable, and economically competitive; the treatment agents must be delivered in a well-controlled manner. Conventional gravity- and pressure-driven methods are available to deliver and recover fluids. Gravity-driven methods rely on infiltration and collection due to hydraulic gradients. Typically delivery is by surface distribution and collection is by trench or similar drains. Pressure-driven methods rely on pressure gradients supplied by a source pump, a blower or steam generator, or an extraction pump or blower. A system of wells typically is used for delivery and recovery. The conventional delivery and recovery systems are highly dependent on the physicochemical environment in the subsurface.

Innovative approaches are being developed and tested to improve the performance of delivery and recovery technologies in low-conductivity or heterogeneous geologic settings. The innovative delivery and recovery technologies may be devised to increase the conductivity in the treatment zone, decrease the conductivity below the treatment zone, or improve the efficiency of contact between the treatment agents and the material to be treated. Conductivity modification technologies include hydraulic fracturing, pneumatic fracturing, radial well drilling, jet slurrying, and kerfing. Technologies to improve the distribution or application efficiency of treatment agents include colloidal gas bubble (aphron) generation, ultrasonic methods, and cyclic pumping or steaming (U.S. EPA, 1990, EPA/540/2-90/002, p. 96).

Auger-mixing technologies have been developed to deliver treatment agents with less reliance on a favorable existing geology. Auger mixing is applicable to delivery but not to recovery of treatment agents. The main examples of auger delivery are steam injection and addition and mixing of solidification/stabilization binders with augers. One vendor is testing auger mixing for addition of bioremediation nutrients.

Technologies to apply energy rather than fluids also are available for in situ treatment. Energy delivery systems reduce dependence on in situ conductivity but are sensitive to other in situ parameters. The key to energy delivery is good coupling of the electric or electromagnetic field to the soil being heated. The electric properties change as the moisture content changes. The energy input processes vaporize water so the electrical coupling properties of the soil must change as treatment proceeds. The changing soil properties increase the challenge in designing an efficient energy application system.

Systems for pneumatic fracturing and hydraulic fracturing to improve subsurface conductivity and a system to inject oxygen microbubbles to remediate groundwater have been accepted in the SITE Program. The demonstration of a pneumatic fracturing system was completed at a site located in South Plainfield, New Jersey (Mack and Aspan, 1993, p. 321). The Applications Analysis Report is in preparation (U.S. EPA, 1992, EPA/540/R-92/077, p. 5).

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3.2 In Situ Solidification/Stabilization

In situ solidification/stabilization refers to treatment processes that mix or inject treatment agents into the contaminated material in place to accomplish one or more of the following objectives:

- Improve the physical characteristics of the waste by producing a solid from liquid or semiliquid wastes
- Reduce the contaminant solubility
- Decrease the exposed surface area across which mass transfer of contaminants may occur.

In situ S/S relies on the delivery and effective mixing of binders with the contaminated soil. The critical factors applicable for in situ solidification/stabilization with inorganic binders such as cementitious materials (cements and pozzolans), silicates, or lime are shown in Table 3-1.

Table 3-1. Solidification/Stabilization Critical Factors and Conditions for Cement-Based Treatment Systems[a]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Presence of VOCs (*)	<50 ppb (1)(2)	• VOCs can vaporize during processing or curing; therefore, low levels of VOCs are favorable • Organic materials can interfere with bonding	• Analysis for VOCs • Treatability tests measuring volatile emissions
Contaminant depth (*)	Varies with technology (1)	• In-place mixing with conventional construction type equipment is limited to near surface • Auger systems demonstrated to 30 feet • Grout injection depth typically is not a major limitation	• Waste composition and spatial distribution
Specific gravity, viscosity, and general mixing properties (*)	No action levels specified (1)(3)	• Good mixing is needed to ensure contact of the waste and binder so a good S/S product is obtained	• Waste-specific gravity • Waste particle morphology and size distribution • Waste viscosity
SVOC content of waste (*)	SVOCs <10,000 ppm (4)	• Organic materials can interfere with bonding • SVOCs can vaporize during processing or curing; therefore, low levels of volatile compounds are favorable (due to heat evolution in some processes, the favorable limit can be much lower for some contaminants and S/S binder combinations)	• Analysis for SVOCs and PAHs • Treatability tests measuring volatile emissions
Oil and grease content of waste (*)	No action levels specified (1)	• Oil and grease can coat the waste particles inhibiting setting or reducing the strength of the final product	• Analysis for oil and grease
Leachability data (*)	No action levels specified (2)	• Mobile and soluble materials are more difficult to treat	• Leachability testing
Phenol content	<5% (5)	• Phenol concentration greater than 5% can reduce the compressive strength of the final product	• Phenol content in waste
Fine particle	Limited amount of fine insoluble particulate (4)	• Fine particulates can coat the waste particles and weaken the bond between the waste solids and cement	• Particle-size analysis, particularly size fraction under 200 mesh
Soluble inorganic salts (e.g., chlorides) not targeted by binder formulation	No action levels specified (1)	• Low concentrations are more favorable • Threshold effects commonly occur • Above some concentration levels, soluble salts can reduce the physical strength of the final product, cause large variations in setting time, or reduce the dimensional stability of the cured matrix	• Treatability testing • Analysis of inorganic content
Cyanide content of the waste	<3,000 mg/kg (4)	• Cyanides interfere with bonding of waste materials	• Analysis for cyanides
Sulfate content of the waste	<1,500 ppm for Type I Portland cement (6) Various cement types can tolerate higher sulfate levels but no action level specified (6)(3)	• Presence of sulfates can retard setting • High sulfate levels in waste can cause treated waste to spall during curing due to formation of expansive hydrates	• Analysis for sulfate
Binder heat of hydration	No action levels specified (5)	• Large amount of heat generated by binder hydration reactions, particularly in large mass treatment, can increase temperature and volatilize organic contaminants	• Total and time-dependent heat output due to hydration of binder • Treatability tests measuring volatile emissions

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.
(1) Conner, 1990, pp. 189, 205, and 464-477.
(2) U.S. EPA, 1993, EPA/530/R-93/012, pp. 4-51 and A-8.
(3) U.S. EPA, 1990, EPA/540/2-90/002, pp. 14-16.
(4) U.S. EPA, 1988, EPA/540/2-88/004, p. 93.
(5) U.S. EPA, 1991, EPA 540/2-91/009, p. 3.
(6) Arniella and Blythe, 1990, p. 93.

The most common binders are Portland cement, pozzolans (siliceous or aluminous materials that can react with calcium hydroxide to form compounds with cementitious properties), and cement/pozzolan mixtures. Inorganic binder systems using sodium silicate, cement/silicate, or proprietary binder systems also are in use. Solidification/stabilization encompasses a wide variety of physical and chemical mechanisms to reduce contaminant mobility and/or impart other desirable properties to the waste. S/S treatment using inorganic binders ties up free water by hydration reactions. Mobility of inorganic compounds can be reduced by formation of insoluble hydroxides, carbonates, or silicates; substitution of the metal into a mineral structure; sorption; physical encapsulation; and other mechanisms.

S/S treatment of organic contaminants with cementitious formulations is more complex than treatment of inorganic contaminants. Wastes where organics are the primary contaminant of concern generally are not suited to S/S treatment because of the potential for volatilization of organics and reduced S/S product quality when organics are present. This is particularly true with VOCs where the mixing process and heat generated by cement hydration reactions can increase organic vapor losses. However, S/S can be applied to wastes that contain lower levels of organics (particularly when inorganics are present at high concentrations) and/or the organics have a low vapor pressure, high water solubility, or both. Furthermore, recent studies have indicated that addition of silicates or modified clays to the binder system may improve S/S performance with organics (U.S. EPA, 1993, EPA/530/R-93/012, pp. 4-12 and 4-13).

The most significant challenge in applying S/S in situ for contaminated soils is achieving complete and uniform mixing of the binder with the contaminated matrix (U.S. EPA, 1990, EPA/540/2-90/002, p. 12). Three basic approaches are used for mixing the binder with the matrix:

- Vertical auger mixing
- In-place mixing
- Injection grouting.

In vertical auger mixing, a system of augers is used to inject and mix binder into the soil. Auger-type mixing systems developed by Novaterra (formerly Toxic Treatments USA); International Waste Technologies (IWT)/Geo-Con, Inc.; and S.M.W. Seiko, Inc. have been accepted in the Superfund Innovative Technology Evaluation (SITE) Demonstration Program. SITE demonstrations have been completed for the Novaterra (U.S. EPA, 1991, EPA/540/A5-90/008) and IWT systems (U.S. EPA, 1990, EPA/540/A5-89/004). The treatment depth is limited by the length of available auger equipment. Current testing indicates a limit of about 30 feet. Based on the SITE Program test of in situ S/S using the IWT/Geo-Con auger system, estimated treatment costs were $111/ton and $194/ton for 4-auger and 1-auger systems, respectively. The costs included equipment, startup and fixed costs, labor, supplies, utilities, analytical, facility modification, and demobilization (U.S. EPA, 1990, EPA/540/A5-89/004, p. 26). Note that some of the auger systems, particularly the Novaterra system, may inject steam (or steam and hot air) instead of binders to perform steam stripping of organics. These operations are discussed in Section 3.9.

In-place mixing involves spreading and mixing of binder reagents with waste by conventional earth-moving equipment such as draglines, backhoes, or clamshell buckets. The technology is applicable only to surface or shallow deposits of contamination.

The reported cost of in-place mixing is $38/yd^3. The cost includes labor, equipment, monitoring and testing, reagents, and miscellaneous supplies. Not included are costs for equipment mobilization and demobilization, engineering and administration, and health and safety (Arniella and Blythe, 1990, p. 101).

For injection grouting, a binder containing dissolved or suspended treatment agents is forced into the formation under pressure and allowed to permeate the soil. Grout injection can be applied to contaminated formations lying well below the ground surface. The injected grout then cures in place to give an in situ treated mass. Grout injection is widely used for soil stabilization. A grouting system for very fluid wastes developed by Hazardous Waste Control has been accepted for testing in the SITE Program (U.S. EPA, 1992, EPA/540/R-92/077, p. 100).

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3.3 Soil Vapor Extraction

In situ soil vapor extraction (SVE) is the process of removing VOCs from the unsaturated zone to the surface for treatment. Blowers attached to extraction wells alone or in combination with air injection wells induce airflow through the soil matrix. The airflow strips the volatile compounds from the soil and carries them to extraction wells. The process is driven by partitioning of volatile materials from condensed phases (sorbed on soil particles, dissolved in pore water, or nonaqueous liquid phases) to the clean air being introduced by the vacuum extraction process. Air emissions from the systems typically are controlled ex situ by adsorption of the volatiles onto activated carbon, thermal destruction (i.e., incineration or catalytic oxidation), or condensation by refrigeration (U.S. EPA, 1991, EPA/540/2-91/006, p. 3). Application of soil vapor extraction relies on the ability to deliver, control the flow, and recover stripping air. A decision logic for treatability testing based on contaminant vapor pressure and air permeability of the soil has been described in the literature (U.S. EPA, 1992, EPA/600/K-92/003, pp. 4-8 and 4-9).

The critical factors to consider during review of SVE technology application are presented in Table 3-2. The SVE

Table 3-2. Soil Vapor Extraction Critical Factors and Conditions[a]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Contaminant vapor pressure, P_v (*)	P_v >0.5 mmHg at 20°C (Reference describes decision logic) (1)	• Contaminants of higher volatility are more easily removed by air stripping	• Contaminant vapor pressure at expected soil temperature
Air conductivity of soil (*)	>10^{-4} cm/sec (2) (Decision logic described) (1)	• High conductivity results in a large radius of influence for extraction wells	• Hydrogeologic flow regime
Soil moisture content (*)	<10 volume % (2)	• Soil moisture inhibits airflow and can reduce vapor pressure of soluble organics	• Soil moisture content
Clay content of soil (*)	No action levels specified (1)	• Low clay content is desirable • Presence of clay increases sorption and inhibits volatilization	• Soil composition • Soil color • Soil texture
Humic content in soil (*)	No action levels specified (3)	• Low humic content is desirable • Presence of humic materials increases sorption and inhibits volatilization	• Soil composition • Soil color • Soil texture
Soil sorption capacity (*)	Specific surface area <0.1 m^2/g (2)	• Contaminants held by sorption mechanisms are more difficult to remove	• Soil-specific surface area • Soil absorption isotherms
Contaminant water solubility (*)	<100 mg/L (2)	• Dissolved organics are more difficult to remove by air stripping	• Contaminant solubility at expected soil temperature
Henry's law constant (*)	>0.001 dimensionless (4)	• Compounds that partition to the vapor phase are more easily removed by stripping	• Henry's law constant
Dominant contaminant phase	Contaminant present as a separate phase (vapor or liquid) and not sorbed to the soil (2)	• Vapors are more easily removed by air stripping	• Contaminant composition and physical form
Soil temperature	>20°C (2)	• Higher soil temperatures are more favorable to volatilization	• Soil temperature
Depth to groundwater	Contaminant in the unsaturated zone (2)(5)	• Technology only effective in the unsaturated zone • Need to avoid water intrusion into extraction wells	• Depth to groundwater • Seasonal variation of groundwater conditions

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.
(1) U.S. EPA, 1992. EPA/600/K-92/003, pp. 4-8 and 4-9.
(2) U.S. EPA, 1990. EPA/600/2-90/011, p. 40.
(3) U.S. EPA, 1988. EPA/540/2-88/004, p. 89.
(4) U.S. EPA, 1992. EPA/540/R-92/077, p. 175.
(5) U.S. EPA, 1991. EPA/540/2-91/003, p. 52.

technology has been used in commercial operations for several years. It has been chosen as a component of the RODs at more than 80 Superfund sites (U.S. EPA, 1992, EPA 542/R/92-011, pp. 31-46).

Vertical wells are the most widely used SVE design method. Vertical wells are best used at sites where the contamination extends far below the land surface. Horizontal wells or trenches may be more practical than vertical wells where the depth to groundwater is less than 12 feet. Vertical wells generally are inappropriate for sites with a shallow water table due to the potential upwelling of the water table that may occur after application of a high vacuum (U.S. EPA, 1991, EPA/540/2-91/003, p. 52).

SVE systems have been accepted in the SITE Program (U.S. EPA, 1992, EPA/540/R-92/077). SITE demonstrations of soil vapor extraction systems were completed at a Superfund site in Burbank, California (U.S. EPA, 1991, EPA/540/-A5-91/002) and a Superfund site in Groveland, Massachusetts (U.S. EPA, 1989, EPA/540/A5-89/003). A reference handbook on soil vapor extraction (U.S. EPA, 1991, EPA/5-40/2-91/003) and screening computer software for an approach to the design, operation, and monitoring of SVE systems are available (U.S. EPA, 1993, EPA/600/R-93/028).

Based on available data, SVE treatment cost estimates typically are $50/ton for treatment of soil. The reported estimates of cost ranges are $15 to $60/yd^3 (U.S. EPA, 1990, EPA/600/2-90/011, p. 40) and $27 to $66/ton (U.S. EPA, 1989, EPA/540/A5-89/003, p. 11). The cost ranges

include consideration of site preparation; equipment purchase, installation, and operation; residual well cuttings disposal; analysis; and demobilization. The high end of the range includes off-gas treatment, whereas the lower cost does not. Off-gas treatment can amount to more than 50% of the total cost of an SVE system (U.S. EPA, 1990, 937.5-06/FS, p. 3-141).

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3.4 In Situ Bioremediation

In biological processes, microorganisms degrade organic compounds either directly to obtain carbon and/or energy, or fortuitously in a cometabolic process with no significant benefit to the microorganism. The ultimate goal of in situ bioremediation is to convert organic contaminants into biomass and innocuous by-products of microbial metabolism such as carbon dioxide, inorganic salts, and water. Successful in situ bioremediation can occur only if microbial populations are present that can be stimulated to degrade the contaminants of concern. In situ bioremediation capitalizes on natural biological processes to enhance in situ degradation of organic contaminants. Although biodegradation of organic contaminants occurs naturally in situ, often a critical factor, such as oxygen, is limiting, thus limiting the amount of biodegradation that can occur.

To increase the amount of biodegradation that occurs, in situ amendments often are necessary. These amendments may include electron acceptors (such as oxygen), carbon sources, moisture, nutrients, or heat. The critical factors to consider during review of in situ bioremediation applications are presented in Table 3-3.

Bacteria, actinomycetes, and fungi in the subsurface make up the most significant group of organisms involved in biodegradation. These communities are diverse and adaptable, capable of taking advantage of xenobiotic compounds. Microbial populations at older sites generally are acclimated to the contaminants of concern. Consequently, lack of biodegradation in situ rarely is due to lack of populations able to degrade the compounds, but more likely is due to environmental conditions that limit the extent and rate of biodegradation. Typically the most important parameters are electron acceptor availability, moisture levels, temperature, pH, and nutrients.

Another critical parameter affecting the extent of in situ bioremediation is bioavailability of the contaminant(s) of concern. Bioavailability is a general term to describe the accessibility of contaminants to the degrading populations. Bioavailability consists of (1) a physical aspect related to phase distribution and mass transfer, and (2) a physiological aspect related to the suitability of the contaminant as a substrate (U.S. EPA, 1993, EPA/540/S-93/501, p. 4). Compounds with greater aqueous solubilities and lower affinity to sorb onto the soil generally are more bioavailable to soil microorganisms and are more readily degraded. Bioavailability also depends on the suitability of the compound as a metabolic substrate or cosubstrate.

Aerobic (>0.2 mg/L oxygen) or anaerobic conditions may predominate in the subsurface. Mineralization of many organic compounds occurs aerobically; therefore, aerobic bioremediation is the most developed and most feasible in situ biotechnology. In situ bioremediation under aerobic conditions involves delivering oxygen and nutrients to the subsurface through an injection well or infiltration system. The oxygen and nutrients enhance the activity of indigenous aerobic microorganisms that degrade the contaminants of concern. In general, aerobic processes can be suitable for remediation of petroleum hydrocarbons, halogenated and nonhalogenated aromatics, polyaromatic hydrocarbons, halogenated and nonhalogenated phenols, biphenyls, organophosphates, and some pesticides and herbicides. Biodegradation rates are compound specific, so treatability judgments should be based on literature data for the contaminants present or on treatability tests.

Although mineralization of many compounds occurs aerobically, some halogenated hydrocarbons may be transformed under anaerobic conditions. These halogenated hydrocarbons include unsaturated alkyl halides (e.g., PCE and TCE) and saturated alkyl halides (e.g., 1,1,1-trichloroethane and trihalomethane). In addition, supplying nitrate as an electron acceptor under anaerobic conditions may allow biodegradation of some phenols, cresols, and lower-molecular-weight polycyclic aromatic hydrocarbons (PAHs).

Anaerobic bioremediation is at a much earlier stage of development than aerobic bioremediation. Establishing and maintaining anaerobic conditions in situ is more difficult than establishing and maintaining aerobic conditions. Anaerobic treatment systems can have undesirable secondary effects such as formation of volatile forms of metals (such as methylated mercury or arsines), toxic "deadend" intermediates such as vinyl chloride and hydrogen sulfide, or nuisance odor compounds.

Addition of amendments to promote in situ biodegradation generally relies on the ability of aqueous solutions to infiltrate into the contaminated area. Aqueous-supplied amendments have met with limited success, as the electron acceptor or nutrient often is metabolized before it reaches the contaminated area. Consequently, there is a high level of microbial activity near or in the infiltration wells, often resulting in plugging and poor flow.

In extreme environments, moisture or heat addition may significantly improve bioremediation processes. Surface insulation, warm water infiltration, and buried heat tape have been used to increase the soil temperature. Their use has

Table 3-3. Bioremediation Critical Factors and Conditions[a]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Spatial variation of waste composition or concentration (*)	No action levels specified (1)	• Homogeneous conditions are desirable • Large variation in the contaminant concentration causes variation in biological activity giving inconsistent biodegradation	• Waste composition and spatial distribution
Contaminant biodegradability (*)	Ratio of biological oxygen demand (BOD) to chemical oxygen demand (COD) >0.1 (3)	• Resistance to biological action inhibits decontamination	• Waste composition • Waste BOD and COD • Presence of metals or salts • Treatability testing
Oxygen content (*)	Aerobic metabolism: dissolved O_2 >0.2 mg/L (4) Air-filled pore space of >10% (4) Anaerobic metabolism: gas-phase O_2 concentration <1% (4)	• Oxygen depletion slows aerobic biological activity • Oxygen is toxic to anaerobic systems	• Oxygen monitoring
Available soil water (*)	>25% and <85% of water-holding capacity (4)	• High moisture content reduces bacterial activity by limiting the transport of oxygen • Low moisture content inhibits bacterial activity	• Percent water saturation of pores
Presence of elevated levels of metals, highly chlorinated organics, pesticides and herbicides, or inorganic salts (*)	No action levels specified (1)	• Materials can be toxic to microorganisms • Lower levels are desirable • Threshold effects commonly occur	• Identification of specific compound, oxidation state (metals), and concentration
In situ temperature	>10°C (3) Optimum temperature typically 20°C to 40°C (5)	• Optimum temperature range increases growth rate • More diverse microbial populations are present in optimum range	• Temperature history and/or monitoring covering at least three seasons
Soil nutrient content	Carbon/nitrogen/phosphorus ratios about 100:10:1 (4) Carbon/sulfur ratio noted as important but no action level specified (1)	• Lack of adequate nutrients slows biological activity	• Carbon/nitrogen/phosphorus ratio • Form of nitrogen (e.g., nitrate, ammonia, organic nitrogen) • Carbon/sulfur ratio
Water solubility	>1,000 mg/L (2)	• Contaminants with low solubility generally are more difficult to degrade • Toxic contaminants with high solubility, however, may be more effective in suppressing bioactivity	• Contaminant solubility in water at treatment temperature
pH	Between 5-9 pH units (5)	• When pH is outside of range, biological activity is inhibited	• Soil pH
Redox potential	Aerobes and facultative anaerobes: >50 millivolts (mV) (4) Anaerobes: <50 mV (4)	• Reflects oxygen availability in the soil • Indicates the oxidation/reduction potential of the matrix	• Soil redox potential
Organic carbon content	Total organic carbon (TOC) of groundwater between 10 and 1000 mg/L (3)	• Low concentrations may cause organisms to favor other food; high concentrations may be toxic to the organisms	• TOC

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.
(1) U.S. EPA, 1988, EPA/540/2-88/004, p. 114.
(2) U.S. EPA, 1990, EPA/600/2-90/011, p. 48.
(3) U.S. EPA, 1990, EPA/600/2-90/027, p. 85.
(4) U.S. EPA, 1993, EPA/540/S-93/501, p. 3.
(5) U.S. EPA, 1990, EPA/540/2-90/002, pp. 40 and 47.

resulted in increased microbial activity and contaminant degradation (Leeson et al., 1993).

The reported costs for application of in situ bioremediation range from $14 to $98/ton (U.S. EPA and U.S. Air Force, 1993, p. 60). The EPA Vendor Information System For Innovative Treatment Technologies (VISITT), Version 2, contains information from 11 vendors on in situ soil bioremediation technologies. The costs indicated by the vendors typically range from $8 to $250/yd^3 (U.S. EPA, 1993, EPA/542/R-93-001).

A variety of in situ bioremediation systems have been accepted in the SITE Program. Technologies include the use of naturally occurring microorganisms, addition of cultured bacteria, and addition of white-rot fungi. Water and nutrients generally are applied by well injection or infiltration. However, one technology assembles a containment tank in situ to form a controlled area for the bioremediation, and one technology uses vertical augers to distribute organisms and nutrients. All of the technologies stimulate aerobic biodegradation, except one, which combines anaerobic and aerobic microbial activity (U.S. EPA, 1992, EPA/540/R-92/077, p. 208).

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3.5 Bioventing

Bioventing is the process of aerating subsurface soils to stimulate in situ biological activity and promote bioremediation. Although bioventing is related to SVE, their primary objectives are different. SVE is designed and operated to maximize the volatilization of low-molecular-weight compounds, with some biodegradation occurring. In contrast, bioventing is designed to maximize biodegradation of aerobically biodegradable compounds, regardless of their molecular weight, with some volatilization occurring. Although both technologies involve venting of air through the subsurface, the differences in objectives result in different design and operation of the remedial systems. Bioventing uses lower air flow.

Bioventing normally is applied to certain types of organics, particularly petroleum hydrocarbons. It generally is not considered useful for treating compounds such as PCBs and chlorinated hydrocarbons.

The critical factors to consider during review of bioventing are presented in Table 3-4. The significant features of this technology include optimizing airflow to reduce volatilization while maintaining aerobic conditions for biodegradation; monitoring local soil gas conditions to ensure aerobic conditions, not just monitoring vent gas composition; adding moisture and nutrients as required to increase biodegradation rates at some sites; and manipulating the water table (dewatering) as required to ensure air/contaminant contact. The in situ respiration test is useful as a rapid screening test of the applicability of bioventing (Hinchee and Ong, 1992, p. 1305).

Table 3-4. Bioventing Critical Factors and Conditions[(a)]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Spatial variation of waste composition or concentration (*)	No action levels specified (1)	• Homogeneous conditions are desirable • Large variation in the contaminant concentration causes variation in biological activity giving inconsistent biodegradation	• Waste composition and spatial distribution
Initial soil gas concentrations (*)	Initial soil gas concentrations of O_2 (<5%), CO_2 (>10%), and total petroleum hydrocarbons (~10,000 ppm) (2)	• These concentrations suggest high microbial activity due to hydrocarbon degradation and generally indicate that bioventing is feasible	• Soil gas monitoring
Soil permeability (*)	Soil air permeabilities >0.1 darcy (2)	• Low soil permeabilities restrict airflow through the soil, decreasing the amount of air that can be provided for microbial activity	• Soil air permeability testing
Presence of elevated levels of metals, highly chlorinated organics, pesticides and herbicides, or inorganic salts (*)	No action levels specified (1)	• Lower levels are desirable • Threshold effects commonly occur • Materials can be toxic to microorganisms	• Waste composition
pH	Between 5-9 pH units (3)	• When pH is outside of range, biological activity is inhibited	• Soil pH

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.

(1) U.S. EPA, 1988, EPA/540/2-88/004, p. 114.
(2) Hinchee et al., 1992.
(3) U.S. EPA, 1990, EPA/540/2-90/002, pp. 40 and 47.

Understanding the distribution of contaminants is important to any in situ remediation process. Much of the hydrocarbon residue at a fuel-contaminated site is found in the unsaturated zone soils, in the capillary fringe, and immediately below the water table. Seasonal water table fluctuations typically spread residues in the area immediately above and below the water table. Any successful bioremediation effort must treat these areas. Bioventing provides oxygen to unsaturated zone soils and can be extended below the water table when integrated with a dewatering system.

Currently, conventional enhanced bioreclamation processes use water to carry oxygen or an alternative electron acceptor to the contaminated zone. This is common whether the contamination is present in the groundwater or in the unsaturated zone. In most cases where water is used as the oxygen carrier, the oxygen solubility is the limiting factor for biodegradation. If pure oxygen is used and 40 mg/L of dissolved oxygen is achieved, approximately 80,000 lb of water must be delivered to the formation to degrade 1 lb of hydrocarbon. If 500 mg/L of hydrogen peroxide is successfully delivered, then approximately 13,000 lb of water must be used to degrade the same amount of hydrocarbon. As a result, even if hydrogen peroxide can be successfully used, substantial volumes of water must be pumped through the contaminated formation to deliver sufficient oxygen.

The use of an air-based oxygen supply for enhancing biodegradation relies on airflow through contaminated soils at rates and configurations that will both ensure adequate oxygenation for aerobic biodegradation and minimize or eliminate the production of a hydrocarbon-contaminated off-gas. The addition of nutrients and moisture may be desirable to increase biodegradation rates; however, field research to date does not indicate the need for these additions (Dupont et al., 1991; Miller et al., 1991). A key feature of bioventing is the use of narrowly screened soil gas monitoring points to sample gas in short vertical sections of the soil. These points are required to monitor local oxygen concentrations, because oxygen levels in the vent well are not representative of local conditions.

Bioventing systems can be configured in either injection or extraction mode, or a combination of the two to push or pull air through the vadose zone. A system using only air injection has the advantage of not creating a point source emission. This technology relies on the ability to move air through the contaminated soil. Low-permeability soils are more difficult to treat with bioventing.

Bioventing was accepted in the SITE Program in June 1991. Treatability tests were performed at the Reilly Tar site in St. Louis Park, Minnesota, and the site was found to be suitable for a test of the effectiveness of bioventing in treating PAHs. A single-vent system was installed and will be operated for a 3-year test period (Alleman, 1993). The U.S. EPA has completed one field study of bioventing and is conducting several others (Sayles, 1993).

The reported range of costs for applying bioventing is $60 to $90/ton (U.S. EPA and U.S. Air Force, 1993, p. 61).

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3.6 In Situ Vitrification

In situ vitrification is a thermal treatment process that converts contaminated soils to stable glass and crystalline solids. It originally was developed to stabilize transuranic contaminated wastes and is being extended to treatment of other hazardous wastes. For in situ vitrification processes, high voltage is applied via electrodes placed in the soil to induce current flow. The current heats the soil to melt-formation temperature. Heating destroys or vaporizes organic contaminants. After heating stops, the melt cools to form a stable solid material. Application of in situ vitrification requires conduction of electricity through the media to be treated.

One application of the technology is based on electric melter technology, and the principle of operation is joule heating, which occurs when an electrical current is passed through a molten mass. Field application requires insertion of electrodes into contaminated soils to supply the current flow. Because unmelted soil is not conductive, a starter path of flaked graphite and frit is placed between the electrodes to act as the initial flowpath for electricity. Resistance heating in the starter path creates a melt to carry more current. The melt grows outward and downward from the starter path (U.S. EPA, 1990, EPA/540/2-90/002, p. 17). The melt can grow to encompass a volume of 1000 tons. The maximum treatment depth is about 20 feet with possible extension to 30 feet as the technology develops. Large areas are treated in overlapping blocks.

Critical factors to consider during review of in situ vitrification technology application are presented in Table 3-5.

The electric current flow heats soil to temperatures as high as 1370°C (U.S. EPA, 1991, EPA 540/2-91/009, p. 7). If the silica content of the soil is high enough, contaminated soil is converted into durable glass. The combustible wastes are pyrolyzed and other contaminants are incorporated into the vitreous mass. Off-gases released during the melting process are trapped in an off-gas hood.

The main requirement for the technology is the ability for the soil melt to carry current during heating and then solidify to a stable mass as it cools. Wet soils can be treated by in situ vitrification, but highly permeable soils and the presence of groundwater increase operating costs. If the soil moisture is recharged by groundwater, the electrical input needed to vaporize the water increases costs. Buried combustibles or containers such as tanks and drums introduce the possibility of explosion.

The reported typical treatment rate is 3 to 5 tons per hour (U.S. EPA, 1991, EPA 540/2-91/009, p. 7). In situ vitrification is reported to provide above average long-term effectiveness and permanence, and reductions in toxicity, mobility, and volume.

In situ vitrification has been tested on a large scale ten times, including two demonstrations on transuranic-contaminated (radioactive) sites: (1) at Geosafe's test site, and (2) at the U.S. Department of Energy's (DOE's) Hanford Nuclear Reservation. More than 130 tests at various scales have been performed on a broad range of waste types in soils and sludges. The technology has been selected as a preferred remedy at several private, EPA Superfund, and DOE sites but has not been implemented in full-scale application. In situ vitrification has been selected for the SITE Program (U.S. EPA, 1992, EPA/540/R-92/077, p. 97). Tests are being performed at the Parsons/ETM site in Grand Ledge, Michigan.

There have been no full-scale applications to serve as a basis for cost estimation. A DOE life-cycle cost analysis suggests the overall cost of in situ vitrification would be approximately $790/ton (U.S. EPA and U.S. Air Force, 1993, p. 63). A commercial vendor of the technology indicates an estimated cost range of $300 to $400/ton (Hansen and FitzPatrick, 1991).

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Table 3-5. In Situ Vitrification Critical Factors and Conditions[(a)]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Soil composition (*)	>30% SiO_2 >1.4% Na_2O+K_2O on dry weight basis (1)	• Required to form melt and cool to stable treated waste form	• Weight loss on ignition • Soil mineral composition as oxides (x-ray fluorescence)
Contaminant depth (*)	>6 ft and <20 ft (1)	• Overburden assists in capture of volatile metals • Deep contamination requires surface excavation to allow placement of electrodes	• Contaminant composition and distribution
Organic liquid content of contaminated material (*)	<1 to 7% organic content depending on the BTU content of the organic (1)	• Can generate excessive hot off-gas on combustion	• Contaminant composition • Heat of combustion of organic materials
Presence of in situ voids (*)	Individual void volume <150 ft^3 (1)(2)	• Can generate excessive off-gas • Can cause excessive subsidence	• Subsurface geology
Conductive metal content (*)	<5% to 15% of total melt weight and continuous conductive path <90% of distance between electrodes (1)(2)	• Can create a conductive path resulting in uneven current flow and uneven heating	• Subsurface matrix conditions
Presence of sealed containers (*)	None present (1)	• Containers can rupture during heating resulting in a large pulse of off-gas generation	• Contaminant composition and distribution
Presence of combustible solids	<3,200 kg combustible solids per meter of depth or average concentration <30% in the soil to be treated (1)	• Can generate excessive off-gas volumes on combustion	• Contaminant composition and distribution
Presence of groundwater	Groundwater control required if contamination is below the water table and soil hydraulic conductivity is $>10^{-4}$cm/sec (1)	• Water inflow increases energy required to vaporize water	• Contaminant distribution • Location of water table • Seasonal variation of groundwater conditions
Surface slope	<+/–5% (1)	• Melt may flow under influence of gravity	• Site surface slope
Location of structures	Underground structures and utilities located >20 ft from melt zone (1)	• Items closer than 20 ft to the melt zone must be protected from heat	• Contaminant composition and distribution • Subsurface conditions

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.
(1) Pacific Northwest Laboratory, 1993.
(2) U.S. EPA, 1991, EPA 540/2-91/009, p. 3.

3.7 In Situ Radiofrequency Heating

Radiofrequency heating is a technique for rapid and uniform heating of large volumes of soil in situ. This technique heats the soil to the point where volatile and semivolatile contaminants are vaporized into the soil pore space. Vented electrodes are then used to recover the gases formed in the pores during the heating process. The extracted gases can be incinerated or subjected to other treatment methods. Application of radiofrequency heating relies on efficient electromagnetic coupling of the radiofrequency source and the media being heated.

Radiofrequency heating is accomplished by use of electromagnetic energy in the radiofrequency band. The heating process does not rely on the thermal conductivity of the soil. The energy is introduced into the soil matrix by electrodes inserted into drilled holes. The mechanism of heat generation is similar to that of a microwave oven. A modified radio transmitter serves as the power source, and the industrial, scientific, and medical band provides the frequency at which the modified transmitter operates. The exact operational frequency is obtained from an evaluation of the areal extent of the contamination and the dielectric properties of the soil matrix.

The critical factors to consider during review of radiofrequency heating technology application are presented in Table 3-6. Full implementation of a radiofrequency heating system at a contaminated hazardous waste site requires four major subsystems.

- A radiofrequency energy depositions array
- Radiofrequency power-generating, transmitting, monitoring, and control systems
- A gas and liquid condensate handling and treatment system
- A vapor containment and collection system.

Radiofrequency heating originally was developed and tested for recovery of heavy oil. Three treatability tests of radiofrequency heating on contaminated soils have been performed. The first test was conducted at Volk Air National Guard Base, Camp Douglas, Wisconsin. The treated volume was 500 ft^3 heated to a depth of 7 feet. The contaminants were in a fire training area where waste oils, fuels, and other hydrocarbons had been placed and ignited to simulate aircraft fires (U.S. Air Force, 1989, p. 1). The second test, performed at Rocky Mountain Arsenal, heated a 1600-ft^3 volume to a depth of 13 feet to treat organochlorine pesticides and organophosphorus compounds (U.S.

Table 3-6. Radiofrequency Heating Critical Factors and Conditions[(a)]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Moisture content (*)	No action level specified (1)	• A low moisture content is desirable • High moisture content increases cost due to energy needed to vaporize water • Radiofrequency (RF) energy absorption properties (dielectric constant and loss tangent) change as soil dries, complicating design and operation of the RF energy supply system	Soil moisture content
Contaminant boiling point (*)	Boiling point below 300°C (2)	• Approximate economic limit of radiofrequency heating	Contaminant boiling point or vapor pressure as a function of temperature
Conductive metal content (*)	No action level specified (3)	• Metals strongly absorb RF energy, creating uneven heating	Subsurface matrix composition
Soil dielectric constant	No action level specified (1)	• Dielectric material is needed to couple with radiofrequency fields for energy transfer • Change of properties with changing moisture content is more important than actual magnitude of the dielectric constant	Dielectric constant as a function of moisture content
Soil loss tangent	No action level specified (1)	• Dielectric material is needed to couple with radiofrequency fields for energy transfer • Change of properties with changing moisture content is more important than actual magnitude of the loss tangent	Loss tangent as a function of moisture content

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.

(1) Sresty et al., 1986, p. 88.
(2) U.S. EPA, 1990, EPA/540/2-90/002, p. 83.
(3) Just and Stockwell, 1993, p. 248.

Army, 1992, p. 2-1). A demonstration of a phased-array radiofrequency antenna system to heat vadose zone clay deposits contaminated with chlorinated hydrocarbons was completed at the DOE Savannah River Laboratory (Kasevich et al., 1993, p. 23). Two radiofrequency heating technologies have been accepted in the SITE Program. The demonstrations are being conducted at Kelly Air Force Base, Texas and are scheduled for completion in 1994 (U.S. EPA, 1992, EPA/ 540/R-92/077, p. 109).

The vendor indicates that the approximate cost range for application of radiofrequency heating is $30 to $100/ton of soil treated, depending on the moisture content (5% to 20%) and the treatment temperature (100°C to 250°C) (U.S. EPA, 1989, EPA/600/S2-89/008, p. 2)(Sresty et al., 1992, p. 363).

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3.8 Soil Flushing

Soil flushing is a process whereby the zone of contamination is flooded with an appropriate washing solution to remove the contaminant from the soil. Water or an aqueous solution is injected into or sprayed onto the area of contamination. The contaminants are mobilized by solubilization, formation of emulsions, or a chemical reaction with the flushing solutions. After passing through the contamination zone, the contaminant-bearing fluid is collected by strategically placed wells and brought to the surface for disposal, recirculation, or on-site treatment and reinjection. Application of soil washing relies on the ability to deliver, control the flow, and recover the flushing fluid.

The critical factors to consider during review of soil flushing technology application are shown in Table 3-7. Soil flushing requires the identification of a flushing solution that is available in sufficient quantity at a reasonable cost.

Flushing solutions may be water; acidic aqueous solutions (such as sulfuric, hydrochloric, nitric, phosphoric, or carbonic acids); basic solutions (such as sodium hydroxide); chelating or complexing agents; reducing agents; or surfactants. Water will extract water-soluble or water-mobile constituents. Acidic solutions can be used to remove metals or basic organic materials. Basic solutions may be used for some metals such as zinc, tin, or lead and some phenols. Chelating, complexing, and reducing agents may be needed to recover some metals. Surfactants can assist in emulsification of hydrophobic organics (U.S. EPA, 1991, EPA/540/2-91/021, p. 2).

Soil flushing to remove organic materials has been demonstrated at both bench and pilot scale. Several systems are in operation and many systems are being designed for remediation of Superfund sites. Studies have been conducted to determine the appropriate solvents for mobilizing various classes and types of chemical constituents. Most of the applications involve remediation of VOCs (U.S. EPA, 1992, EPA/542/R-92/011, pp. 26-29).

The soil flushing technology may be easy or difficult to apply, depending on the ability to flood the soil with the flushing solution and to install collection wells or subsurface drains to recover all the applied liquids. Provisions also must be made for ultimate disposal of the elutriate. The achievable level of treatment varies and depends on the contact of the flushing solution with the contaminants, the appropriateness of the solutions for the contaminants, and the hydraulic conductivity of the soil. The technology is more applicable to permeable soils.

Water can be used to flush water-soluble or water-mobile organics and inorganics. Hydrophilic organics are readily solubilized in water. Organics amenable to water flushing can be identified according to their soil/water partition coefficients or estimated from their octanol/water partition coefficients. Organics considered generally amenable to soil flushing with water or water and surfactants are those with an octanol/water partition coefficient (K_{oc}) of less than about 1000. High-solubility organics (e.g., lower-molecular-weight alcohols, phenols, and carboxylic acids) and other organics with a coefficient less than 10 may already have been flushed from the site by natural processes. Medium solubility organics (K_{oc} = 10 to 1000) that can be effectively removed from soils by water flushing include low- to medium-molecular-weight ketones, aldehydes, and aromatics and lower-molecular-weight halogenated hydrocarbons, such as TCE and tetrachloroethylene (PCE) (U.S. EPA, 1990, EPA/-600/2-90/011, p. 50).

Soil flushing for inorganic treatment is less well developed than soil flushing for organics. Some applications at Superfund sites have been reported, however. One system is operational at a landfill with mixed organics and metals, and another is operational at a chromium-contaminated site (U.S. EPA, 1992, EPA/542/R-92/011, pp. 27 and 29).

Several other inorganic treatment systems are in the design or predesign phases at Superfund sites. Inorganics that can be flushed from soil with water are soluble salts such as the carbonates of nickel, zinc, and copper. Adjusting the pH with dilute solutions of acids or bases will enhance inorganic solubilization and removal.

Removal of inorganic contaminants by soil flushing typically requires injection and recovery of a chemical leaching solution. The leaching solution must be selected to remove the contaminant while not harming the in situ environment. Selection of the leaching solution also may be limited by Land Disposal Restrictions or Underground Injection Control regulations.

Estimated costs for application of soil flushing range from $75 to $200/yd^3, depending on the waste quantity. These are rough estimates and are not based on field studies (U.S. EPA and U.S. Air Force, 1993, p. 56).

Table 3-7. Soil Flushing Critical Factors and Conditions[a]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Equilibrium partitioning of contaminant between soil and extraction fluid (*)	No action levels specified (1)	• Contaminant preference to partition to the extractant is desirable • High partitioning of contaminant into the extraction fluid decreases fluid volumes	• Equilibrium partitioning coefficient
Complex waste mixture (*)	No action levels specified (1)	• Complex mixtures increase difficulty in formulation of a suitable extraction fluid	• Contaminant composition
Soil-specific surface area (*)	<0.1 m^2/g (2)	• High surface area increases sorption on soil	• Specific surface area of soil
Contaminant solubility in water (*)	>1,000 mg/L (2)	• Soluble compounds can be removed by water flushing	• Contaminant solubility
Octanol/water partitioning coefficient (*)	Between 10 and 1000 (2)	• Very soluble compounds tend to be removed by natural processes • More hydrophilic compounds are amenable to removal by water-based flushing fluids	• Octanol/water partitioning coefficient
Spatial variation in waste composition (*)	No action levels specified (1)	• Changes in waste composition may require reformulation of extraction fluid	• Statistical sampling of contaminated volume
Hydraulic conductivity (*)	$>10^{-3}$ cm/sec	• Good conductivity allows efficient delivery of flushing fluid	• Hydrogeologic flow regime
Clay content (*)	No action levels specified (3)	• Low clay content is desirable • Presence of clay increases sorption and inhibits contaminant removal	• Soil composition • Soil color • Soil texture
Cation exchange capacity (*)	No action levels specified (3)	• Low cation exchange capacity is desirable • Cation exchange capacity increases sorption and inhibits contaminant removal	• Cation exchange capacity
pH (*)	No action levels specified (3)	• May affect treatment additives required, compatibility with materials of construction, or flushing fluid formulation	• Soil pH
Buffering capacity (*)	No action levels specified (3)	• Indicates matrix resistance to pH change	• Soil buffering capacity
Flushing fluid characteristics (*)	Fluid should have low toxicity, low cost, and allow for treatment and reuse (1) Fluid should not plug or have other adverse effects on the soil (1)	• Toxicity increases health risks and increases regulatory compliance costs • Expensive or nonreusable fluid increases costs • If the fluid adheres to the soil or causes precipitate formation, conductivity may drop, making continued treatment difficult	• Fluid characterization • Bench- and pilot-scale testing
Soil total organic carbon content	<1 wt% (2)	• Soil flushing typically is more effective with lower soil organic concentrations	• Total organic carbon content of soil
Contaminant vapor pressure	<10 mmHg (2)	• Volatile compounds tend to partition to the vapor phase	• Contaminant vapor pressure at operating temperature
Fluid viscosity	<2 centipoise (cP) (2)	• Lower-viscosity fluids flow through the soil more easily	• Fluid viscosity at operating temperature
Organic contaminant density	>2 g/cm^3 (2)	• Dense insoluble organic fluids can be displaced and collected by soil flushing	• Contaminant density at operating temperature

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.

(1) U.S. EPA, 1988, EPA/540/2-88/004, p. 79.
(2) U.S. EPA, 1990, EPA/600/2-90/011, p. 54.
(3) U.S. EPA, 1991, EPA/540/2-91/021, p. 3.

The Superfund site at Palmetto Wood, South Carolina, cited costs of $3,710,000 (capital) and $300,000 (annual operation and maintenance). These totals, on a unit basis, equal $185/yd^3 for capital costs and $15/yd^3 per year for operation and maintenance (U.S. EPA, 1990, EPA/600/2-90/011, p. 53).

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3.9 Steam/Hot Air Injection and Extraction

In situ steam injection/extraction removes volatile and semivolatile hazardous contaminants from soil and groundwater without requiring excavation. Steam injection may be supplemented by hot air injection. In a few experimental studies, hot air or hot combustion off-gas has been injected to strip organics from in situ soil without steam (Smith and Hinchee, 1993, p. 156). Waste constituents are removed from the soil by this technology but are not actually treated. Steam enhances the stripping of volatile contaminants from soil and can be used to displace contaminated groundwater under some conditions.

Steam extraction is effective for compounds with lower vapor pressures than those remediated with ambient-temperature SVE systems. By increasing the temperature from initial conditions to the steam temperature, the vapor pressure of the contaminants increases, causing them to be more volatile. Steam is injected to form a displacement front by steam condensation to displace groundwater. The contaminated liquid and steam condensate are then collected for further treatment and/or recycling to the steam generator.

Mobilized nonaqueous-phase liquid and groundwater also may be collected for treatment and disposal. Application of steam/hot air injection and extraction relies on the ability to deliver, control the flow, and recover the heating fluid.

The critical factors to consider during review of steam/hot air injection and extraction technology application are presented in Table 3-8.

A limited number of commercial-scale in situ steam injection/extraction systems currently are in operation in the United States, but in situ steam injection/extraction is a rapidly developing technology. In situ steam injection/extraction is being considered as a component of the remedy for only one Superfund site, i.e., the San Fernando Valley in California (Area 1) (U.S. EPA, 1991, EPA/540/2-91/005, p. 6).

There are two main types of steam/hot air injection/-extraction systems: a mobile system and a stationary system. The mobile system consists of a unit that volatilizes contaminants in small areas in a sequential manner by injecting steam and hot air through rotating cutter blades that pass through the contaminated medium. The stationary system uses wells to inject steam into the soil to volatilize and displace contaminants from the undisturbed subsurface. Examples of both types of steam injection technologies have been accepted in the SITE Program (U.S. EPA, 1992, EPA/540/R-92/077).

For the mobile technology, the most significant factor influencing cost is the treatment rate. Treatment rate is determined primarily by the soil type (soils with higher clay content require longer treatment times), the waste type, and the on-line efficiency. An evaluation of a SITE demonstration indicated costs of $67 to $317/yd^3 for treatment rates of 10 to 3 yd^3/hr, respectively. These costs are based on a 70% on-line efficiency and include consideration of site preparation; equipment purchase, installation, and operation; and demobilization (U.S. EPA, 1991, EPA/540/A5-90/008, p. 21). Cost estimates for the general application of steam/hot air injection fall in the range of $50 to $300/yd^3 (U.S. EPA, 1991, EPA/540/2-91/005, p. 6).

Table 3-8. Steam/Hot Air Injection and Extraction Critical Factors and Conditions[(a)]

Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Soil conductivity (*)	No action levels specified (1)	• Low soil conductivity inhibits vapor flow	• Hydrogeologic flow regime
Humic content in soil (*)	No action levels specified (1)	• Low humic content is desirable • Presence of humic materials increases sorption and inhibits volatilization	• Soil composition • Soil color • Soil texture
Contaminant vapor pressure (*)	Boiling point below 250°C (2)	• More volatile contaminants are more easily removed by air stripping	• Contaminant boiling point or vapor pressure as a function of temperature

(a) Also see Table 2-3 for generic factors.
(*) Indicates higher-priority factors.
(1) U.S. EPA, 1988, EPA/540/2-88/004, p. 89.
(2) U.S. EPA, 1990, EPA/600/2-89/066, p. 51.

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