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Soil Washing/Soil Flushing

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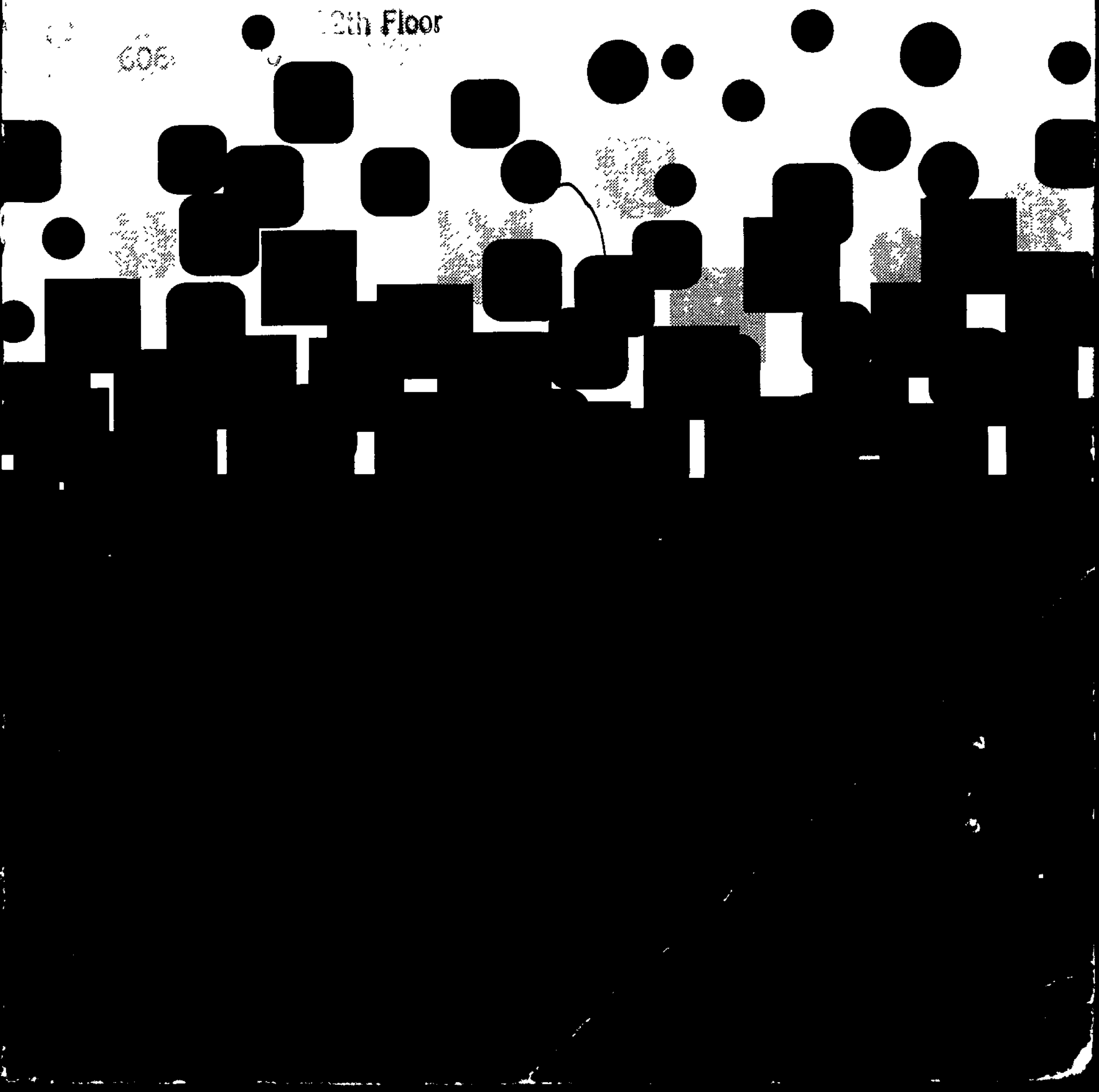

INNOVATIVE SITE REMEDIATION TECHNOLOGY

SOIL WASHING/ SOIL FLUSHING

One of an Eight-Volume Series

Edited by
William C. Anderson, P.E., DEE
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1993

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Air & Waste Management Association

The Air & Waste Management Association is a nonprofit technical and educational organization with more than 14,000 members in more than fifty countries. Founded in 1907, the Association provides a neutral forum where all viewpoints of an environmental management issue (technical, scientific, economic, social, political, and public health) receive equal consideration.

This worldwide network represents many disciplines: physical and social sciences, health and medicine, engineering, law, and management. The Association serves its membership by promoting environmental responsibility and providing technical and managerial leadership in the fields of air and waste management. Dedication to these objectives enables the Association to work towards its goal: a cleaner environment.

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Hazardous Waste Action Coalition

The Hazardous Waste Action Coalition (HWAC) is an association dedicated to promoting an understanding of the state of the hazardous waste practice and related business issues. Our member firms are engineering and science firms that employ nearly 75,000 of this country's engineers, scientists, geologists, hydrogeologists, toxicologists, chemists, biologists, and others who solve hazardous waste problems as a professional service. HWAC is pleased to endorse the monograph as technically sound.

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INTRODUCTION

This monograph on soil washing and soil flushing is one of a series of eight on innovative site and waste remediation technologies that are the culmination of a multiorganization effort involving more than 100 experts over a two-year period. It provides the experienced, practicing professional guidance on the application of innovative processes considered ready for full-scale application. Other monographs in this series address bioremediation, chemical treatment, solvent/chemical extraction, stabilization/solidification, thermal desorption, thermal destruction, and vacuum vapor extraction.

1.1 *Soil Washing*

Soil washing is an ex situ, water-based process that employs chemical and physical extraction and separation processes to remove organic, inorganic, and radioactive contaminants from soil. It is usually employed as a pretreatment process in the reduction of the volume of feedstock for other remediation processes.

The contaminated soil is excavated and staged, pretreated to remove oversized material, and washed with water and, possibly, other cleaning agents to separate and segregate the contaminants. The process recovers a clean soil fraction and concentrates the contaminants in another soil portion.

The principal advantage of soil washing lies in its ability to concentrate contaminants in a residual soil as a pretreatment step, facilitating the application of other remediation processes. In reducing the volume of soil that must be treated, soil washing can reduce the overall cost. Soil washing performance is highly sensitive to site conditions. The process is most effective when applied to soils and sediments containing large proportions of sand and gravel and is relatively ineffective when applied to soils having a high silt and clay content.

1.2 Soil Flushing

Soil flushing is the enhanced in situ mobilization of contaminants in a contaminated soil for the purpose of their recovery and treatment. Soil flushing uses water, enhanced water, or gaseous mixtures to accelerate one or more of the same geochemical dissolution reactions that alter contaminant concentrations in groundwater systems. The process accelerates a number of subsurface contaminant transport mechanisms that are found in conventional groundwater pumping.

In general, soil flushing is most effective in homogeneous, permeable soils, such as, sands or certain silty sands. The process may be effective also in the recovery of mobile degradation products formed after soil treatment with chemical oxidizing agents and in the enhancement of oil recovery operations. Effective application of the process requires a sound understanding of the manner in which target contaminants are bound to soils and of hydrogeologic transport. Depending on the matrix, organic, inorganic, and radioactive contaminants are amenable to soil flushing.

1.3 Development of the Monograph

1.3.1 Background

Acting upon its commitment to develop innovative treatment technologies for the remediation of hazardous waste sites and contaminated soils and ground water, the U.S. Environmental Protection Agency (EPA) established the Technology Innovation Office (TIO) in the Office of Solid Waste and Emergency Response in March, 1990. The mission assigned TIO was to foster greater use of innovative technologies.

In October of that same year, TIO, in conjunction with the National Advisory Council on Environmental Policy and Technology (NACEPT), convened a workshop for representatives of consulting engineering firms, professional societies, research organizations, and state agencies involved in remediation. The workshop focused on defining the barriers that were impeding the application of innovative technologies in site remediation projects. One of the major impediments identified was the lack of reliable data on the performance, design parameters, and costs of innovative processes.

The need for reliable information led TIO to approach the American Academy of Environmental Engineers®. The Academy is a long-standing, multidisciplinary environmental engineering professional society with wide-ranging affiliations with the remediation and waste treatment professional communities. By June 1991, an agreement in principle (later formalized as a Cooperative Agreement) was reached. The Academy would manage a project to develop monographs describing the state of available innovative remediation technologies. Financial support would be provided by the EPA, U.S. Department of Defense (DOD), U.S. Department of Energy (DOE), and the Academy. The goal of both TIO and the Academy was to develop monographs providing reliable data that would be broadly recognized and accepted by the professional community, thereby, eliminating or, at least, minimizing this impediment to the use of innovative technologies.

The Academy's strategy for achieving the goal was founded on a multiorganization effort, WASTECH® (pronounced Waste Tech), which joined in partnership the Air and Waste Management Association, the American Institute of Chemical Engineers, the American Society of Civil Engineers, the American Society of Mechanical Engineers, the Hazardous Waste Action Coalition, the Society for Industrial Microbiology, and the Water Environment Federation, together with the Academy, EPA, DOD, and DOE. A Steering Committee composed of highly respected representatives of these organizations having expertise in remediation technology formulated the specific project objectives and process for developing the monographs (see page iv. for a listing of Steering Committee members).

By the end of 1991, the Steering Committee had organized the Project. Preparation of the monograph began in earnest in January, 1992.

1.3.2 Process

The Steering Committee decided upon the technologies, or technological areas, to be covered by each monograph, the monographs' general scope, and the process for their development and appointed a task group composed of five or more experts to write a manuscript for each monograph. The task groups were appointed with a view to balancing the interests of the groups principally concerned with the application of innovative site and waste remediation technologies — industry, consulting engineers, research, academe, and government (see page iii for a listing of members of the Soil Washing/Soil Flushing Task Group).

The Steering Committee called upon the task groups to examine and analyze all pertinent information available, within the Project's financial and time constraints. This included, but was not limited to, the comprehensive data on remediation technologies compiled by EPA, the store of information possessed by the task groups' members, that of other experts willing to voluntarily contribute their knowledge, and information supplied by process vendors.

To develop broad, consensus-based monographs, the Steering Committee prescribed a twofold peer review of the first drafts. One review was conducted by the Steering Committee itself, employing panels consisting of two members of the Committee supplemented by at least four other experts (See *Reviewers,* page iii, for the panel that reviewed this monograph). Simultaneous with the Steering Committee's review, each of the professional and technical organizations represented in the Project reviewed those monographs addressing technologies in which it has substantial interest and competence. Aided by a Symposium sponsored by the Academy in October 1992, persons having interest in the technologies were encouraged to participate in the organizations' review.

Comments resulting from both reviews were considered by the Task Group, appropriate adjustments were made, and a second draft published. The second draft was accepted by the Steering Committee and participating organizations. The statements of the organizations that formally reviewed this monograph are presented under *Reviewing Organizations* on page v.

1.4 Purpose

The purpose of this monograph is to further the use of innovative soil washing/soil flushing site remediation and waste processing technologies, that is, technologies not commonly applied, where their use can provide better, more cost-effective performance than conventional methods. To this end, the monograph documents the current state of the art of soil washing and soil flushing technologies.

1.5 Objectives

The monograph's principal objective is to furnish guidance for experienced, practicing professionals and users' project managers. The monograph is intended, therefore, not to be prescriptive, but supportive. It is intended to aid experienced professionals in applying their judgment in deciding whether and how to apply the technologies addressed under the particular circumstances confronted.

In addition, the monograph is intended to inform regulatory agency personnel and the public about the conditions under which the processes it addresses are potentially applicable.

1.6 Scope

The monograph addresses soil washing and soil flushing, technologies that are not yet conventional, that is, not commonly applied, but that have been sufficiently developed so that they can be used in full-scale applications. It addresses all aspects of the technologies for which sufficient data were available to the Soil Washing/Soil Flushing Task Group to describe and explain the technologies and assess their effectiveness, limitations, and potential applications. Laboratory- and pilot-scale studies were addressed, as appropriate.

Application of site remediation and waste treatment technology is site specific and involves consideration of a number of matters besides alternative technologies. Among them are the following that are addressed only to the extent essential to understand the applications and limitations of the technologies described:

- site investigations and assessments;
- planning, management, specifications, and procurement;
- regulatory requirements; and
- community acceptance of the technology.

1.7 Limitations

The information presented in this monograph has been prepared in accordance with generally recognized engineering principles and practices and is for general information only. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application.

Readers are cautioned that the information presented is that which was generally available during the period when the monograph was prepared. Development of innovative site remediation and waste treatment technologies is ongoing. Accordingly, postpublication information may amplify, alter, or render obsolete the information about the processes addressed.

This monograph is not intended to be and should not be construed as a standard of any of the organizations associated with the WASTECH®Project; nor does reference in this publication to any specific method, product, process, or service constitute or imply an endorsement, recommendation, or warranty thereof.

1.8 Organization

This monograph and others in the series are organized under a uniform outline intended to facilitate cross reference among them and comparison of the technologies they address. Chapter 2.0, Process Summary, provides an overview of all material presented. Chapter 3.0, Process Identification, provides comprehensive information on the processes addressed. Each process is fully analyzed in turn. The analysis includes a description of the process (what it does and how it does it), its scientific basis, status of development, environmental effects, pre- and posttreatment requirements, health and safety considerations, design data, operational considerations; and comparative cost data to the extent available. Also addressed are process unique planning and management requirements and process variations.

Chapter 4.0, Potential Applications, Chapter 5.0, Process Evaluation, and Chapter 6.0, Limitations, provide a synthesis of available information and informed judgments on the processes. Each of these chapters addresses the processes in the same order as they are described in Chapter 3.0. Chapter 7.0, Technology Prognosis, identifies elements of the processes that require further research and demonstration before full-scale application can be considered.

2

PROCESS SUMMARY[1]

2.1 *Soil Washing*

2.1.1 Process Identification and Description

Soil washing is an ex situ process employing chemical and physical extraction and separation techniques to remove a broad range of organic, inorganic, and radioactive contaminants from soils. The process entails excavation of the contaminated soil, mechanical screening to remove various oversize materials, separation processes to generate coarse- and fine-grained fractions, treatment of those fractions (soil washing), and management of the generated residuals. It is a separation and volume reduction process, typically used in conjunction with other technologies. By concentrating the contaminants in a smaller volume for further treatment, it enables more overall cost-effective treatment.

Surficial contaminants are removed through abrasive scouring and scrubbing action in a step using a washwater that is sometimes augmented by surfactants or other agents. The soil is then separated from the spent washing fluid, which carries with it some of the contaminants. The recovered soils consist of a clean, coarse fraction, sands and gravels (>230 mesh or >63 microns (μm)), a contaminated fine fraction, silts and clays (<230 mesh or <63 μm), and a contaminated organic/humic fraction. The contaminated fines typically carry the bulk of the chemical contaminants and generally require further treatment using another remediation process, such as, thermal destruction, thermal desorption, or bioremediation.

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[1] This chapter is a summary of Chapters 3.0 through 7.0. Sources are cited, where appropriate, in those chapters — Ed.

2.1.2 Potential Applications

Soil washing may be used to treat soils containing a wide variety of organic, inorganic, and radioactive contaminants, including:

- petroleum and fuel residues;
- radionuclides;
- heavy metals;
- polychlorinated biphenyls (PCBs);
- pentachlorophenol (PCP);
- pesticides;
- cyanides;
- creosote;
- semivolatiles; and
- volatiles.

Soil washing is most appropriate for treating noncomplex soils that contain at least 50% sand and gravel, such as, coastal sandy soils and soils with glacial deposits and is relatively ineffective in treating soils that are rich in clay and silt sized particles. Further, soils with a relatively high cation exchange capacity (the capacity to exchange cations for those in the polluting substance) tend to bind pollutants more tightly, which can limit the ability of the soil washing process to effectively separate the pollutant from the soil.

Studies have shown that soils contaminated with fuel oil, jet fuel, and waste oil from underground tank system releases can be effectively treated by soil washing. According to Superfund Innovative Technology Evaluation (SITE) Program reports, removal efficiencies for residual metals and hydrocarbons of 90 to 98% have been achieved when heat and surfactants are added to the washwater. Although studies have shown that soil washing can be effective in removing gasoline and diesel fuels from soils, thermal desorption, biodegradation, vapor extraction, or other processes may be more effective and appropriate.

Soil washing can be used to remove volatile organic compounds (VOCs) and other materials having a relatively high vapor pressure or water solubility quotient. Removals of 90 to 99% or more of VOCs can be achieved by simple water washing. Removal rates for semivolatile organic materials tend to be lower, on the order of 40 to 90%, and the addition of surfactants to the washwater is often required to aid in the washing and/or separation.

Removal of metals and pesticides, which tend to be less soluble in water, often requires the addition of acids or chelating agents. Table 4.1 (on page 4.5) shows the general effectiveness of soil washing in removing various types of chemical groups.

Site characterization is the first and most important step in determining whether soil washing may be effectively applied. Removal efficiencies are highly dependent on the specific blend of physical and chemical characteristics of the soil and the contaminants and on the spatial distribution of pollutants throughout the soil. Among the extensive data required for site characterization are the site geology and hydrogeology, soil type and composition versus depth, soil chemistry, and variability of contaminants in the soil. It is important to know how soil type and contaminant concentrations change with latitude and depth in order to develop an accurate profile of the feedstock soil and to guide sampling efforts in collecting representative soils for further characterization and for bench and pilot testing. Table 4.2 (on page 4.6) summarizes key soil parameters that should be measured.

Bench- and pilot-scale tests should be conducted on representative contaminated soil samples to determine whether soil washing can be used to effectively remove the contaminants and determine the requirements for soil feedstock preparation. In addition, these tests provide the bases for gauging the performance capabilities of commercially available systems at the particular site.

2.1.3 Process Evaluation

Full-scale projects are now being implemented in the U.S., primarily using applications already proven in Europe. Several variations have been tested in the SITE Program. The project reports are cited and the contractors are identified in this monograph. In 1989, the United States Environmental Protection Agency (US EPA) funded an evaluation of existing soil washing configurations. The summary of the report of the evaluation is included here as table 4.6 (on page 4.12).

Soil washing has been selected for remedial application at 23 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Superfund) National Priorities List (NPL) sites and one other, lower priority CERCLA site. None of these applications involve the separation and recovery of volatile contaminants, but, instead, will involve the treatment of soils for semivolatile, polynuclear aromatic hydrocarbon (PAH), dioxin, pesticide, and heavy metal contamination. The average amount of soil to be washed at these sites is nearly 34,000 m^3 (44,000 yd^3), ranging from 1,400 to 150,000 m^3 (1,800 to 200,000 yd^3).

The selection of a soil washing system usually depends upon the quality of the oversize materials, coarse-grained materials, fine-grained fraction containing the concentrated contaminants, and other residuals produced. In most applications, the principal objective is to meet treatment standards for the oversize materials and coarse fraction so that they may be placed back on site. The major measure of effectiveness, therefore, is the ability to meet specified standards for the residuals that are targeted for placement back on site.

Soil washing performance is closely tied to two key physical soil characteristics evaluated during site characterization — particle size distribution and cation exchange capacity — which should be carefully evaluated in light of the overall site geology and the vertical and horizontal extent of the chemical contamination. Many contaminants tend to bind to the fine particle (silts and clays) fraction of the soil and will be separated from the clean soil during the washing process to much the same extent as the fines are separated from the coarse (sands and gravels) fraction.

When used as a pretreatment step for other remediation processes, soil washing presents two key advantages. The first is its ability to substantially contribute to *waste minimization*, that is, concentrating a large proportion of the nonvolatile and heavy metal contaminants into a residual soil product representing less than half the original soil volume. The washed soil product may be suitable for redepositing on site or other beneficial uses. The second advantage lies in its potential *cost-effectiveness*. Lower remediation costs result for many sites through the reduction of sheer volume of contaminated soil that must be treated by more expensive methods.

Soil washing is a relatively low-cost alternative for separating wastes. The soil washing system can be operated as a closed treatment system permitting control of fugitive dusts and volatile emissions, an asset in securing public acceptance.

Compared with thermal processes, soil washing has a broad range of acceptable influent concentrations. But the range can be exceeded by a broadly divergent or heterogeneous feed stream, a risk that can be reduced through proper attention to treatability studies and pilot tests.

2.1.4 Limitations

The waste matrix may pose the most significant limitation. Complex mixtures of contaminants make it difficult to formulate a single suitable washing fluid and may require sequential washing steps with different additives. Further, frequent changes in the contaminants and their concentrations in the feed soil can disrupt the process requiring modification of the wash fluid formulation and the operating settings.

Soil washing will usually not be cost-effective in treating soils having a high percentage of clay and silt (e.g., more than 30 to 50%); high humic content in the soil makes separation of contaminants very difficult. It may be relatively ineffective in treating soils contaminated with a high concentration of mineralized metals or hydrophobic organics. Hydrophobic contaminants can be difficult to separate from soil particles into the aqueous washing fluid.

Certain chelating agents, surfactants, and other additives may be hazardous and are often difficult and expensive to recover from the spent washing fluid. Further, some of these additives may be retained in the contaminated soil and treatment sludge residuals and may cause added difficulty in residuals management.

The main risk in soil washing operations is that of inaccurate site characterization. The material encountered during site remediation may not be like the soils studied in treatability or pilot scale tests.

Also, site conditions may impose limitations. For example, a source of process water is required, commercial electrical power is normally required (although mobile generators may be used), permits for wastewater discharges must be obtained, land use must be approved, and, in remote areas, a roadway may have to be constructed to provide access.

2.1.5 Comparative Cost Data

A clear understanding of the site is essential to developing costs that may be used in comparing soil washing with other technologies. Table 5.3 (on page 5.5) provides a detailed listing of components for use in estimating costs. Because no hazardous waste sites in the U.S. have been treated using soil washing, cost information must be based upon the literature and information provided by vendors. Based upon projects in the range of 23,000 to 180,000 tonne (25,000 to 200,000 ton), the estimated treatment price, including disposal of sludges and all known cost components, is in the range of \$170 to \$280/tonne (\$150 to \$250/ton).

2.1.6 Technology Prognosis

Continuing process development will focus on additional treatment of the fine-grained fractions, potentially decreasing the residual material that must be disposed of off site and reducing unit treatment prices. Work is underway on bioslurry reactors for use in further degrading the organic constituents in the fines and on developing extraction and recovery techniques to remove inorganics. Improved extraction and recovery may result in recovered contaminants with market value.

Although soil washing will undoubtedly continue to be offered in mobile configurations, the European experience has clearly demonstrated that fixed-based plants are more efficient. The key barrier that will need to be addressed in order to realize effective fixed-based plants is the ultimate disposal of residuals that are generated from the fixed plant, particularly, the clean products.

2.2 *Soil Flushing*

2.2.1 Process Identification and Description

Soil flushing is an in situ process that uses water, enhanced water, or gaseous mixtures to accelerate the mobilization of contaminants from a contaminated soil for recovery and treatment. The process accelerates one or more of the same geochemical dissolution reactions, such as, adsorption/desorption, acid/base reactions, and biodegradation, that alter contaminant concentrations in groundwater systems. In addition, soil flushing accelerates a number of subsurface contaminant transport mechanisms, such as, advection and molecular diffusion, that are found in conventional groundwater pumping.

Soil flushing can be broken down into three separate activities — site characterization, fluid injection, and contaminant mobilization and recovery techniques. Site characterization requires a field understanding of hydrogeology, geochemistry, and the relative permeability and lithology above, within, and below the zone of contamination.

The fluids used can be applied or drawn from groundwater and can be introduced to the soil through surface flooding or sprinklers, subsurface leach fields, and other means. When the contaminants have been flushed, the contaminated fluids can be removed either from a perched condition, from a groundwater system, or, depending upon the contaminants and the fluids used, can be left in place.

Soil flushing techniques used to mobilize contaminants are classified as conventional and unconventional. Conventional techniques are further classified as:

- natural restoration;
- well and capture methods in the vadose zone; and
- pump-and-treat systems in the saturated zone.

Unconventional techniques consist of primary, secondary, and tertiary recovery techniques. Primary recovery encompasses, among other methods, neutral water drive and gravity drainage; secondary recovery involves waterflooding and pressure maintenance methods; and tertiary recovery consists of gaseous and chemical processes and thermal methods.

2.2.2 Potential Applications

In situ soil flushing should be considered for applications involving petroleum hydrocarbons, chlorinated hydrocarbons, metals, salts, pesticides, herbicides, and radioisotopes. Many industrial sites throughout the U.S. have chlorinated hydrocarbons in the subsurface, and since excavation and other existing remediation strategies require access, in situ soil flushing offers clear advantages. Other advantages include no soil replacement and/or disposal costs, minimal disruption of the ecosystem, cost advantages at greater depths, and minimized worker exposure to contaminants.

In general, soil flushing is most effective in homogeneous permeable soils. Soil flushing may also be appropriate for the recovery of mobile degradation products formed after soil treatment with chemical oxidizing agents, and enhancement of oil recovery operations.

Adaptation of Enhanced Oil Recovery (EOR) and in situ mining techniques provide the potential for substantially increasing the rate of waste extraction and, thereby, lowering costs. In general, EOR techniques involve the injection of materials that are not normally found in the soil in order to facilitate the removal of hydrocarbon type wastes.

2.2.3 Process Evaluation

Bench scale tests of soil flushing have been very successful, but field application has not shown the same success, because of reduced permeability by plugging and biofouling. Field operations may be subject also to flow instabilities resulting in finger type flow of the flushing fluid and failing to reduce the contamination between the fingers.

Large variations of removal efficiencies in the field are attributable more to site hydrology than to the contaminants. The vadose zone is poorly understood by most investigators, as is the relationship between capillary pressure, water content, and permeability. Since the success rate under laboratory conditions is high and that in the field is not, it appears that a better understanding of the vadose zone is required to successfully implement soil flushing.

2.2.4 Limitations

The generation of large quantities of contaminated elutriate, the recovered mixture of water, surfactants, and contaminants, can pose a limitation. On-site treatment may have to be devised if access to compatible wastewater treatment facilities is not available.

A variety of site conditions can limit the use of soil flushing:

- Soils with pockets of low hydraulic conductivity may limit effectiveness;
- Pipes and underground utilities may limit effectiveness of flushing underground storage tank sites;
- Soil flushing will be less effective where the contaminants are relatively insoluble or tightly bound to the soil; and
- The lack of an adequate supply of process water.

There may be limitations in the use and effectiveness of surfactants. Hard water may render a surfactant ineffective, soil of high clay content can cause chemical adsorption of the surfactant to the soil, and, in some situations, a surfactant may biodegrade too quickly. High rates of surfactant consumption raise the cost of soil flushing.

There is a limitation in treating contaminated soils located in the vadose zone. Soil retention capacities must be satisfied before contaminants will be transmitted through the vadose zone.

Nonhomogeneous subsurface conditions, nonuniform distribution of contaminants, or a nonaqueous phase liquid (NAPL), will cause channeling and uneven treatment. It may be difficult to determine whether the flushing solution has contacted the waste material and whether cleanup objectives can be achieved within estimated flushing water volumes. Quite often, NAPLs accumulate in layers in the form of either light nonaqueous phase liquids (LNAPLs) or dense nonaqueous phase liquids (DNAPLs), and often must be removed before appreciable soil flushing of soluble contaminants can be accomplished. The solubilization of product into the groundwater will otherwise continue as a source for quite some time. Heterogeneities in natural geological materials make the prediction and detection of contaminant behavior in groundwater difficult in practice.

Pump-and-treat programs have been unable to bring the concentration levels down to required levels because of problems related to nonideal aquifer conditions such as heterogeneity, anisotropy, and variable density. In addition, pump-and-treat programs suffer from well construction effects, vandalism, operational failures, and other problems.

State regulations may require vadose zone monitoring, contending that solute transport models in the vadose zone are not reliable. Site characterization in the vadose zone is a complex problem, and only a few companies specialize in vadose zone investigations. Little is known about predicting dispersion in fractured media. The dispersion of solutes during transport through many types of fractured rocks differs from that described for transport through homogeneous granular materials.

2.2.5 Comparative Cost Data

Section 5.2.3 presents the results of two extensive cost comparisons covering water flooding and subsurface injection techniques. The best-case scenario study uses the equilibrium solubility model for surface flooding and results in a cost estimate of \$61.16/m^3 (\$80/yd^3). The worst-case scenario study uses the two component equilibrium model for subsurface injection and results in a cost estimate of \$126.15/m^3 (\$165/yd^3).

Capital and operating costs are similar for traditional pump-and-treat and chemically-enhanced solubilization processes. Estimates are compared in Section 5.2.3. The cost of in situ flushing is considerably less than that of other remediation processes, which can range as high as \$765 to \$1,530/m^3 (\$1,000 to \$2,000/yd^3).

2.2.6 Technology Prognosis

Additional investigation is required of several factors, such as, soil or water incompatibility, permeability reductions, and flushing chemical retention in the subsurface, although recent development of a "supersurfactant" decreases the concerns about soil or water incompatibility and permeability reductions to some degree. The issues of chemical retention in the vadose and saturated zones must be addressed. For pump-and-treat systems to be more effective, the following areas need more study and improvement:

- hydraulically containing fluids as they are flushed from the system;
- treating the contamination at the surface; and
- eliminating the hydraulic isolation (dead spots) that occurs within well fields.

Although soil flushing will remove the source of contamination in the vadose zone, it must also remove contaminants which have diffused into low permeability sediments. In addition, it must be able to desorb contaminants from sediment surfaces and cause liquid-liquid partitioning of immiscible contaminants in order to mobilize the pollutants of concern.

3

PROCESS IDENTIFICATION AND DESCRIPTION

3.1 *Soil Washing*

3.1.1 Description

Soil washing is a relatively new, commercially proven (since 1982) method for treating excavated soil and dredged sediments that are contaminated with toxic or other hazardous pollutants. It involves the application of a set of established engineering principles, unit processes, and equipment that have been used for years in the mining, mineral processing and ore benefaction, and wastewater treatment industries.

As considered here, soil washing is an ex situ, water-based process that relies on traditional chemical and physical extraction and separation processes for removing a broad range of organic, inorganic, and radioactive contaminants from soil. Following are typical hazardous contaminant groups that can be effectively removed by soil washing:

- petroleum and fuel residues;
- radionuclides;
- heavy metals;
- polychlorinated biphenyls (PCBs);
- pentachlorophenol (PCP);
- pesticides;

- cyanides;
- creosote;
- semivolatiles; and
- volatiles.

Whether soil washing should be applied depends upon three key, individual site characteristics — the soil's mix of contaminants, particle size distribution, and specific gravity. For example, it can generally be said that the higher the percentage of sand and gravel in the soil or sediment, the more effective is soil washing. Soil washing can be a very cost-effective, stand-alone soil treatment process and, in addition, can be used as a volume reduction and feedstock preparation step for other more complex soil-treatment technologies. In both cases, residuals from the treatment process must be anticipated and properly managed.

Most commercially available soil washing systems utilize mechanical screening devices to remove oversize material, separation systems to generate coarse- and fine-grained fractions, treatment units for washing, systems for scrubbing the separated fractions, equipment for rinsing and dewatering, and water treatment and recycling systems for water management. The specifications for each system are largely driven by individual site characteristics.

Soil washing involves the use of wet, mechanical scrubbing and screening processes to separate particles that contain contaminants from those that do not. In this sense, it is a volume reduction or pretreatment technology. It exploits the tendency of contaminants to adhere to the organic matter (leaves, roots, and twigs) and the fine-grained soil fraction (silt and clay), rather than the coarse-grained mineral fraction (sand and gravel). In addition, or, in some cases, alternatively, contaminants may be removed from the soil as a result of being solubilized in the washwater.

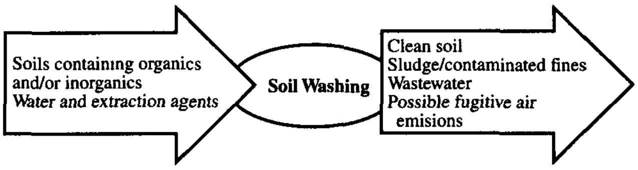
Simply stated, soil washing entails the following steps:

- excavation and staging of contaminated soil or sediment;
- pretreatment of the soil to remove large objects and oversized clods and material;
- washing the soil with water to separate and segregate the contaminants; and

- recovering a clean soil fraction that can be redeposited on site or otherwise beneficially used.

The process frees contaminants and concentrates them in a residual portion of the soil (typically 5 to 40% of the original soil, by volume), where they can be subsequently treated by other remediation techniques. The washwater is treated by conventional wastewater treatment techniques and then recycled. Figures 3.1 and 3.2 (on page 3.4) are basic soil washing flow diagrams.

Figure 3.1
Soil Washing Diagram

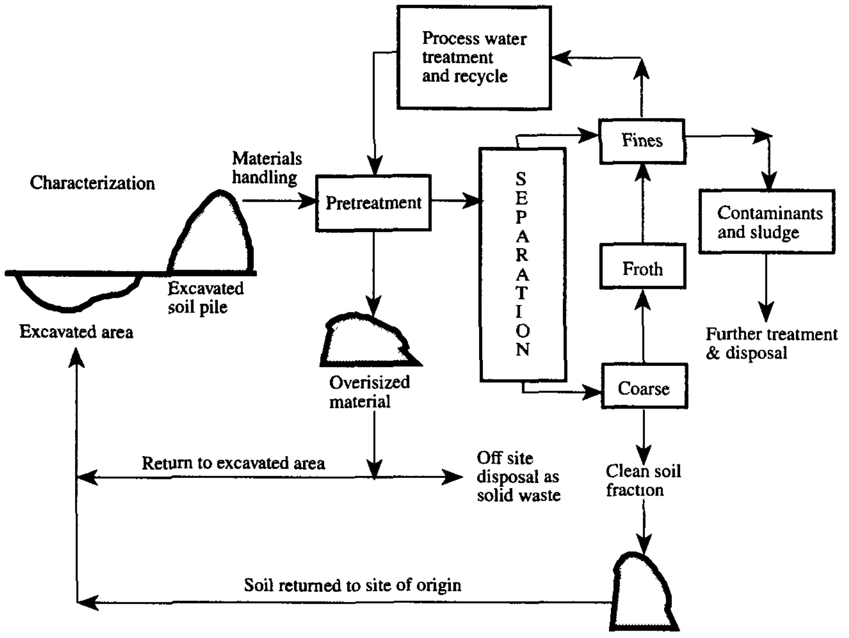


- Separation and volume reduction
- Residuals require subsequent treatment

The soil washing process begins with the excavation and preparation of the feedstock soil. Soil preparation can involve the mechanical screening of the feedstock to remove rocks, debris, and other oversized material. Most soil washing systems cannot accept feed materials that are larger than 50 mm (2 in.) in diameter.

In the second stage, the contaminants are separated and concentrated. This is accomplished primarily through active mixing of the soil with water or an amended water-based washing fluid, separation of the soil from the spent fluid, and recovery of the soil in two distinct fractions. One is a relatively high-volume, coarse sand and gravel fraction (>230 mesh or >63 micron (μm)) that is clean and suitable for use as on-site fill, and the other is usually a smaller-volume, fine silt and clay fraction (<230 mesh or <63 μm) that typically carries the bulk of the chemical contaminants. A third fraction, contaminated, naturally occuring organic material, may be separated from the coarse soil fraction by specific gravity separation.

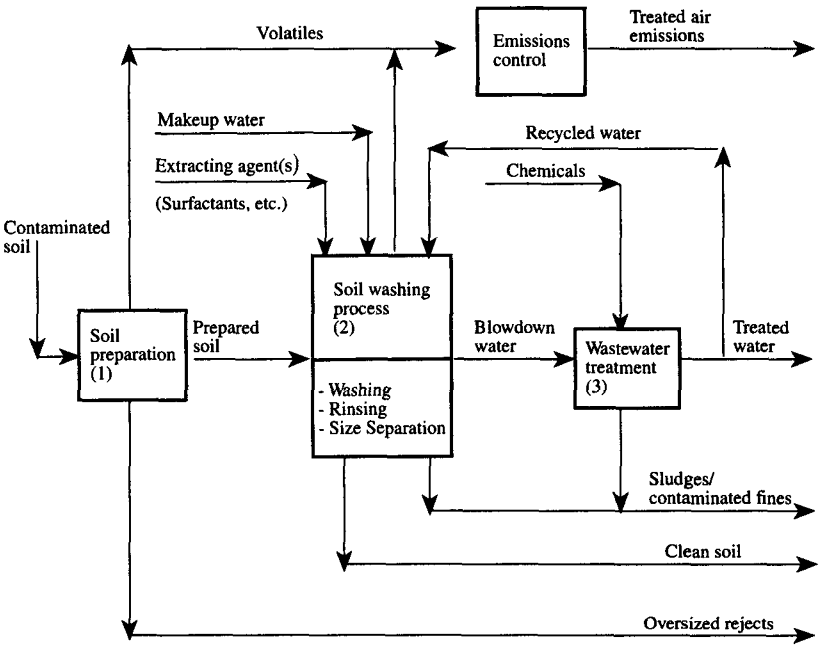
Figure 3.2
Basic Soil Washing Flow Diagram



Surficial contamination that is attached to sand and gravel fractions through forces of adhesion and compaction is removed from the coarse fraction by abrasive scouring or scrubbing action. This washing step is sometimes augmented by adding to the washwater a basic leaching agent, surfactant, pH adjustment, or chelating agent (such as ethylene diamine tetra-acetic acid (EDTA)) to help remove organics or heavy metals. After washing, the coarse soil fraction may be rewashed to further remove residual contaminants and washwater additives. The spent washwater and rinsewater are treated to remove the contaminants prior to recycling back to the treatment unit. Fines and wastewater treatment solids are handled separately.

Figure 3.3 (on page 3.5) illustrates a very simplified soil washing process.

Figure 3.3
Aqueous Soil Washing Process



Source US EPA 1990

3.1.2 Soil Washing Systems

Soil washing systems usually consist of the following six distinct process units:

1. pretreatment;
2. separation;
3. coarse-grained treatment;
4. fine-grained treatment;
5. process water treatment; and
6. residuals management.

The most commonly used equipment is discussed in the following subsections. Undoubtedly, other kinds of equipment may be employed in soil washing and new kinds of equipment will be developed as improvements over the years.

3.1.2.1 Pretreatment

Pretreatment is performed to remove grossly oversized material and to prepare a homogeneous feed stream of reasonable size for delivery to the soil washing plant. Unit processes that may be employed are scalping, crushing and grinding, mechanical screening, jigging and tabling (specific gravity separation), blending and mixing, and magnetic material removal.

Grossly oversized material can be anything from solid construction debris and waste down to pea gravel-size material (approximately 50 mm (2 in.) in diameter). It is usually material that is not grossly contaminated, does not require treatment by another method, or that can be reclaimed as a by-product (metals, wood, etc.). Scalping, mechanical screening, and jigging and tabling are examples of processes that can make the initial separation. Crushing and grinding (reduction to natural grain size) may be necessary to liberate contaminated particle surfaces in order to successfully wash this fraction. Blending and mixing can reduce large variations in the size and contaminant distribution in the feed stream so as to provide products of more consistent quality.

3.1.2.2 Separation

Separation systems are designed to make a precise first cut at the selected interface of coarse- and fine-grained solids. The most common cut point is usually between 63 and 74 microns (230 and 200 mesh). The two fractions above and below the cut point generally require different treatment methods for final cleaning. In addition, the coarser solids will be separated through use of conventional techniques (usually hydrocyclones), while the finer solids must be settled by various methods. Thus, two streams will issue from this basic separation step and go on to separate processes. It is important that a relatively clear break be made within the critical particle size range. Hydrocyclones are almost always employed to make the first size separation, although mechanical screens are sometimes used where contaminant-specific requirements apply. This is screening primarily at a larger particle size, such as 500 microns (28 mesh Tyler) or larger. There is difficulty screening at finer sizes.

There will be some fine-grained solids that carry over into the coarse fraction with the washwater accompanying the coarse fraction. The fine-grained solids accompanying the coarse fraction will be in the same proportion as the washwater applied to the coarse fraction. Accordingly, the washwater from the coarse fraction processing will have to be recycled to the fine-grained solids treatment to recover the fine-grained solids.

Another separating device often employed is the upflow classifier, sometimes called a hydrosizer. It is used primarily to remove organic material, such as, roots, leaves, twigs, wood chips, coal, and other light debris. Separation is effected by forcing water upward through a relatively fluid bed, separating the materials through specific gravity difference and upward velocity currents. Spiral concentrators can be employed to separate either lighter or heavier materials from the sand grains.

3.1.2.3 Coarse-Grained Treatment

After the separation step, there will be a small amount of material finer than 63 to 74 microns (230 to 200 mesh), but it should constitute less than 5% of the total solids by weight. In addition, some fine-size particles will probably be found in the water removed in dewatering the coarse-grained fraction. Additional cycloning follows and then, this water should be sent to the fine-grained treatment process for recovery of these solids.

The contaminants of interest will be found predominantly in the finer solids, but the coarse fraction may also require treatment to remove any polluting material that is adsorbed on or coats the solids. Several debris washing methods, for example, surface attrition, acid or base treatment for solubilization, or specific solvents for dissolving the contaminants, can be employed to release the pollutant from the solids into the liquid fraction. The solids can then be separated further and sent either to the fine-grained treatment or to the water treatment process for removal of the target contaminants.

The removal of contaminants from the sand-like particles can be effected by two methods, attrition scrubbing or flotation. Sand dewatering methods are important because they also remove contaminants trapped in the washwater. This washwater must be appropriately processed for destruction of pollutants.

3.1.2.4 Fine-Grained Treatment

At the beginning of fine-grained treatment, this fraction is now finer than 63 and 74 microns (230 and 200 mesh) and typically consists of an appreciable proportion of solids in the colloidal range 6 to 10 µm. In addition, the solids concentration, coming primarily from the cyclone overflow in the separation step, will be relatively dilute, as low as 5 to 10% solids by weight. These solids will settle slowly, and some will not settle at all because of their clay and colloidal nature. The separation and concentration of the contaminated fines fraction is necessary before the selection of an appropriate residuals management strategy. Fine-grained treatment precedes the residuals management step, whose strategy depends upon the nature and concentration of contaminants, cleanup standards, economics, etc. Residuals management is discussed in Subsection 3.1.2.6.

3.1.2.5 Process Water Treatment

Contaminated washwater may result from the soil washing process. This washwater will contain some or all of the following materials and contaminants:

- Some coarse-grained sands, particularly from 360 µm (40 mesh) down to >63 µm (230 mesh). There may be little or no contaminants attached to these solids.
- Fine-grained solids <63 µm (<230 mesh) — these solids will still contain attached contaminants and colloidal silt and clay material;
- Dissolved salts that are present in the original soil, probably mostly sodium and chlorine-containing compounds. There must be enough bleed-out of the water to prevent an excessive buildup. Depending on the type of dissolved salts, this water may be discharged to a municipal sewer in accordance with local requirements;
- Organic humic compounds (leaves, twigs, roots, etc.) that must be removed to acceptable levels;
- A pH value that may have to be changed to a desirable range either for recycle or disposal;
- Dissolved or solubilized heavy metals requiring treatment and removal; and
- Other contaminants, such as, free-floating petroleum hydrocarbons requiring removal.

The washwater must be treated either for recycling back to the process or for disposal. Water to be recycled usually does not need to be of the quality that must be produced for discharge to sewers or water courses. Therefore, it is always cheaper to reuse the water as long as there is not a deleterious effect on the soil washing treatment processes.

The washwater to be disposed of either in a city sewer or a water course must meet regulatory discharge limits, such as:

- pH range, e.g., 6 to 9;
- total dissolved solids, in addition, there may be maximum limits for particular ions or compounds;
- biochemical oxygen demand (BOD) and chemical oxygen demand (COD);
- oil and grease content, both dissolved and undissolved;
- suspended solids content; and
- other hazardous or toxic waste limits.

If any of the above effluent discharge criteria cannot be met, the washwater will have to be manifested as an industrial or hazardous waste and discharged at an appropriate waste treatment and disposal center.

It is emphasized that the water can always be recycled back to the appropriate processing step for additional treatment. Factors that caused inefficient treatment may be correctable resulting in water of disposable quality.

Depending upon the washwater's composition, various steps are employed in process water treatment. The more common are:

- neutralization;
- carbon treatment;
- ion exchange;
- flocculation;
- sedimentation and thickening;
- dewatering; and
- volatile organics stripping.

3.1.2.6 Residuals Management

The quantities of products and residual materials generated by a soil washing plant will vary directly in proportion to the grain-size distribution of primary feed material to be processed. The quantities of these streams can be rapidly estimated by bench-scale wet sieve analysis and elutriation (upflow classification).

Contaminated fines and sludges resulting from the process may be disposed of in a regulated landfill and/or require further treatment through one or a combination of the following treatment technologies in order to permit disposal in an environmentally safe and acceptable manner: incineration; low temperature thermal desorption; chemical extraction/dechlorination; bioremediation; solidification/stabilization; or vitrification.

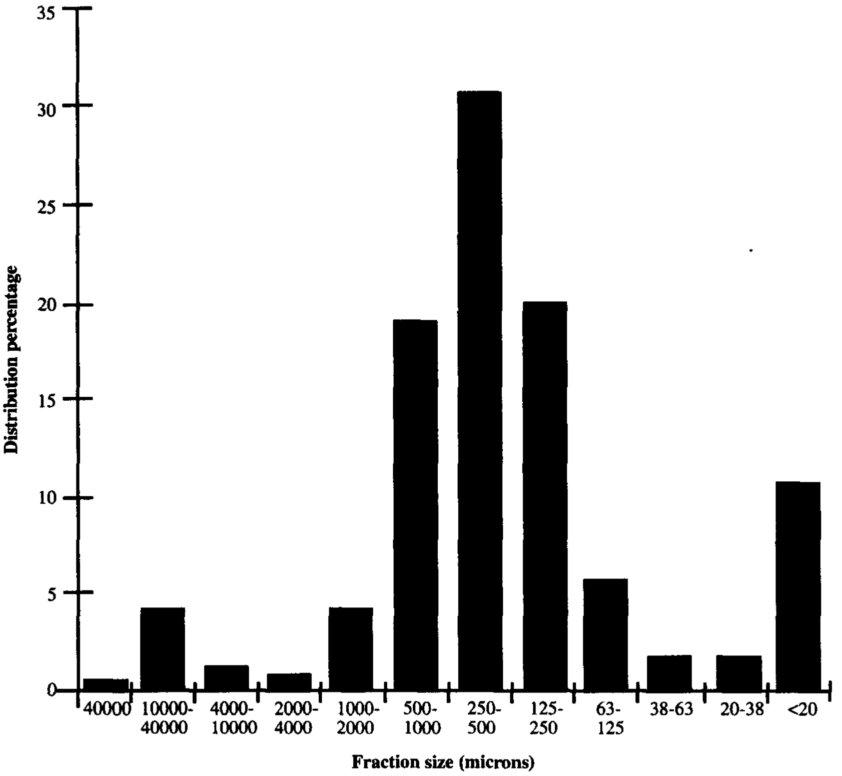
There are a number of residual technology vendors that can provide information and costs associated with the above systems. The US EPA Vendor Information System for Innovative Treatment Technologies (VISITT) data base provides information about vendors (US EPA 1992c). See also the Soil Washing Vendors List in Appendix A.

The contaminated feed material usually will require removal of the organic vegetative material (leaves, twigs, roots, grass, etc.), through specific gravity separation. This material, although a relatively small portion of the contaminated feed material, will partition the greatest quantity of contaminants because of its highly porous nature and carbon-based adsorptive characteristics.

3.1.3 Scientific Basis

A normally distributed soil consists of oversize material (gravels and cobbles), coarse-grained particles (sands), and fine-grained particles (clays and silts). The first step in soil washing is to acquire an understanding of the particle size distribution (see figure 3.4 on page 3.11) of the soil to be washed and, by analyzing the retained fractions, characterize the soil matrix-contaminant relationship. It is very common to find the majority of the contaminants "residing" in the fines, as indicated in figure 3.5 (on page 3.12). This often results from the complex chemical and electrical forces in the lattice of fines. Additionally, contaminants tend to weather in soils and sediments. Weathering occurs through physical degradation, oxidation or reduction, hydrolysis, dehydrohalogenation, biological decay, and radioactive decay. Over time, they become tightly bound through physical or chemical forces to the organic matter (roots, leaves, peat, humus, and other naturally-occurring organic material) and to the fine-grained mineral particles (i.e., fine sand, silt, and clay fractions) in the soil. Such weathering has been observed repeatedly in soils contaminated

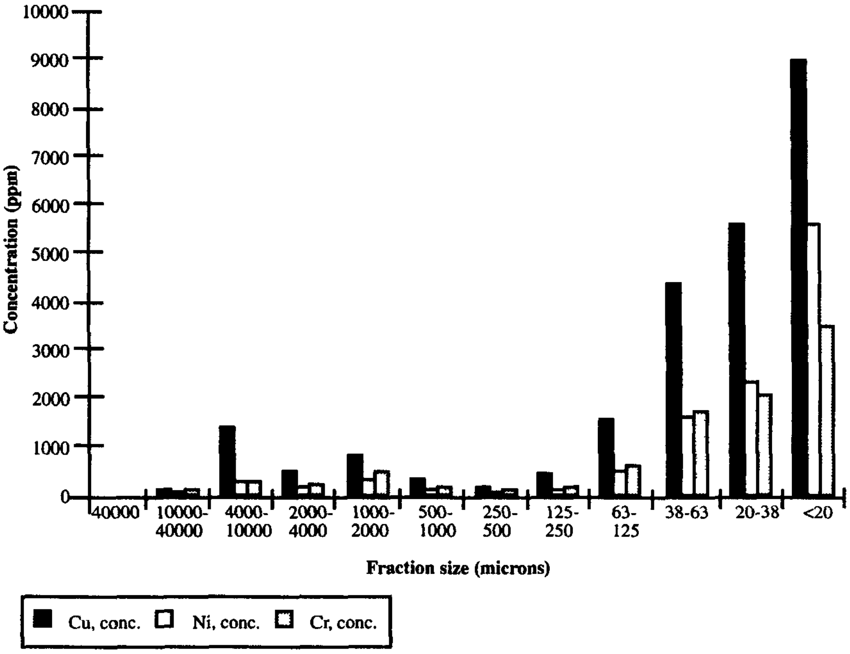
Figure 3.4
Basic Sample Composite: Particle Size Distribution



with heavy metals, organic solvents, petroleum products, dioxins, PCBs, and several pesticides.

Clay, silt, and colloidal particles, those having a size of less than 63 microns (passing 230 mesh), tend to be loosely attached to the larger, coarse sand and gravel particles by physical forces, primarily adhesion and compaction. Physical washing or attrition scrubbing of the contaminated soil with water will effectively break the physical forces of compaction and adhesion, separating the organic material and fine sand, silt, and clay particles from the coarse sand and

Figure 3.5
Basic Sample Composite: Concentrations vs. Particle Size



gravel particles. Separation techniques based on particle size and specific gravity can be used to effectively collect and segregate the fine soil fractions from the coarse fractions.

Soil contaminants will be collected and concentrated in the fine sand, silt, colloidal, and organic material. They will be segregated from the coarse sand and gravel to the same extent that the fine sand, silt, humus, and clay are separated and segregated from the coarse material. Increasing the efficiency of the washing process will directly increase the separation and segregation efficiency for the majority of the contaminant mix.

Soil composition is a key factor governing the performance of soil washing. Mineral silts and clays are the principal hosts for adsorption of hazardous contaminants because of their relatively high surface area-to-volume ratio and their strong cohesive properties. Roots, leaves, peat, humus, and other naturally-occurring organic matter also have a high affinity for many contaminants due to their carbonaceous makeup and porous structure. Experience has shown that the cost of soil washing is roughly inversely proportional to the overall silt, clay, and organic content of the soil. Generally, soils that tend to be lower in organic matter and clay or silt content tend to respond better to soil washing.

3.1.4 Design Data and Equipment Sizing

Each contaminated site presents unique characteristics. The quantity and quality of the contaminants of interest and their relationship with the mineralogy of the soil or sediment require each site to be evaluated individually for the optimum combination of washwater additives necessary to solubilize, mobilize, precipitate, and complex, the organic and/or inorganic chemical constituents.

In order to properly design a full-scale (>9 tonne/hr (>10 ton/hr)) soils and sediment washing plant, information is required to assess the applicability of this volumetric reduction technology. To determine initial data requirements the following questions should be answered:

a. *What quantity of material is to be processed on site?*

   In general, a site should have a minimum of 4,500 tonne (5,000 ton) of contaminated feed material to justify equipment mobilization and demobilization, and site preparation costs;

b. *Is the material to be processed by soils and sediment washing appropriate for volumetric reduction and waste minimization?*

   Approximately 70% of the particle size matrix of the candidate soil and sediment material should be >74 μm (>200 mesh). This break is at the fines/sand definition, at which point the washing technology can effectively concentrate the contaminants of interest into the fine silt, clay, and colloidal fractions;

c. *What is the contaminant of interest (or generic group, that is, polynuclear aromatic hydrocarbons (PNAs), reactive sulfides, cyanides, PCBs, etc.) and what is the target and regulatory cleanup standard (value) for the process for treatment of the cleanable coarse fraction?*

Target values vary widely, from EPA region-to-region and state-to-state regulatory agency, even for the same target contaminant. Many hazardous waste site remedial Record of Decisions (RODs) are now being determined on a health risk analyses basis or on the demonstrated removal efficiency of the best demonstrated available technology (BDAT); and

d. *What is the ultimate objective of the management of the concentrated fines that the soils and sediment washing technology will produce?*

The contaminants will generally partition to the silt, clay, and colloidal fractions of the contaminated matrix because of these particles' very high cation exchange capacities that will tend to complex the contaminant into the fine material. The relatively high surface areas of fine particles present excellent hosts for contaminant absorption. These fines must be subsequently managed by another remediation process or processes, each of which has varying feedstock requirements as to, for example, maximum particle size and, particularly, moisture content of the enriched fines. The selection of the residual management technology, or technologies, will affect the design and configuration of the front-end soils and sediment plant. Dependent upon the specific residuals management technology, fines are either thickened to approximately 35% solids for heavy metal extraction or bioslurry operations or are dewatered to approximately 50 to 60% solids by filter press operations.

3.1.4.1 Bench-scale Treatability Data

Bench-scale studies are performed to specifically evaluate and optimize each of the system's unit operations. The studies also enable determination of where the primary contaminants will partition according to soil grain-size distribution.

A bench-scale treatability study enables the initial identification of fugitive emissions that could emanate from a full-scale operation from either volatile organic contaminants, or unanticipated chemical reactions of washwater additives and unidentified contaminants within the waste material matrix, or the mineralogy of the material itself.

Soil and sediment washing typically uses standardized modules that can be incorporated in or deleted from a full-scale operation, depending upon material and contaminant characteristics. Examples of modules that are interchangeable within the basic system configuration and their functions are:

- Dual Step Grizzly Bar Screen — classification, separation and removal of >50 mm (>2 in.) oversized debris from raw feed;
- Tramp Metal Separator — removal of ferrous tramp iron and steel from >9.52 mm (>0.375 in.) feed material;
- Rotary Trommel Screen — system utilized for initial breakup and deagglomeration of lumpy contaminated soil fractions. Primary feed is approximately 50 mm (2 in.) with screened coarse product fractions occurring at >9.52 mm (>0.375 in.);
- Oil and Grease Separation System — concentration and removal of light and heavy hydrocarbon oil products from wastewater system for separate concentration and disposal;
- Attrition Scrubbing Module — a high-energy unit processing system that contacts <9.52 mm (<0.375 in.) contaminated material with chemical wash additives to effectively solubilize appropriate contaminants and to "deslime" or mobilize the highly contaminated fines (<74 μm (<200 mesh)) material. The attrition cells function at a 50 to 65% solids content;
- Dense Media Separator Module — separation and removal of vegetative and marine organic materials (leaves, twigs, roots, wood chips, plants, shells, etc.) based upon specific gravities;
- Cyclone Separator Unit — a high efficiency, solids and liquid separation device utilized for desliming <74 μm (<200 mesh) clay silt and colloidal material from coarse (sand and gravel) soils fractions. The unit operates with no internal moving parts on the basis of the differing specific gravities of light and heavy media. For a coarse sand underflow, it delivers approximately 70 to 75% solids, regardless of influent solids loading concentrations;
- Reverse Slope Dewatering Module — a high-frequency mineral screen assembly specifically designed for final rinsing, dewatering, desliming, and removal of very fine material from mineral slurries. Each unit utilizes snap-in, modular screen deck panels and replaceable, bolt-in, side liner plates;

- Washwater Clarifier Treatment Module — a compact water-treatment system specifically designed for flocculation and sedimentation and gravity separation of fine (<74 µm (<200 mesh)) contaminated clay, silt, and colloidal materials. This system utilizes a quiescent settling zone for preliminary sludge densification prior to removal by sludge pumps. The unit incorporates a pH adjustment system and polymer mix tank and chemical feed pump for coagulation operations;
- Dissolved Air Flotation Module — for the precipitation, flocculation, and removal of dissolved heavy metal hydroxide and oil fractions from wastewater;
- Sludge Densifier — gravity conditioner to bring residual fine solids content within sludge to a maximum of 30% to 35% for subsequent residual management technologies requiring a thickened slurry feed, such as, biodegradation, chemical extraction, or stabilization/solidification; and
- Continuous Belt Filter — module for continuous dewatering operation of mineral (<63 µm (<230 mesh)) sludges and intermittent metal hydroxide Dissolved Air Flotation scum dewatering. Solids content of filter cakes will range from 40 to 60% solids.

Bench-scale treatability evaluations are critical not only in identifying applicable chemical additives for wash solutions, but also in identifying which critical unit process module needs to be included in a full-scale remedial system.

3.1.4.2 Pilot-scale Treatability Data

When a large (>18,000 tonne (>20,000 ton)) site requires additional treatability evaluation in order to provide more complete engineering design data because of significant variations in a site's soil matrix composition or contaminant partitioning, it may be desirable to employ a pilot treatability system. This system could be taken to the client's site to evaluate the effect of changes in soils and washing chemical additives (i.e., surfactants, chelants, etc.). Operation of such a plant is often permitted under the EPA's small quantity treatability exemption.

It is estimated the system would enable effective treatment and evaluation of several tons of material on site. Approximately 90 to 900 tonne (100 to 1,000 ton) of contaminated material should be processed for each heterogeneous soil type or contaminant group. On-site operation of the pilot plant greatly simplifies the logistics of securing representative samples of contaminated materials for feasibility testing, manifesting, and transporting off site and for managing residuals of treated material following the completion of a field test program.

3.1.4.3 Full-scale Plant Size or Capacity

The specification of plant size or capacity is based upon a combination of the following factors:

- the physical characteristics of soils to be treated;
- amount of material to be processed;
- the desired separated cut point;
- client's decision whether to have plant operated on an 8, 16, or 24 hr/day basis; and
- operational season (whether freezing temperatures are probable).

Whether the operation of the plant be on a one-, two-, or three-shift basis is generally based upon the client's decision either to expedite the remedial project or to extend operations over multiple fiscal years in order to have a longer payout period.

Typical plant operations are based upon two eight-hour shifts accounting for 14 hr/day feed with an hour for start-up and an hour for shutdown each day. Planned maintenance activities are generally scheduled for Saturdays with interim emergency repairs and part replacements being accomplished as required.

Although there are commercial soil washing plants as small as 1.8 tonne/hr (2 ton/hr) capacity, an economically and practically sized plant should have a rated capacity of 23 tonne/hr (25 ton/hr). Soils and sediment washing equipment vendors typically design plants at 23, 45, and 90 tonne/hr (25, 50, and 100 ton/hr) capacities. The largest commercial sediment washing plant is sized for 318 tonne/hr (350 ton/hr) operations.

A 23 tonne/hr (25 ton/hr) plant with a 14 hour day on-line feed factor will have an anticipated capacity of 7,940 tonne/month (8,750 ton/month) based upon a 25 day/month operational period. A 46,000 tonne (50,000 ton) site would be processed in less than 6 months. A 23 tonne/hr (25 ton/hr) plant requires 3 to 5 operational technicians/shift.

As to the power needed, the typical 23 tonne/hr plant will require 440V, 3 phase and an estimated 775 - 800 hp. A 45 tonne/hr (50 ton/hr) plant will require 1,000 - 1,200 hp.

The "footprint" of a typical 23 tonne/hr soils washing plant is approximately 15 x 30 m (50 x 100 ft) for the operational modules; an area of 23 x 45 m (75 x 150 ft) is required for a 45 tonne/hr system. The area required for a complete soils 23 tonne/hr washing plant encompassing a feeder module, oversized material pile, clean soil product bins, and sludge cake lugger boxes is approximately 30 x 60 m (100 x 200 ft); a 45 tonne/hr plant will require approximately 38 x 76 m (125 x 250 ft).

In 1978, EPA designed and fabricated a Mobile Soil Washing System (MSWS). This four trailer system consists of: (1) scalping screen and rotary trommel washing screen, (2) four stage countercurrent froth flotation system, (3) 120 cm (48 in.) wide plate and frame filter press for dewatering operations, and (4) physical and chemical treatment system for the recycling of process washwater. The MSWS has a rated capacity of approximately 3.6 tonne/hr (4 ton/hr), dependent upon the portion of fines in the contaminated feed material.

In order to more rapidly assess the applicability of soil washing at a potential site while minimizing the expense of mobilization and operation of the 3.6 tonne/hr (4 ton/hr) MSWS, EPA designed and fabricated a 227 kg/hr (500 lb/hr) pilot soils washing system, which is self-contained upon two 14 m (45 ft) trailers. This unit is referred to as a Mobile Volume Reduction Unit (MVRU). It is available for field operational support for Superfund predesign site activities through the EPA's Risk Reduction Engineering Laboratory (RREL), Edison, New Jersey. It has been used on a creosote Superfund Site in Pensacola, Florida.

3.1.5 Pre- and Posttreatment Requirements

Pretreatment requirements for soil washing are dependent upon the amount and type of oversized debris and moisture in the material. If a site contains large quantities of oversized (>15 cm (>6 in.)) material, such as, construction rubble (chunks of concrete, reinforcing bars, asphalt slabs, brick, pipe, etc.) bulk containers (drums, pails, buckets) or general trash and debris (paper, cardboard, wire, metal, wood, plastic, tires, etc.) there should be a preprocessing step by which this material is either screened or scalped out. There are a number of commercial systems which readily accomplish this task. A major concern during the preprocessing step is the control of fugitive dusts and volatile organic contaminant emissions.

Oversized material may have small-to-significant quantities of contaminated soils adhering to its surfaces through adhesion or compaction. Most large objects, such as boulders and refrigerators, can be adequately decontaminated through high-pressure spraying using water or water with industrial detergents, steam cleaning, or high-pressure washing, along with the introduction of an abrasive sand through a process known as hydro-blasting.

Posttreatment requirements generally do not appertain because soil washing is usually applied in combination with other treatment technologies, either as a feedstock preparation step or as a subsequent separation technology in a treatment train. Table 3.1 (on page 3.20) shows treatment trains of innovative technologies that have been selected for remedial sites.

3.1.5.1 Fugitive Dust and Volatile Organic Contaminant Emission Control

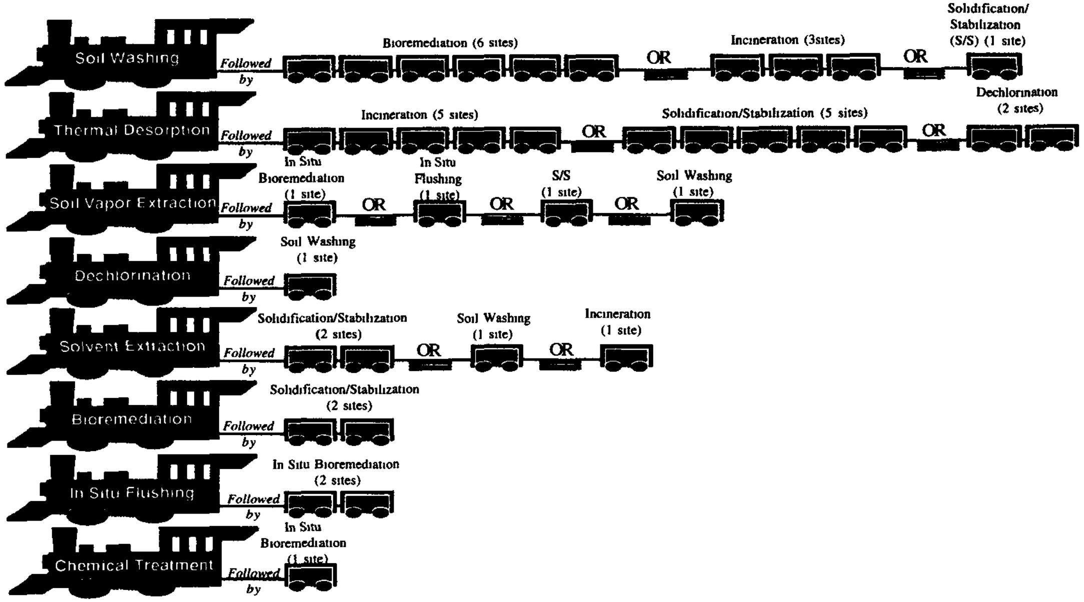
The primary safety concerns in handling contaminated soils and sediments are two-fold: (1) worker exposure, and (2) downwind, off-site community exposure. Chemical constituents which exhibit moderate to high volatility are of principal concern. Most of the release of these high-vapor pressure materials will occur during excavation and removal of the contaminated matrix, *prior* to preliminary screening and soil/sediment washing and processing. Volatile organic compounds must be managed at this stage.

The U.S. EPA has issued a report evaluating numerous techniques for the control and treatment of fugitive dusts and emissions in the handling and treatment of contaminated soils from Superfund sites.(9) Preliminary wetting or "fogging" of dry contaminated soils during excavation will effectively suppress the majority of volatile organic chemicals and virtually any associated dusting and blowing of inorganic fine fractions. Obviously, during dredging operations, the contaminated sediments are totally saturated, eliminating any possibility of dusting.

The control, collection, and treatment of fugitive dusts and emissions has readily been accomplished in full-scale soil and sediment washing through application of covers and shroud assemblies incorporated into the conveyor, hopper bin, and tank designs, along with large volume air handling systems, such as a Calgon Vapor Pack 10 Absorbers containing 5,400 kg (12,000 lb) of activated carbon or biofilters. These subcomponents are negatively vented through the application of explosion-proof, inducted-draft air fans. Any volatile emissions or nuisance vapors are collected and drawn through granular, vapor phase, activated carbon packs or canisters. Once the carbon has been exhausted

Table 3.1

Treatment Trains of Innovative Treatment Technologies Selected for Remedial/Removal Sites



Innovative treatment technologies in this report may be used with established or other innovative treatment technologies in treatment "trains". Technologies may be combined to reduce the volume of material requiring subsequent treatment, to prevent the emission of volatile contaminants during excavation and mixing, or to address multiple contaminants within the same medium.

Source: US EPA 1992a

or experiences "break through", it can be removed from the system for either on-site or off-site regeneration and then placed back into service.

For extremely toxic or dusty materials (i.e., dioxin, radionuclides) high-efficiency particulate air (HEPA) systems have been very successful in full-scale remedial operations.

An alternative method for fugitive volatile emission and dust control is the erection of a temporary structure over either the excavation site, treatment system, or both. The structures can be of either sheet metal, (i.e., Butler Buildings), or supported fabric, internal frame design (i.e., Rubb or Sprung Structures). The structure can be negatively vented through a vapor collection and treatment system.

Each site must be assessed for the possible deleterious effects of fugitive vapor and dust emissions. This assessment may indicate the need for a long-term ambient air monitoring program. This is accomplished through the positioning of long-term (24 hour) air sampling stations around the site and at the face of the contaminated soil and sediment excavation. Once adequate data are obtained, identifying primary volatile chemical constituents and their concentrations, properly-sized vapor and dust emission collection and control systems can be readily incorporated into the site-specific remedial technology design and operating procedures.

Semivolatile and nonvolatile organic chemicals (i.e., oils, greases, diesel fuels) pose little or no environmental or health threat to workers or the off-site community at large. Because of their inherently low vapor pressure, little to no volatilization is generally detected. All volatilization rates are temperature dependent. The colder the ambient operational temperature, the less volatilization will occur.

3.1.5.2 Debris Washing

Material between 45 and 15 cm (18 and 6 in.) diameter can be subjected to a series of high pressure water knives or sprays while being processed upon a vibratory screen deck. Oversized material, if appropriate, can be returned to a crusher/shredder for resizing, and subsequent washing.

Debris and oversized material ranging from 5 to 15 cm (2 to 6 in.) diameter can be processed through a log washer unit for desliming operations. This heavy-duty equipment employs two counter rotating sets of paddles mounted on a heavy shaft while the feed material is a submerged section of the unit. As new make-up water is introduced into the unit, the contaminated fines are discharged via an overflow weir assembly for subsequent treatment.

3.1.6 Operational Requirements

3.1.6.1 Site Infrastructure Requirements

Site infrastructure requirements for a soil washing plant operation include, but are not limited to, all civil engineering works associated with roads, foundations, water, power, and the storage of supplies. An area approximately 13 x 13 m (42 x 42 ft) is required for a 14 tonne/hr (15 ton/hr) soils washing plant versus 15 x 30 m (50 x 100 ft) for a 23 tonne/hr (25 ton/hr) plant. It is important to consider also the staging, prescreening, and blending areas that will be required for feeding the soils into the plant. These areas can be provided under a flexible plan of soils management.

3.1.6.2 Scale-up of the Soil Washing Process

Factors such as: (1) waste feedstock preparation, (2) performance capabilities, (3) analytical data, and (4) worker and community health and safety considerations must be taken into consideration when predicting scale-up from the bench-style testing to pilot-scale testing and to the full-scale soil washing treatment systems.

In scaling up the cost and performance estimates from bench-scale testing to the full-scale soil washing system, the parameters to be considered are:

a. Performance capabilities of the soil washing process, including design parameters for:
   - soil throughput in dry tons per hour;
   - optimum washwater usage in gallons per dry ton of soil; and
   - dosages of additives (if any) mixed with the washwater;

b. Nature and form of contaminant concentrations in the fines soil fraction. Basically, the question is, where do the contaminants partition within the soils gradation analysis? It is desirable to be able to estimate the volume and physical and chemical characteristics (i.e., sulfides/sulfates) of this fraction in order to design treatment systems (e.g., dewatering, stabilization, etc.) and estimate disposal costs;

c. Identification of contaminants and their concentrations in the spent washwater. Generally, this water is treated for recycling back into the washing process. Therefore, treatment will include separation of the fine soil particles. In addition, other treatment steps may be necessary to remove organics, inorganics, and additive chemicals. Scale-up design requires estimates of the process water volume and quality requirements;

d. Risk analysis evaluation for worker and community protection. This entails characterizing and quantifying bulk excavated soil contamination levels pertinent to worker and community protection during excavation. (Health and Safety Plans (HASPs) and any risk analysis evaluation being conducted require this information.); and

e. Cost of screening (removing debris, rocks, and other materials) for bulk soil washing.

3.1.6.3 Manpower Requirements

Operational experience indicates that a 14 tonne/hr (15 ton/hr) and a 23 tonne/hr (25 ton/hr) plant each require three operators, and, therefore, operation of the 23 tonne/hr plant should maximize revenues. The cost of labor will be the same as that for a 14 tonne/hr plant, but the capital equipment cost per ton of processed material will be reduced. Each team should include a supervising engineer and, for projects of long duration, a part-time administrative assistant.

Depending upon the size and complexity of the soil washing plant operation, a 45 tonne/hr (50 ton/hr) module designed plant can be erected with four workers and a 20 ton crane in approximately 5 working days. Leak testing of tanks, pumps and interconnect systems, adjustment of sump level controllers, scale calibration, feed conveyors, flow balancing, etc., requires approximately 3 technicians working 5 days.

The design and operation of full-scale soil washing systems is based upon practices traditionally found in the mining and ore processing industries and systems utilized in sand and aggregate plants.

3.1.6.4 Materials Handling Requirements

The basic processing equipment is very similar to that of a small mining operation. It is designed and manufactured for very heavy duty and long service. Normal start-up procedures will include water and slurry testing before introduction of contaminated soils. Normal plant start-up problems can be expected. During steady operations, the crew will be directly involved in daily controls.

Excavation is required for soil washing, and the wastes must be screened to break up soil clods to remove rocks, branches, debris and the oversize foreign material. Large soil clods must be reduced in size by crushing and grinding, if necessary, to achieve a feed size required by the equipment, normally less than 5 cm (2 in.) top size. The waste material, washwater, and any additives that are needed will require mixing to ensure adequate separation of the contaminants.

3.1.7 Unique Planning and Management Needs

The following are the three primary planning and management considerations:

- Soils Management — A requisite for effective soil washing is the proper excavation, preparation, and staging of material to be treated. Success can depend mainly on whether only soils requiring treatment are fed and whether they are fed in the most balanced quantity;
- Flexibility of the Process — Soil washing is not a fixed process; it is flexible and can be modified for each unique project. Bench-scale testing is a good start, but may not clearly identify the actual forces and capabilities of a continuous process system; and
- Permitting — Major projects will typically be conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or the Resource Conservation Recovery Act (RCRA) regulations. Projects under CERCLA are exempt from permitting when supported by approvable designs, while RCRA Corrective Action Program responses may be exempt as a Corrective Action Management Unit (CAMU) action.

3.1.8 Comparative Cost Data

Cost information presented here is based upon the literature and information provided by vendors. It is essential to have a clear understanding of the site in order to develop working cost estimates so that the technology may be compared fairly with other alternatives. The development of the range of costs should, therefore, include such considerations as:

- capitalized costs of equipment, depreciation, and interest;
- plant operations labor;
- variable costs of operations, including chemicals, safety equipment, utilities, and process sampling;
- transportation and disposal of residuals requiring management; and
- management costs, including overhead and profit.

A detailed listing of cost components is set forth in table 3.2.

3.1.9 Special Health and Safety Requirements

Although control of fugitive dust and volatile organic contaminant emissions is a major concern, the incorporation of specifically engineered control systems

Table 3.2

Major Cost Components of a Full-Scale Soil Washing Operation[a]

1. Soil excavation.
2. Transport of excavated soil to the processing unit.
3. Temporary stockpiling of excavated soil.
4. Prevention of contaminant releases to the environment during Steps 1 through 3 above due to rain, wind, volatilization, accidental release, etc.
5. Bulk soil pretreatment steps, such as, screening, crushing, and physical/chemical characterization.
6. Management of the screened-out rocks, roots, debris, etc.
7. Washwater supply facilities, e.g., storage tanks, pumps, piping, controls.
8. Additive (if any) supply facilities, e.g., storage tanks, pumps, piping, controls.
9. The soil washing process system, which may consist of a series of mixers, washers, screens, conveyors, cyclones, and other units. It is assumed that generally this cost will be obtained from the manufacturer.
10. Temporary stockpiling, transport, and deposition of the adequately clean, washed soil product fraction.
11. The dirty washwater treatment process, which is usually a treatment train that may include clarifiers, chemical reactors, filters, carbon contactors, dewatering presses, tanks, etc.
12. Recycle or disposal of the treated wastewater fraction.
13. Further treatment and disposal of the dirty soil fraction
14. Further treatment and disposal of the water treatment sludge.
15. Permitting and legal services.
16. Engineering design.
17. Services during construction.
18. Contingencies.

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[a] Where applicable, the engineer performing the cost estimate will usually break down the cost estimate components listed above into:

(1) construction (roads, foundations, buildings, etc);
(2) process equipment (mixers, tanks, screens, pumps, clarifiers, etc);
(3) material handling equipment (power shovel, bulldozer, portable conveyor, trucks, etc.); and
(4) labor (operators, supervisors, analytical, etc.); energy (electrical power, diesel fuel, etc.), utilities (water, sewage, etc.), materials (chemical additives, spare parts, etc.), and various overhead administrative and profit items.

usually is not necessary. This is due to the relatively small concentrations of contaminants within the material utilized during typical full-scale operations and the wet environment of a soil washing operation. For hazardous waste-site operations, all operations personnel must be trained in accordance with Occupational Safety and Health Administration (OSHA) Instruction 1910.120 (series), with the normal soil washing plant being operated under a "modified Level D" protective equipment designation. This requires safety shoes, work coveralls, possibly Tyvek Splash Coveralls or rainsuits, hard hats, impervious gloves, and safety glasses or goggles. For dusty operations, or operations with radionuclides, such as the contaminated feed end of the plant, full-face, air-purifying respirators or self-contained breathing apparatus (SCBA) should be employed. If necessary, personnel must use air-purifying respirators for personal protection.

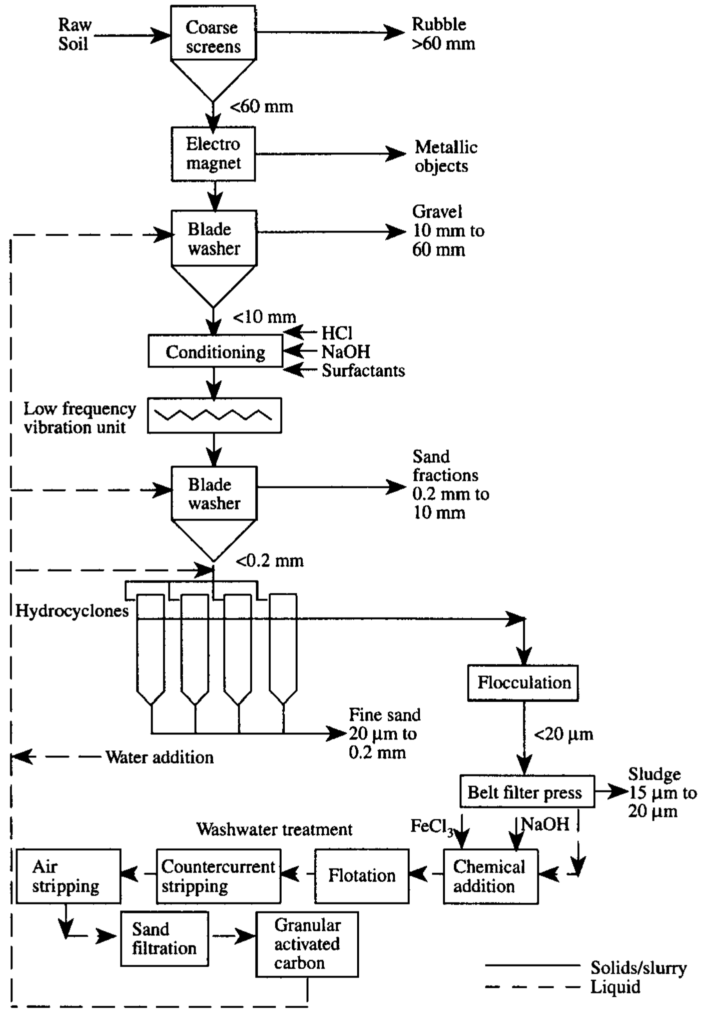
3.1.10 Technology Variations

The "soil washing system" is not limited to a fixed arrangement of equipment. There are many variations in soil washing systems, many employing process units other than those described in Section 3.1.2 above. The process configuration employed is usually a function of the soil-contaminant relationship and the flexibility desired in the process. Several actual process flow diagrams that have been used in the field will be employed here for illustration.

Figure 3.6 (on page 3.27) shows a system used by Harbauer GMBH of Germany. The process involves chemical extraction of the process wastewater. Blade washers (very high-pressure, wide streams of water), are employed to blast off contaminants from the sand and gravel fractions. The <200 μm (<70 mesh) solids and water are then sent to small diameter cyclones to provide a 0.200 x 0.020 mm fine sand fraction. The <200 μm solids' overflow is flocculated and dewatered on a continuous belt filter press. The filtrate or washwater is subjected to several different steps as required by the contaminants in these streams. Chemical additions are performed to enhance the precipitation, flotation, or countercurrent stripping steps with an insoluble liquid. The final wastewater effluent is passed through sand filtration for complete solids removal and then through activated carbon for removal of trace organics and color agents. The treated water is then directed to reuse to close the circuit.

Figure 3.7 (on page 3.28) presents a process flow diagram of a mobile system installed on two trucks. The system was developed by the U.S. EPA in order to test whether clean sand could be produced from contaminated soils

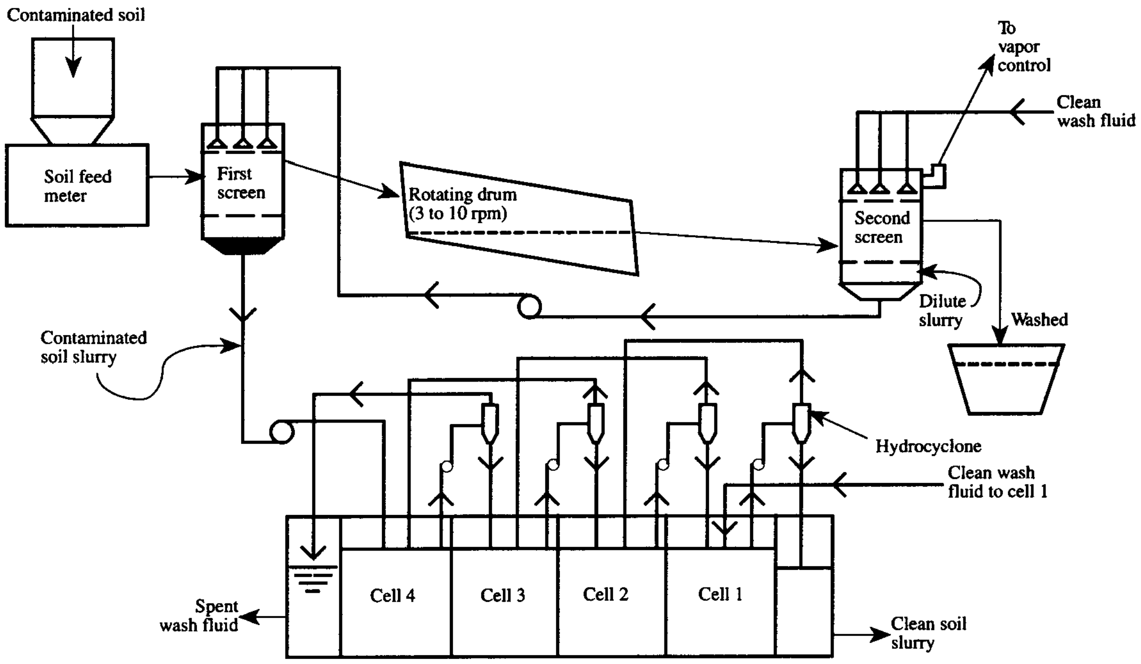
Figure 3.6
Flow Schematic of the Haubauer Soil Washing Installation: Chemical Extraction/Soil Washing



Source: US EPA 1988a

Figure 3.7

Schematic of the EPA Mobile Soil Washing System: Chemical Extraction/Soil Washing



through the use of screens and cyclones. Soil is metered to the first screen where wet screening through spray water addition is performed, allowing undersized solids to pass through the screen as a soil slurry. Oversize solids are directed to a rotating drum to break any consolidated solids down to true grain size. This stream is passed to a second screen where clean water is applied and the oversize material goes as washed solids. The screen undersize, along with the bulk of the water, is passed back to the first screen as the spray water. Thus, fine solids are more likely to flow to the contaminated soil slurry.

The fine solids from the first screen underflow are conveyed to the final stage of a four-stage countercurrent cyclone operation. Fresh water is used as a repulp fluid for the second stage underflow, which is the feed to the first-stage cyclone. From this first-stage unit, the resultant clean sand is produced from the cyclone underflow, while the overflow is the repulp fluid for second stage feed. Water is moving in a countercurrent fashion to the fine solids coarser than the desired split size, for example, 63 μm (230 mesh). Thus, the most contaminated (<63 μm) solids and water result from the fourth-stage cyclone overflow.

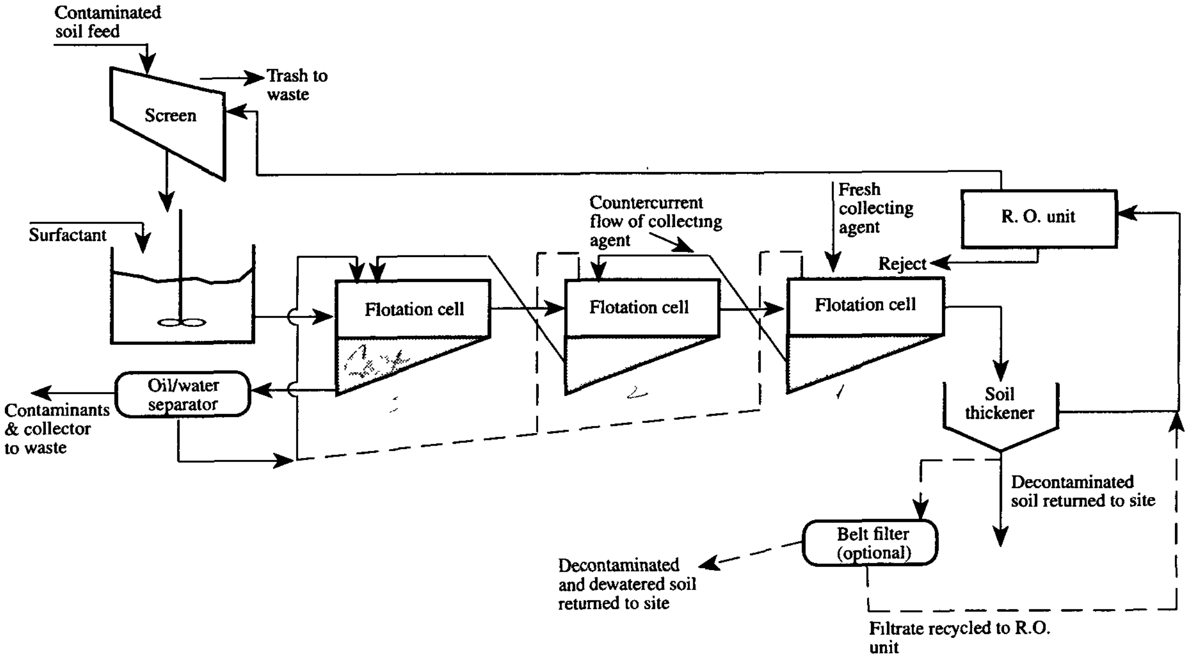
Three products are produced: sand, fines, and spent washing fluids. The spent washing fluids should contain the large majority of the very fine particles, contaminants, and dissolved solids. This disposition permits analysis of the two sand fractions to ascertain whether they can be disposed as clean products and whether the spent washing fluids can be treated for contaminant removal. Tests can be performed at varying water-to-soil ratios to determine optimum operating parameters.

Another countercurrent operation, conducted with flotation cells, is shown in figure 3.8 (on page 3.30). Contaminated soil comes from the underflow of the trash screen and is then contacted with the selected surfactant. The soil solids move forward from the third (and last) flotation cell as froth product to the second cell feed and finally as froth product to the first stage cell. All flotation cells underflows flow in the opposite direction to the froth products. The third stage underflow is passed to an oil and water separator where the bulk of the contaminants and the collector reagent issues as an overflow and the underflow water is returned back to the third stage feed. The fresh collector agent is added to the first stage feed and flows countercurrent to the soil, the latter appearing as froth product in each of the three stages.

The first stage froth product goes to a gravity thickener, and the underflow is considered decontaminated soil. The overflow is then sent to a reverse osmosis unit so that the resultant water product can be recycled.

Figure 3.8

Waste-Tech Services, Inc., Soil Washing Plant Flow Sheet

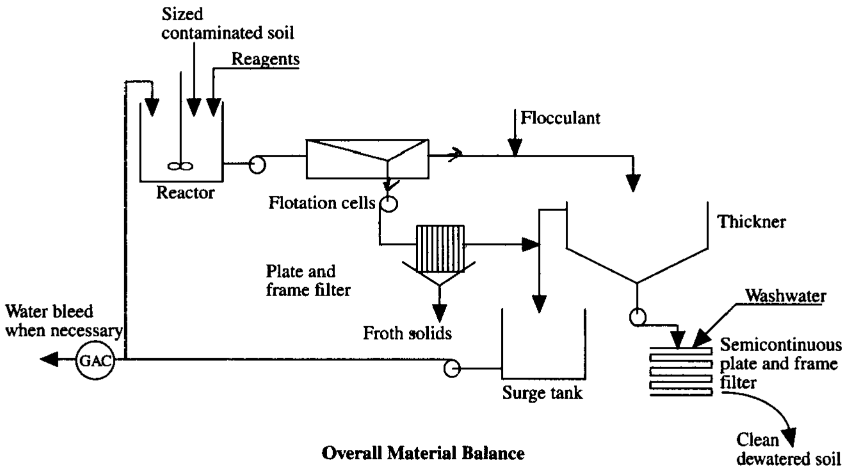


Source: US Patent No. 4,783,263, Nov 8, 1988

A countercurrent operation increases the opportunity for recovering clean soil, while the contaminants are increased in relation to the waste stream. In addition, water consumption is reduced.

Figure 3.9 is a flow diagram of a typical system using flotation cells to remove the contaminants as a froth product in a relatively simple operation. Water and reagents are fed with the presized contaminated soil, freeing the target contaminants, while collectors are added so the contaminants will be captured in the froth product. The froth product is dewatered in a plate and frame filter press for final disposal, and recyclable filtrate is produced for process water. The flotation underflow is flocculated and then acts as feed to a gravity thickener. The underflow is dewatered by a semicontinuous plate and frame filter. The filter cycle time can range from approximately 5 to 15 minutes and can be

Figure 3.9
Generalized Flowsheet and Material Balance for
50 TPD Soil Washing Plant



Overall Material Balance

Sized Contaminated Soil	Froth Solids	Clean Dewatered Soil
50 TPD	8.5 TPD	41.5 TPD
80% solids	47% solids	86.7% solids
1% organics	5-9% organics	nil organics
40 TPD soil	4 TPD soil	36 TPD soil
9.5 TPD water	4 TPD water	5.5 TPD water

automatically controlled with a consistent feed. Washwater is used to keep the filter cloth from binding. The filtrate, along with the thickener overflow, is returned to the process water tank. A granular activated carbon column is employed to remove organics and other color agents from any bleed stream used to control dissolved salts buildup.

This is a good example of a simple process for producing a clean dewatered soil along with a concentrated contaminant stream. The key to the process is the kind of reagents that are used in the initial reactor to produce a floatable contaminant product.

An elaboration of the previous process is presented in figure 3.10 (on page 3.33). Both dry and wet screening are employed to remove the > 5 mm (>0.2 in.) solids. The undersize solids in slurry form are subjected to high-intensity mixing with appropriate chemical reagents to clean the 5 mm (0.2 in.) by 63 µm (230 mesh) fraction sands. This sand fraction is then separated by hydrocyclones with the underflow dewatered on screens.

Hydrocyclone overflow is also screened to remove unwanted material, such as, grass, coke, and other light solids. The screen underflow is flocculated and passed to a tiltable plate separator, which is an adjustable angle lamella clarifier. The settled solids are <63 µm (<230 mesh), and can be treated either as clean material or as contaminated solids, depending upon their quality.

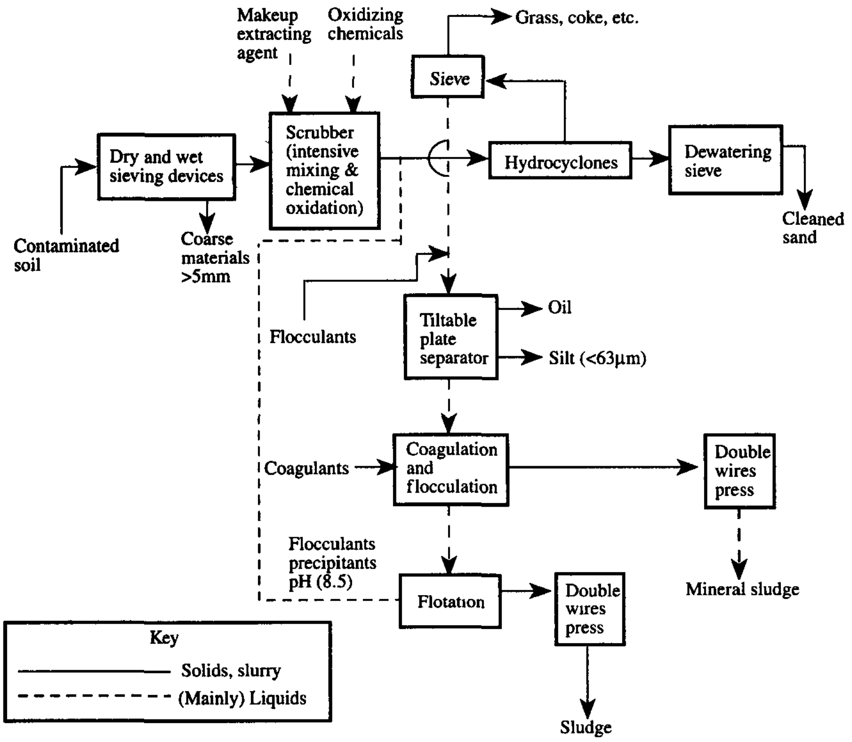
The clarifier overflow is sent to an oil-contaminated water separator, which is subjected to coagulation and flocculation and fed to a thickener. The overflow from this thickener is sent to a flotation cell. The flotation product and the underflow from the thickener are sent to individual belt presses for dewatering. All filtrates and flotation underflow are used as recycled process water for dilution before being fed to the hydrocyclones.

This kind of process yields a great deal more flexibility (as well as a more complex operation), while producing a clean sand coarser than 63 µm and dewatered contaminants.

A final flow diagram, of a very complex process for treating highly contaminated soils, is presented in figure 3.11 (on page 3.34). After screening to remove gross solids, the undersize is sent to an attrition mill for scrubbing of the solid surfaces. A single- or double-decked screen is applied to the attrition scrubber discharge. Oversize is sent to a crusher to reduce the particle size and is then returned to the scrubber.

Figure 3.10

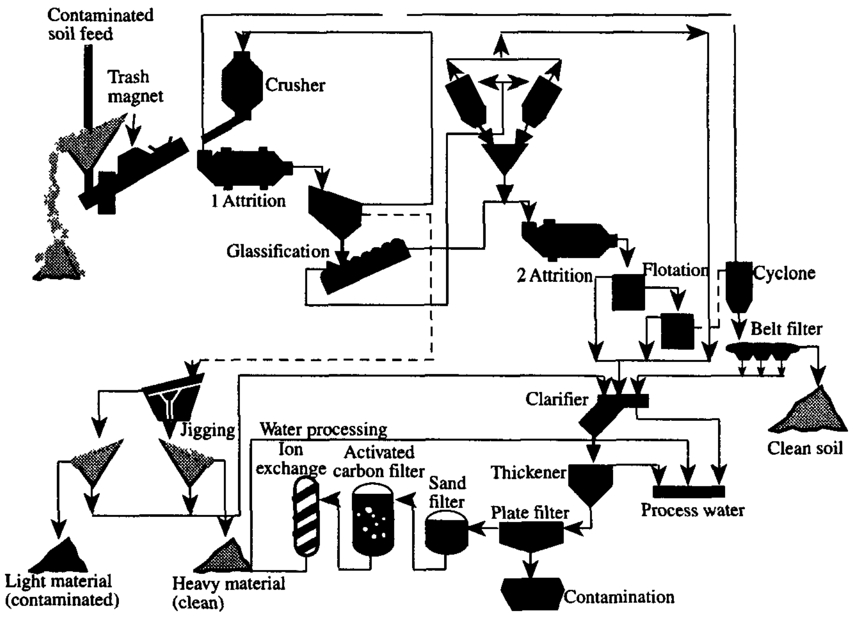
Process Scheme of the Heijmans Milieutechniek Installation: Chemical Extraction/Soil Washing



The undersize from the screen is sent to a spiral classifier with spiral product passed to a second attrition scrubber. The overflow of the spiral classifier (now the finer sizes) is sent to the hydrocyclones to make a 63 μm split. The cyclone overflow contains the <63 μm solids which flow to a lamella clarifier.

The >63 μm solids in the hydrocyclone underflow also pass to the second attrition scrubber, and this product is subjected to flotation. The froth product contains the contaminants while the flotation underflow contains clean sand coarser than 63 μm. The latter is concentrated in hydrocyclone underflows and final dewatering is accomplished on a horizontal continuous belt filter. Filtrate is also sent to the lamella clarifier.

Figure 3.11
Deconterra^R Process Flow Sheet



Overflow from the clarifier is process water, while the underflow is further thickened in a conventional gravity thickener. This overflow also returns to the process water stream. The thickened underflow, now containing the contaminants, is dewatered on a plate and frame filter press and disposed. The filtrate is clarified by a sand filter and is then directed to a carbon column and an ion exchange system for cleaning the process water for recycle.

The second-deck screen oversize is fed to a jig, where applicable, to separate lesser specific gravity solids from the greater. The light solids jig product is screened and dewatered and considered contaminated. The heavy solids are also screen dewatered and are considered clean after confirmatory analysis. The screened underflow is returned to the lamella clarifier.

The process, while very complex, can produce clean products and isolate the contaminants into the volume-reduced sludge cake. A bleed stream to control dissolved salts and contaminant build-up is also included to completely close the water circuit.

It is emphasized that processes are designed for the specific soil matrix and contaminant problem being addressed. The range of these technology variations demonstrates that soil washing is a flexible process incorporating a broad range of process trains.

3.1.11 Status of Development

At this writing, soil washing had been selected as a remedial source control technology at 23 Superfund sites, at which full-scale projects are in progress or have been completed. They include eight wood preserving sites (polynuclear aromatic hydrocarbons (PAHs)), PCP, and metals), one lead battery recycling site, three pesticide sites, one site containing volatile organic compounds (VOCs) and metals, and two containing metals only. Soil washing has been selected for one emergency response action. It is widely used in Europe, especially in Germany, the Netherlands, and Belgium.

See also Subsection 3.1.4.3 for a discussion of the Mobile Soil Washing System (MSWS) and Mobile Volume Reduction Unit (MVRU) designed by U.S. EPA.

3.2 *Soil Flushing*

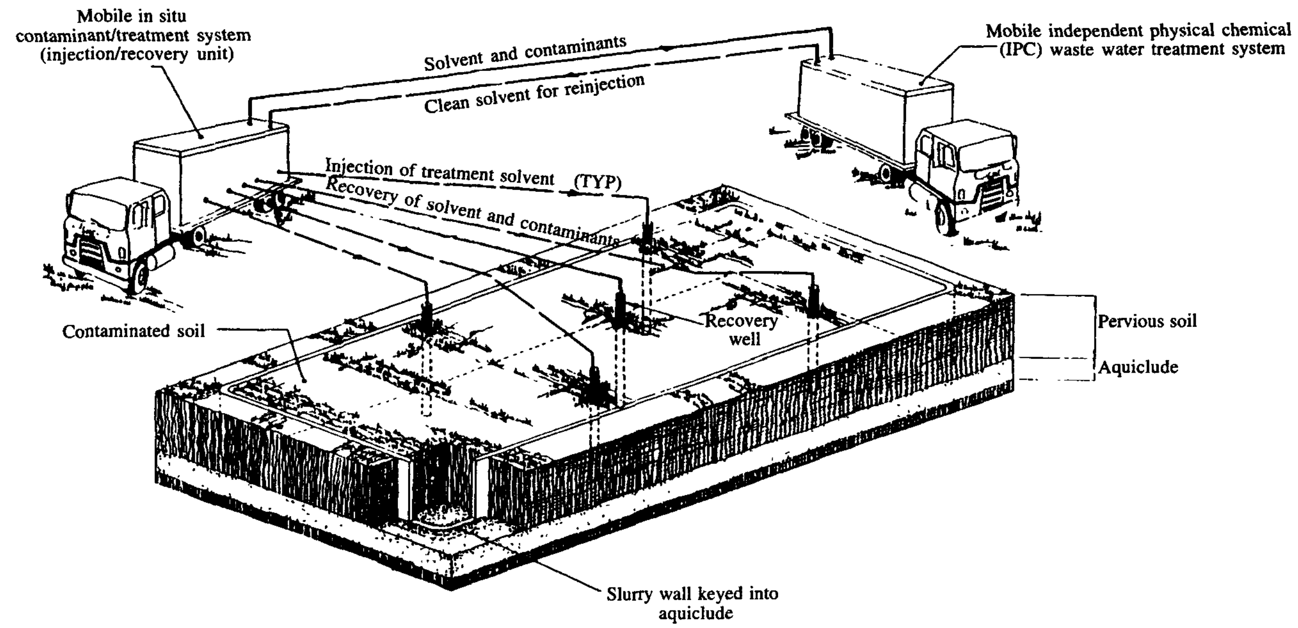
In situ soil flushing accelerates the in situ mobilization of contaminants from a contaminated soil for recovery and treatment (see figure 3.12 on page 3.36). Depending on the matrix, organic, inorganic, and radioactive contaminants are amenable to soil flushing.

The process uses water, enhanced water, or gaseous mixtures to accelerate one or more of the same geochemical dissolution reactions that alter contaminant concentrations in groundwater systems, such as:

- adsorption/desorption;
- acid/base reactions;
- solution/precipitation reactions;
- oxidation/reduction reactions;
- ion pairing or complexation; and
- biodegradation.

Figure 3.12

Schematic of In Situ Flushing Field Test System



In addition, soil flushing accelerates a number of subsurface contaminant transport mechanisms that are found in conventional groundwater pumping, including:

- advection;
- dispersion, as expressed by the dispersivity coefficient;
- molecular diffusion; and
- depletion via volatilization or solubilization.

The fluids can be applied and/or drawn from the groundwater in the immediate area. They can be introduced to the soil either through spraying (see figures 3.13 and 3.14 on page 3.38), surface flooding, subsurface leach fields, or subsurface injection (figure 3.15 on page 3.39).

Figure 3.13
Soil Flushing Sprinkler System of the Poly-Carb Site, Wells, Nevada

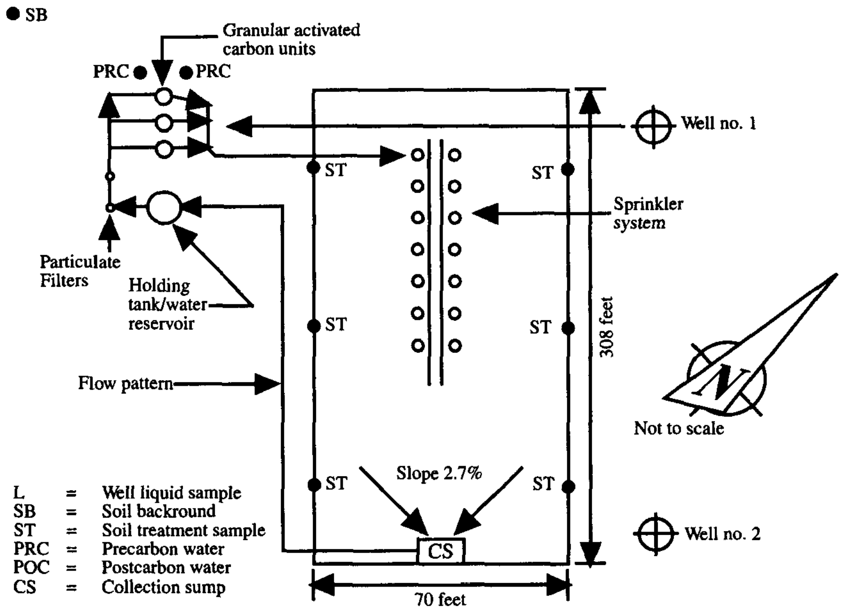
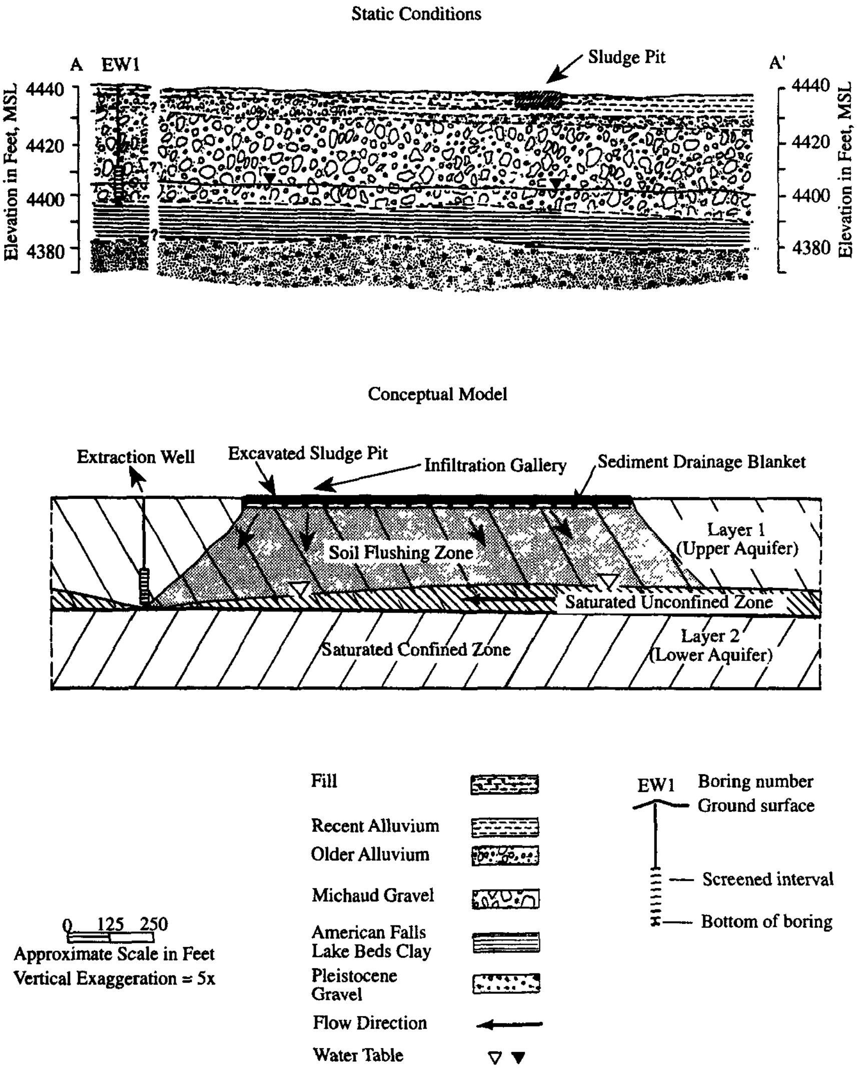


Figure 3.14

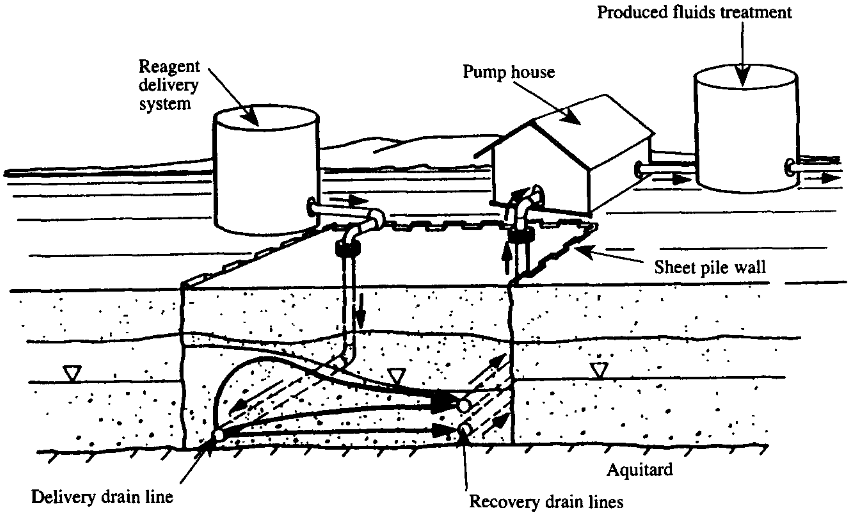
Site Cross Section and Idealized Conceptual Model
Union Pacific Railroad NPL Sludge Pit Pocatello, Idaho



Explanation:
This cross section is a diagrammatic interpretation of subsurface conditions based on interpolation and extrapolation of data from borings.
Actual conditions are substantially more complex than depicted and will vary between borings.

Source: Applied Geotechnology, Inc. 1990

Figure 3.15
Example of Soil Flushing Injection Scheme



Reprinted by permission of the National Water Well Association from "Chemically Enhanced In Situ Soil Washing" by T.Sale and M. Pitts in the Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemcials in Ground Water: Prevention, Detection and Restoration, Houston, Texas, 1989. Copyright 1989 National Water Well Association.

Once the infiltrated or percolated mixture has flushed the contaminants to a certain location, the contaminated fluids must be removed. They can be removed either from a perched condition or from a groundwater system. With some organics and inorganics, it is reasonable to conclude that with a large depth-to-water ratio, and because of limited contaminant mobility, the contamination may be left in place over a vertical profile. For example, where petroleum organic contamination has been flushed using surfactants and nutrients, passive bioremediation might be selected and the contamination left in place.

Effective application of the process requires a sound understanding of the manner in which target contaminants are bound to soils and of hydrogeologic transport. In addition, since soil washing increases contaminant mobility, consideration needs to be given to the potential consequences of deviations from the assumed site condition that could spread contamination. This concern can usually be addressed by employing conservative design parameters and the observational approach. Brief discussions of these and other scientific bases for soil flushing is integrated into the following subsections.

3.2.1 Process Description

3.2.1.1 Soil Flushing Solutions

Flushing solutions may include water, dilute acids and bases, complexing and chelating agents, reducing agents, solvents, or surfactants. In many cases, water can be used to flush water-soluble contaminants. Surfactants can be added to increase the mobility of certain semivolatile and inorganic contaminants and chelating agents can be added to solubilize heavy metals. Acids or bases can also be added to improve flushing efficiency.

Surfactants can be used to improve the solvent property of the recharge water, emulsify nonsoluble organics, and enhance the removal of hydrophobic organics sorbed onto soil particles. Surfactants improve the effectiveness of contaminant removal by improving both the detergency of aqueous solutions and the efficiency by which organics may be transported by aqueous solutions. Surfactants were originally developed for the tertiary recovery of oil; however, they have also been demonstrated to remove contaminants from soil.

Applicability of other flushing agents must be evaluated on a case-specific basis. The effectiveness and rate of cleanup are site- and contaminant-specific, with hydrogeological transport models or field tests used to assess performance. Column studies can also be performed using site-specific soils, contaminants, and flushing solutions.

3.2.1.2 Dissolution Reactions

If the input of contaminants in a groundwater system is discontinued, contaminants will be dissolved back to the liquid phase as lower concentration groundwater flushes through the previously contaminated zone. In theory, after contamination input is discontinued and if all partitioning reactions are completely reversible, all contamination should be eventually removed from the system as complete desorption occurs. Many substances do not, however, react sufficiently fast relative to the rate of groundwater movement to enable a sufficiently rapid rate of dissolution. Therefore, dissolution of contaminants by adsorption or other geochemical processes from the pore water to the solid phase causes the advance rate of the contaminant mass moving from a point source to be retarded relative to the ground water mass, and can be described by the retardation factor R_f=v/v_c, and by its inverse, the relative velocity, v_c/v. The solute or contaminant velocity, v_c, can be calculated from the relationship v_c=v/ R_f, such that a larger retardation factor indicates a slower solute velocity.

Retardation can be expressed by the equation:

$$R_f = \frac{v}{v_c} = \frac{v}{\left[1+\left(\frac{1-n}{n}\right)p_s K_d\right]}$$

where v = groundwater velocity

v_c = contaminant velocity

n = total porosity, or $\frac{void\ \ volume}{total\ \ volume}$

p_s = soil relative density

K_d = distribution coefficient, or solute mass per solid phase unit mass

The partitioning of solutes between liquid and solid phases in a porous medium is commonly expressed by the log-log Freundlich isotherm:

$$S = K_d C^b$$

where S = mass of solute species adsorbed or precipitated on the solids per unit bulk dry mass of porous media

C = solute concentration

K_d = distribution coefficient

= *solute mass per solid phase unit mass* concentration of solute in solution

b = slope of the log - relationship between S&C.

A reactive flushing solution can react with other target constituents. Complex wastes containing a range of contaminants with different solubilities and partitioning characteristics may make soil flushing infeasible. Reactive flushing solutions may have toxic or other environmental effects on soil and groundwater and may also pose special problems in the treatment required to dispose or reinject them into the aquifer.

In some situations, a portion of the contaminant mass transferred to the solid part of the porous material by adsorption or precipitation is irreversibly fixed within a reasonable time frame. This portion is not transferred back to the pore water as new water passes through the system and is therefore isolated in the subsurface environment.

When a mixture of reactive contaminants enters the groundwater zone, each species has different dissolution reactions and will travel at a different rate, depending on its relative velocity. After a given time, the concentration distribution of the dissolved reactive species will be retarded at different rates relative to groundwater flow.

3.2.1.3 Transport Mechanisms

Soil flushing also involves the transport of dissolved constituents, primarily by advection, whereby solutes are transported by the bulk mass of the flowing fluid. Dispersion causes spreading of the solute and is caused by molecular diffusion (mixing caused by random molecular motions due to solute thermal kinetic energy) and by mechanical mixing within the substrata. Dispersion is much stronger in the direction of flow (longitudinal dispersion) than in the direction normal to the flow line (transverse dispersion). Longitudinal dispersion is proportional to groundwater velocity. Transverse dispersion remains largely diffusion controlled until the flow velocity is quite high. See Domenico and Schwartz 1990 and Freeze and Cherry 1979 for further discussion.

The dispersion of solutes during transport through many types of fractured rocks cannot be described by the same relationships for homogeneous granular materials. Fractured geologic materials, are notoriously anisotropic with respect to the orientation and frequency of fractures. For example, distribution coefficients are more commonly expressed on the basis of media surface area than on the basis of mass. Little is known about predicting dispersion in fractured media.

Vertical transverse dispersivity can be greater than horizontal, such that if the transverse dispersivity is large, contaminants transported along relatively horizontal flow paths can disperse more in depth than in breadth. Dispersivity can be established only by detailed field testing and experiments.

3.2.1.4 Passive Hydraulic Methods

Conveyance and transport systems include sumps, French drains, and other equipment and designs that allow for passive removal of accumulated free product from the unsaturated zone. (This subsection does not address caps, slurry walls, or other physical barriers to flow or technologies, such as freezing.)

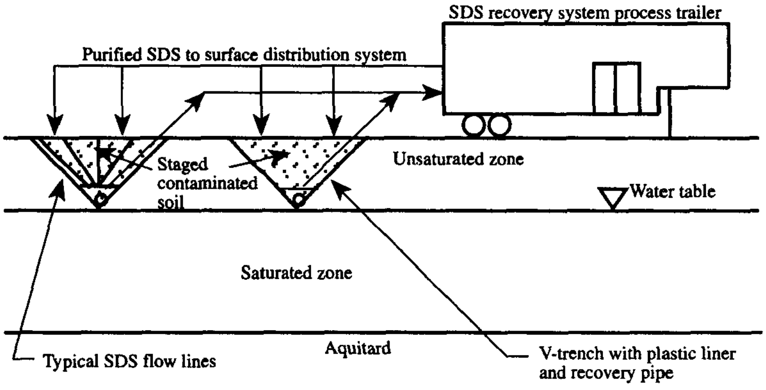
Passive hydraulic methods for removing gross levels of contaminants from unsaturated or saturated zones can be simple and relatively inexpensive, but do nothing to remove contaminants to low levels. They are effective in the unsaturated zone only when perched zones are present or a positive head is introduced by infiltrating waters. The collection system needs to be located down gradient from and as close to the source as is practical. Passive hydraulic methods are unlikely to be selected as a primary cleanup method and might best serve as an initial step in easily collecting gross contaminants before, or in conjunction with, implementation of another technology. For example, when a leaking underground storage tank (UST) is removed, the resulting excavated area might begin to accumulate residual free product. The heavy machinery already on site could be used to enlarge the excavated area to install a sump or French drain to further promote accumulation with little added effort.

Groundwater drawdown will create a groundwater gradient and can also increase permeability in the saturated zone, causing residual liquid contaminants to flow readily toward that zone. An impervious layer can be placed at the base of the trench to prevent reinfiltration of free product. As the product accumulates, it can be pumped out or removed manually. This maintains a gradient that facilitates further seepage into the trench. Figure 3.16 (on page 3.44) shows a drain system for staging contaminated soil in below-grade trenches.

Passive hydraulic methods collect and remove only the mobile liquid and dissolved contaminants (and may also serve as a passive venting system). Contaminants sorbed to soil particles or held as residual saturation are little affected by passive hydraulic methods and typically must be removed by other means. The method is best used in situations where the mobile phase — residual liquid and pore water — content is relatively high. Passive hydraulic methods are most effective for recent releases of significant quantities of contaminants at shallow depths.

Table 3.3 (on page 3.45) lists several critical success factors (CSF) for passive hydraulic methods. The single most important CSF is the amount of contaminant in the liquid phase. This method will not be effective unless significant quantities of liquid contaminant are in the soil.

Figure 3.16
Typical Drain System



3.2.1.5 Soil Flushing Component Activities

Soil flushing can be broken down into three activities — site characterization, injection, and contaminant mobilization and recovery techniques — discussed in the following subsections. (See also figure 3.17 on page 3.46 for a representation of these activities.)

3.2.1.5.1 Site Characterization Site characterization requires a full understanding of hydrogeology, geochemistry, and the relative permeability and lithology above, within, and below the zone of contamination. In general, soil flushing is most effective in homogeneous, permeable soils (e.g., sands, gravels, and silty sand with permeabilities $>10^{-4}$ cm/sec). The relationship between capillary processes, water content, and hydraulic conductivity must be understood before a water-based flushing technique can be effectively used. For gas-phase soil flushing, the intrinsic air permeability and the effect of soil moisture must be measured.

Factors that affect the residual hydrocarbon concentration are:

- water solubility of the hydrocarbon contaminants;
- interfacial tension (IFT) between the hydrocarbon, water and soil, and the contaminant; and

Table 3.3
Worksheet for Evaluating the Feasibility of Soil Flushing

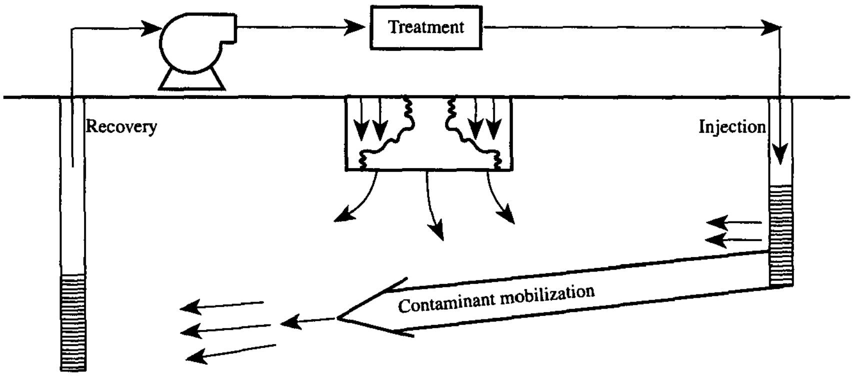
Critical Success Factor	Units	Site of Interest	Success Less Likely	Success Somewhat Likely	Success More Likely
SITE RELATED					
• Dominant Contaminant Phase	Phase		Vapor	Liquid	Dissolved
• Soil Hydraulic Conductivity	cm/sec.		Low ($<10^{-5}$)	Medium (10^{-5}-10^{-3})	High ($>10^{-3}$)
• Soil Surface Area	m^2/kg		High (>1)	Medium (0.1- 1)	Small (<0.1)
• Carbon Content	% Weight		High (>10%)	Medium (1-10%)	Small (<1%)
• Fractures in Rock	----		Present	----	Absent
CONTAMINANT RELATED					
• Water Solubility	mg/L		Low (<100)	Medium (100-1,000)	High (>1,000)
• Sorption Characteristics Soil Sorption Constant	L/kg		High (>10,000)	Medium (100-10,000)	Low (<100)
• Vapor Pressure	mm Hg		High (>100)	Medium (10-100)	Low (<10)
• Liquid Viscosity	cPoise		High (>20)	Medium (2-20)	Low (<2)
• Liquid Density	g/cm^3		Low (<1)	Medium (1-2)	High (>2)

Other Considerations
- Cost is from $150 to $200 per cubic yard
- Using surfactants may increase effectiveness
- Effluent requires separation techniques such as distillation, evaporation, centrifugation.
- *Most effective when used ex situ (above ground).*

- relative permeability of the contaminant and water.

The low solubility of residual hydrocarbons limits the effectiveness of water-based soil flushing methods because the amount of oil that dissolves into water and is flushed from the subsurface is insignificant in comparison with the residual oil left in place.

Figure 3.17
Site Characterization Soil Flushing Activities



Interfacial tension can be described as the unbalanced forces acting on a droplet of free-phase hydrocarbon contamination. The lower the IFT, the greater the tendency of the droplet to be miscible in groundwater. The result of high IFT is the retention of the hydrocarbon on soil particles as opposed to its movement when groundwater is swept through the soil pores.

Relative permeability can be described as the tendency of a porous system to selectively conduct one fluid when two or more fluids are present. The mobility ratio is the term used to describe the effects of relative permeability in the enhanced oil recovery industry. The mobility ratio is defined as:

$$m = \frac{K_D / U_D}{K_O / U_O}$$

where: m = Mobility ratio
K_D = Effective permeability with respect to the displacing fluid
K_O = Effective permeability with respect to the oil
U_D = Viscosity of the displacing fluid
U_O = Viscosity of the oil

The higher the mobility ratio, the greater the tendency of the displacing fluid to flow around, rather than push out the contaminant residual oil.

For homogeneous soils, the vertical and horizontal permeabilities must be measured. Problems, however, begin to develop in layered soils where the contamination is located in the finer-grained materials. For surface flooding applications, the infiltration and percolation rates must be tied into the number of pore volumes required to achieve the cleanup goal. For down-hole injection applications, the vertical and volumetric sweep parameters must be understood.

3.2.1.5.2 Injection The in situ flushing process requires that the flushing fluids be injected into the soil matrix. Injection can be by surface water flooding, surface sprinklers, leach fields, septic systems, vertical and horizontal injection wells, or a trench infiltration system (see figure 3.18 on page 3.48).

3.2.1.5.3 Contaminant Mobilization and Recovery Techniques Soil flushing techniques for mobilizing contaminants can be classified as conventional and unconventional. Conventional soil flushing can be broken down into the following activities:

- natural restoration;
- well-and-capture methods in the vadose zone; and
- pump-and-treat systems in the saturated zone.

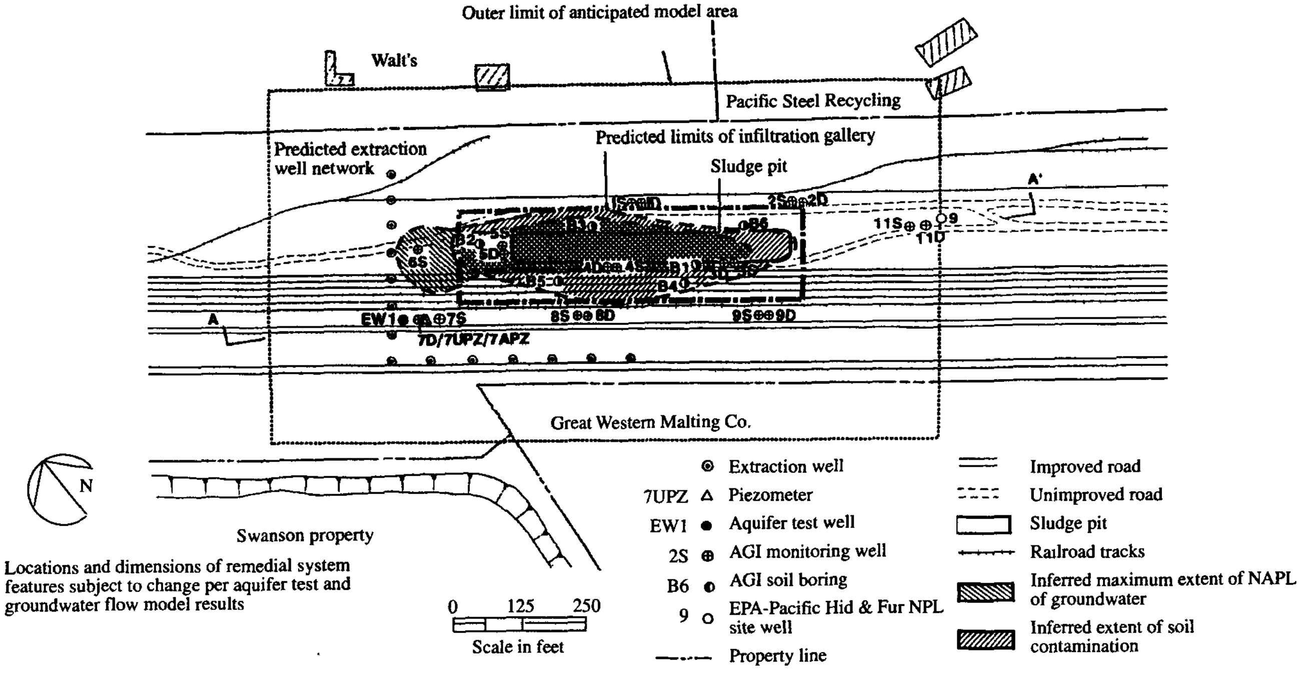
Above ground treatment systems are conventional remedial wastewater treatment applications that are familiar pump-and-treat operations. The treatment system will be sized based upon the recovery volumes and the rates of withdrawal from the collection system. The treatment system is designed to remove and recover contaminants from the waste stream and to provide reinjection water at a certain contaminant concentration level.

The treatment system will be configured to remove specific contaminants of concern. For organic contaminants, in most cases, the treatment system will consist of air stripping, carbon adsorption, and/or biological treatment units. For inorganic treatment, the systems will usually include standard precipitation systems, electrochemical exchange, ion exchange, and/or ultrafiltration systems. For many sites, the contaminants of concern will include organics and inorganics in the same waste stream. For these cases, process treatment trains will be configured to provide appropriate removals. In all cases, the key concern, and the primary contributor to long-term operation and maintenance , will

Figure 3.18

Proposed Froundwater Flow Model Area

Union Pacific Railroad Sludge Pit NPL Site Pocatello, Idaho



Note: Locations and dimensions of remedial system features subject to change per aquifer test and groundwater flow model results be the volume and quality of sludge generated from the process treatment system.

Unconventional soil flushing can be broken down into:

- primary recovery;
- secondary recovery; and
- tertiary recovery —
  - gaseous processes;
  - chemical processes —
    - polymers;
    - surfactants;
    - alkaline agents;
    - in situ solvent extraction; and
  - thermal methods —
    - alkaline, surfactant, and polymer flooding.

Unconventional soil flushing methods can effect primary recovery of contaminants using the natural energy within the system. These methods include a neutral water drive, gravity drainage, solution gas drive, or a gas cap drive.

The secondary recovery methods include waterflooding and pressure maintenance techniques. Tertiary recovery techniques remove the contaminants by the injection of materials not normally found in the soil. Tertiary recovery methods include gaseous processes such as carbon dioxide flooding, an Enhanced Oil Recovery (EOR) technique that relies on achieving a decreased mobility ratio. Carbon dioxide is injected under pressure into a hydrocarbon-contaminated zone. The viscosity of the contaminant decreases as carbon dioxide dissolves into the hydrocarbon. Because this method relies on high pressures, it would be applicable only at relatively large depths in a confined strata. The effectiveness of this technique in environmental applications is not known.

Chemical recovery processes include polymer flooding and surfactant flooding. Polymer flooding is a commonly-used EOR method that may have environmental applications, although this application has not yet undergone extensive evaluation. The contaminant removal effectiveness of the waterflood can be increased by adding polymer to the water, which increases the viscosity of the flood and thus lowers the mobility ratio.

Soil flushing with surfactant solutions to extract hydrophobic organic contaminants appears to be one of the most promising of in situ cleanup technologies. Aqueous surfactant solutions are superior to water alone in extracting hydrophobic contaminants. Both the detergency of aqueous solutions and the efficiency by which organics are transported by aqueous solutions are thought by researchers to be improved by surfactant addition. The processes for improving the detergency of aqueous solutions are preferential wetting, increased contaminant solubilization, and enhanced contaminant emulsification (Edwards, Luthy, and Liu 1991). The addition of surfactants is thought to increase the efficiency by which organics are transported in aqueous solutions by lowering the interfacial tension between the aqueous and contaminant phase, which facilitates the distortion of spherical oil droplets as they pass through the soil.

Another reason the use of surfactants for in situ soil flushing applications appears promising is that numerous environmentally safe and relatively inexpensive surfactants are available commercially.

Enhanced Oil Recovery research has identified an IFT reduction method that may be much more cost-effective than the use of surfactants. When in contact with certain hydrocarbon mixtures, alkaline agents (e.g., sodium carbonate) can react to form surfactants that are created at the aqueous-hydrocarbon interface, and the surfactants can effectively reduce the IFT. The use of a combination of alkaline agents and surfactants may be the most cost-effective way to reduce IFT and to enhance hydrocarbon recovery (Sale and Pitts 1989).

As in surfactant flooding, IFT reduction through the use of alkaline agents is not likely to be effective if unfavorable mobility ratios still exist. Other potential problems with the use of alkaline agents may result from the high pH and reactive nature of these solutions. These problems include precipitation and resultant aquifer plugging, dispersal and expansion of clays, and leaching of trace metals.

In situ solvent extraction involves flooding the subsurface zone containing the residual oil with an organic solvent or water containing an organic solvent. This technique is based on increasing the solubility of the residual oil in the fluid used for flushing the subsurface. This method is not generally considered practicable for the following reasons:

- environmental concerns regarding injecting organics that are effective as solvent into the subsurface;
- residual solvents left in the subsurface;
- difficulties in treating fluid withdrawn from the subsurface that contain miscible mixtures of water, solvent, and oil; and
- high project costs for implementation.

One combination of the techniques described above that has undergone limited testing for environmental applications is alkaline, surfactant, and polymer (ASP) flooding. The addition of an alkaline agent and a surfactant address IFT; the addition of a polymer gives the flood a favorable mobility ratio. In bench-scale tests, an ASP flood was highly effective in displacing residual waste wood-preservatives oil from a subsurface sandy soil (Sale and Pitts 1989).

The most commonly considered thermal methods are hot water flooding and steam flooding. These methods rely on decreasing the residual oil level by increasing contaminant solubility and achieving a more favorable mobility ratio. Contaminant solubility in the soil flushing solution is increased because the water solubility of many organics increases at higher water temperature. More importantly, the viscosity of free-phase hydrocarbon decreases with increasing temperature because of the loss of volatiles, causing a decrease in the mobility ratio.

A major limitation in the use of thermal methods is that at increased temperatures, denser-than-water, free-phase oil may be converted to a floating oil. The effect is that oil initially confined to a narrow lens may float through and wet, previously uncontaminated portions of the subsurface. Costs may also be high because of the heat loss that occurs as large volumes of subsurface materials are heated.

The effectiveness of this technology in environmental applications is unknown. A summary of screening criteria for EOR methods is given in table 3.4 (on page 3.52) and a comparative summary of recovery percentages is given in table 3.5 (on page 3.53).

Table 3.4

Summary of Screening Criteria for Enhanced Recovery Methods

(Should not be taken as absolute values, but as rules of thumb only)

	Oil Properties				Reservoir Characteristics				
Gas Injection Methods	Gravity *API	Viscosity (cp)	Composition	Oil Saturation	Formation Type	Net Thickness (ft)	Average Permeability (md)	Depth (ft)	Temperature °F
Hydrocarbon	>35	<10	High % of C_2-C_7	>30% PV	Sandstone or Carbonate	Thin unless dipping	N.C.	>2000 (LPG) to >5000 (H.P. Gas)	N.C.
Nitrogen & Flue Gas	>24 >35 for N_2	<10	High % of C_2-C_7	>30% PV	Sandstone or Carbonate	Thin unless dipping	N.C.	>4500	N.C.
Carbon Dioxide	>26	<15	High % of C_5-C_{12}	>30% PV	Sandstone or Carbonate	Thin unless dipping	N.C.	>2000	N.C.
Chemical Flooding Surfactant/Polymer	>25	<30	Light intermediates desired	>30% PV	Sandstone preferred	>10	>20	<8000	<175
Polymer	>25	<150	N.C.	>10% PV mobile oil	Sandstone preferred; carbonate possible	N.C.	>10 (normally)	<9000	<200
Alkaline	13-15	<200	Some organic acids	Above waterflood residual	Sandstone preferred	N.C.	>20	<9000	<200
Thermal Combustion	<40 (10-25 normally)	<1000	Some asphaltic components	>40-50% PV	Sand or sandstone with high porosity	>10	>100*	>500	>150 preferred
Steamflooding	<25	>20	N.C.	>40-50% PV	Sand or sandstone with high porosity	>20	>200**	300-5000	N.C.

N.C. - Not critical *Transmissibility >20 md ft/cp **Transmissibility >100 md ft/cp Source: McKee & Whitman 1991

Table 3.5
Comparative Summary

Process	Recovery Mechanism	Typical Recovery %	Typical Agent Utilization
Immiscible gas	Reduces oil viscosity Oil swelling Solution gas drive	5 to 10	10 Mscf gas/ bbl oil
Miscible gas	Same as immiscible plus development of miscible displacement	5 to 15	10 Mscf gas/ bbl oil
Polymer	Increase volumetric sweep efficiency by reducing mobility ratio	5	0.5 to 2 lb polymer/bbl oil
Micellar/Polymer	Same as polymer plus reduction in IFT forces	15	15 to 25 lb surfactant/bbl oil
Alkaline/Polymer	Same as micellar/polymer plus wettabiltiy alteration	5	35 to 45 lb chemical/bbl oil produced
Steam (drive or soak)	Reduces oil viscosity	50 to 65	0.5 bbl oil consumed/bbl oil produced
	Vaporization of light ends		5 to 10 bbl steam/bbl oil
In situ	Same as steam plus cracking of heavy ends	10 to 15	10 Mscf air/bbl oil

Source: McKee and Whitman 1991

3.2.1.6 Measuring Effectiveness

The measurement of the effectiveness of soil flushing requires the use of field monitoring instrumentation to determine soil moisture flux, changes in capillary pressure, and water content. Changes in capillary pressure can be measured using transducerized transmitters; changes in water content can be measured using neutron probes or frequency domain capacitance probes. Change in contaminant concentration can be measured using field soil gas totalizers, portable gas chromatographs, specific ion probes, and radiation monitoring systems.

3.2.2 Status of Development

Soil flushing has been practiced on a commercial level for more than 50 years in the oil and gas industry to mobilize product material near the wellhead. The process is now being modified for application in the treatment of hazardous waste. Some difficulties arise because hazardous waste soil flushing systems must perform in a finer mode to seek out, destabilize, and collect contaminants in low concentrations from extremely difficult geological settings.

Nevertheless, conventional applications of soil flushing have been employed, in most cases, using the treated effluent from a pump-and-treat operation for reinjection and improved contaminant mobilization. Unconventional methods are now being accepted and will be demonstrated soon on specific Superfund sites. Some representative case histories are presented in Appendix B.

In situ soil flushing is in the predesign and design stage at 21 Superfund sites (see figure 3.19).

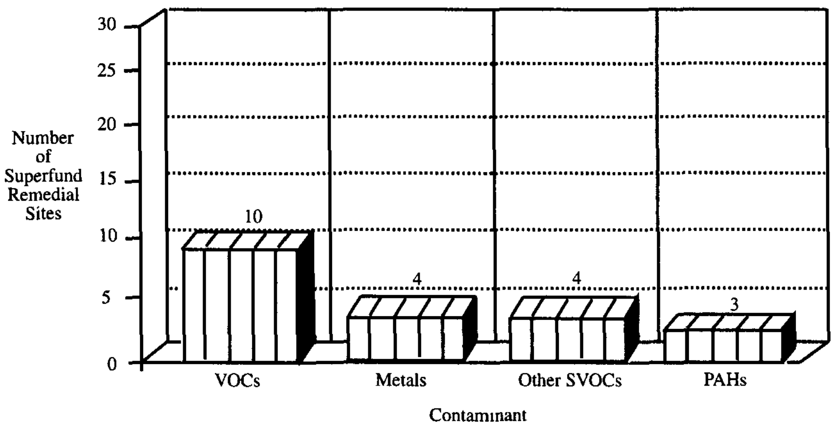
3.2.3 Design Data and Unit Sizing

The following data are required to select the flushing solvent and to predict soil flushing effectiveness:

- site hydrogeology; permeability, geochemistry, direction and rate of vertical and horizontal groundwater flow, vadose zone saturation, bulk density, average particle size, thickness of receiving aquifer, aquifer confinement, aquifer and adjacent aquifer use, porosity, plume location and rate of travel;

Figure 3.19

In Situ Flushing Target Contaminants Through Fiscal Year 1991



Note At some sites, treatment is far more than one contaminant. Treatment may be planned, ongoing, or completed

- soluble contaminant extent and concentration, Freundlich isotherm, molecular diffusions, retardation factor, O_2 concentration, water table fluctuation, solubility, residual nonaqueous phase liquids and their relative density; and
- nonaqueous phase liquid (NAPL) vertical and lateral distribution, density, adsorption coefficient, seasonal relationship of water table to contamination.

Actual field experience with in situ soil flushing for petroleum remediation is very limited, and thus data on effectiveness, costs and limitations are generally unavailable. The petroleum industry has experimented for several years with enhanced oil recovery, which uses surfactants to increase the production of an oil deposit.

3.2.4 Pre- and Posttreatment Requirements

Preflushing of the contaminated area may be required to demonstrate that the monitoring system is working. In addition, preflushing is required to adjust the salinity for both the use of surfactants and the application of polymers. Preflushing also results in a reduction of the adsorption of the surfactant.

As to posttreatment, once the recovery system (i.e., pump-and-treat) has been shut down, infiltration may have to be controlled to prevent further mobilization of residual contaminants. This posttreatment will allow the further breakdown of contamination by microbial activity. In addition, it may be possible to effect posttreatment using bioventing once the permeability has been increased through removal of the bulk of contaminants.

3.2.5 Operational Requirements and Considerations

Once the appropriate surfactant type and dosage are determined from shaker table and column bench studies, the field conditions must be evaluated, controlled and monitored. The field operations require that the surfactant mixing, holding, and delivery systems be monitored. The surfactant application system must be maintained. The recovery drains or the contaminant capture system must be monitored. The recovered fluids treatment system must be maintained. The pumping system for the surfactant delivery and contaminant capture needs to be fully operational. And, finally, the use of any contaminant barriers must be monitored.

In planning soil flushing operations, the likelihood that it may rain should be considered. If the loading rates of waterflooding are scaled to the pump-and-treat system and there is heavy rainfall, the recovery system may not remove all of the contaminated fluids that could migrate downgradient.

3.2.6 Unique Planning and Management Needs

Several unique and extremely important matters must be considered when implementing a soil flushing project. They are:

- A well designed and executed Remedial Investigation must characterize the site to define key contaminants and occurrence within the zone of contamination;
- The dynamics of the vadose zone are particularly complicated and are very different than flow dynamics in the saturated zone. Solute transport mathematical models are not applicable in the vadose zone, and, in fact, limited models are currently available that can describe the vadose zone phenomena. The plan for implementation, therefore, must contain a special approach to the collection of required data in the vadose zone, including water content, capillary pressure, hydraulic conductivity, relative permeabilities, and horizontal and vertical distribution of fine-grained materials;
- The potential for retention of flushing enhancements (chemicals or surfactants) will be very critical to obtaining approval for a soil flushing application; and
- A substantial field test is recommended to confirm the applicability of this technology.

3.2.7 Cost Data

Cost data are sparse. The Superfund site at Palmetto Wood, S.C. cited costs of \$3,710,000 (capital) and \$300,000 (annual O&M). These figures, on a unit basis, equal \$240/m^3 (\$185/yd^3) for capital costs, and \$20/m^3 (\$15/yd^3) annually for O&M. At Palmetto Wood, soil flushing will be used to clean 15,400 m^3 (20,000 yd^3) of soil contaminated with metals (US EPA 1988).

3.2.8 Special Health and Safety Requirements

As in soil washing, workers are usually remote from the waste material. Further, because soil flushing is an in situ remedy, the potential for exposure is even more remote than those activities requiring excavation. Nevertheless, all activities must be performed under an approved HASP, and all activities performed in the field must be conducted by personnel qualified in conformance with the requirements of OSHA directive 1910.120 (series). Operations will be routinely conducted in Level "D" protection, consistent with the direct monitoring requirements of the HASP.

3.2.9 Technology Variations

Soil flushing can be performed in two primary modes: conventional and unconventional (see Subsection 3.2.1.5.3). Conventional applications employ water only as the flushing agent. In the flooding variation, clean water is applied to the site through pumping, spraying, or the routine release from storage areas. Conventional methods also include reinjection of the flushing water through a series of injection wells, through horizontal distribution headers, or through infiltration galleries.

Unconventional applications consist of the enhancement of the flushing water with surfactants, chelants, or other chemicals to aid in the desorption/ dissolution of the target contaminants from the soil matrix to which they are bound.

3.2.10 Summary of Good Practice

In situ soil flushing good practice requires that the appropriate shaker tests and column studies be made in the laboratory to identify the correct surfactants, dosage, and pore volumes for field trial. In the field, good practice requires selection of an appropriate injection technique, based upon site characterization, an appropriate mobilization and recovery technique, and a complete monitoring system capable of demonstrating that the system is working.

4

POTENTIAL APPLICATIONS

4.1 Soil Washing

Soil washing may be used to treat soils containing a wide variety of organic, inorganic, and radioactive contaminants. The technology is most appropriate for noncomplex soils contaminated with either metals or organics.

Because the technology is primarily a separation and volume reduction process, it is usually used in conjunction with other technologies. For example, soil washing may be used to separate and concentrate the contamination into a smaller volume of fine soil particles. Because only this smaller volume of soil and contaminants needs treatment, the additional treatment technology is more cost effective when applied after the soil washing step.

Soil washing is most effective when applied to soils and sediments containing high percentages of sand and gravel. It is most cost-effective when water alone (without additives) is sufficient to achieve target cleanup levels.

4.1.1 Site Characterization

Site characterization is the first and most important step in determining whether soil washing may be effectively applied. In addition, it can provide the basis for informed decisions about the design and execution of bench- and pilot-scale tests that yield the best possible data at the least cost.

Soil data that are necessary to characterize a candidate site include the following:

- site geology and hydrogeology;
- soil type and composition versus depth;

- soil chemistry;
- aerial extent of the soil contamination (vertical and horizontal profiles);
- total amount of contaminated soil to be treated;
- range, concentration, and variability of contaminants in the soil; and
- history, process, and time frame of the conditions leading to the contamination.

Information from geological surveys, aerial photos, topographical surveys, groundwater maps, and nearby soil borings and well logs can provide substantial information about the subsurface conditions likely to be encountered during excavation of the contaminated soil. It is important to know how soil type and contaminant concentrations change with latitude and depth so that an accurate profile of the feedstock soil can be developed. This information will be very helpful also in guiding sampling efforts for collecting representative soils for further characterization and for bench and pilot testing.

4.1.2 Bench- and Pilot-Scale Testing

Site characterization is followed by bench- and pilot- scale tests on representative samples to determine whether soil washing can be used to effectively remove contaminants. Such tests can be used to determine also the requirements for soil feedstock preparation and to gauge the performance capabilities of commercially available systems. If bench test results are promising, pilot test demonstrations should be conducted before final commitment to a full-scale soil washing system.

Guidelines and procedures for soil washing treatability studies are explained in EPA's 37-page interim guidance document titled *Guide to Conducting Treatability Studies Under CERCLA: Soil Washing* (EPA/540/2-91/020A, September, 1991). A fact sheet by the same name, also published by EPA (EPA/540/2-91/020B), highlights and summarizes the material contained in the companion guidance document. Appendix C of this monograph is the September, 1991 issue of the fact sheet.

4.1.3 Potential Applications

The two most important aspects of soil type and composition that should be evaluated during site characterization are:

- particle size distribution; and
- contaminant relationship to the soil matrix.

Soil washing performance is closely tied to these two key physical soil characteristics. Because these characteristics can vary substantially with area and with soil depth across a given site, care must be taken to evaluate them in light of the overall site geology and the vertical and horizontal extent of the chemical contamination.

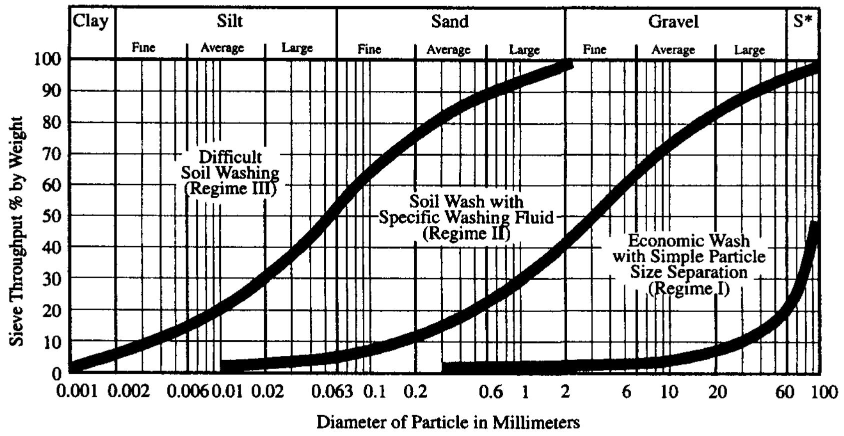
1. Particle size distribution has a direct effect on the ability of a soil washing system to separate contaminants from the major soil mass. Many soil contaminants tend to bind to the fine particle fraction of the soil (i.e., bind with the silt and clay portion). These contaminants will be separated from the clean soil during the washing process to much the same extent as the fines are separated from the coarse sand and gravel fraction. If a soil is tested and found to have a relatively small percentage of silt and clay (e.g., <25%), the probability will be high that soil washing will be effective in reducing contamination in the bulk of the soil. Therefore, knowledge of the typical particle size distribution (and likely variations therein) that will be encountered throughout the contaminated soil area can be particularly valuable as an early indicator (or screening tool) of the potential effectiveness of soil washing in separating out the contaminants.

Soils containing a relatively high percentage of sand and gravel (curve #1, figure 4.1 on page 4.4) will most likely respond favorably to the soil washing treatment process, whereas soils that are rich in clay and silt sized particles (curve #3) are likely to respond poorly. In general, soil washing is most appropriate for soils that contain at least 50% sand and gravel, such as coastal sandy soils and soils with glacial deposits. Grain-size distribution tests should be conducted under wet sieve conditions using American Society for Testing and Materials (ASTM) Method D422.

2. The contaminant relationship to the soil matrix is a very important consideration. Depending upon site conditions, a wide variety of chemical contaminants and pollutants can be removed from soils through soil washing, as table 4.1 (on page 4.5) shows. But the exact removal efficiencies that can be

Figure 4.1

Soil Washing Applicable Particle Size Range



*S=Stone

achieved at a particular site will be highly dependent on the specific blend of physical and chemical characteristics associated with the composition of the soil and the contaminants.

3, In addition to particle size distribution and contaminant relationship to the soil matrix, cation exchange capacity of the soil is another important consideration. Cation exchange capacity measures the tendency of the soil to exchange natural and weakly held cations in the soil for cations in the polluting substance. Soils with a relatively high cation exchange capacity tend to bind pollutants more tightly to the soil. This can limit the ability of the soil washing process to effectively separate the pollutant from the soil. Cation exchange should be measured using EPA Method 9080 (ammonium acetate test) or 9081 (sodium acetate test).

Soil washing can be used to remove volatile organic compounds (VOCs) from soil and other materials that have a relatively high vapor pressure or water solubility quotient (water/octanol partition coefficient). Experience shows that removals of 90 to 99% or more of VOCs can be achieved by simple water washing. Care must be taken, however, to collect the volatile material in a manner that prevents it from being released into the environment. Removals of semivolatile organics tend to be lower, on the order of 40 to 90%, and often require the addition of surfactants to the washwater to aid in the separation. Successful removal of metals and pesticides, which tend to be less soluble in water, may require the addition of acids or chelating agents.

Table 4.1

Applicability of Soil Washing To General Contaminant Groups For Various Soils

	Contaminant Groups	Matrix	
		Sandy/ Gravelly Soils	Silty/Clay Soils
Organic	Halogenated Volatiles	■	▼
	Halogenated semivolatiles	▼	▼
	Nonhalogenated volatiles	■	▼
	Nonhalogenated semivolatiles	▼	▼
	PCBs	▼	▼
	Pesticides (halogenated)	▼	▼
	Dioxins/Furans	▼	▼
	Organic cyanides	▼	▼
	Organic corrosvies	▼	▼
Inorganic	Volatiles metals	■	▼
	Nonvolatile metals	■	▼
	Asbestos	❑	❑
	Radioactive materials	▼	▼
	Inorganic corrosives	▼	▼
	Inorganic cyanides	▼	▼
Reactive	Oxidizer	▼	▼
	Reducers	▼	▼

■ Good to Excellent Applicability: High probability that technology will be successful
▼ Moderate to Marginal Applicability: Exercise care in choosing technology
❑ Not Applicable: Expert opinion that technology will not work
Source: US EPA 1990

Soils contaminated with fuel oil, jet fuel, and waste oil from underground tank system releases can be effectively treated by soil washing. Removal efficiencies for residual metals and hydrocarbons of 90 to 98% have been achieved when heat and surfactants have been added to the washwater. Although studies have shown that soil washing can be effective in removing gasoline and diesel

Table 4.2
Waste Soil Characterization Parameters

Parameter	Purpose and Comment
Key Physical	
Particle Size Distribution:	
>2 mm	Oversize pretreatment requirements
0.25 - 2 mm	Effective soil washing
0.063 - 0.25 mm	Limited soil washing
<0.063 mm	Clay and silt fraction--difficult soil washing
Cation Exchange Capacity	A measure of soils ability to attract and bind pollutants in exchange for naturally occurring ions or elements
Other Physical	
Type, physical form, handling properties	Affects pretreatment and transfer requirements
Moisture content	Affects pretreatment and transfer requirements
Key Chemical	
Organics Concentration Volatility	Determine contaminants and assess separation and washing efficiency, hydrophobic interaction, washing fluid compatibility, changes in washing fluid with changes in contaminants. May require preblending for consistent feed.
Partition coefficient	Use the jar test protocol to determine contaminant partitioning
Metals	Concentration and species of constituents (specific jar test) will determine washing fluid compatibility, mobility of metals postreatment.
Humic acid	Organic content will affect adsorption characteristics of contaminants on soil. Important in marine/wetland sites.
Other Chemical	
pH, buffering capacity	May affect pretreatment requirements, compatibility with equipment materials of construction, wash fluid compatibility.

Source: US EPA 1990

fuels from soils, thermal desorption, biodegradation, or vapor extraction may be more effective and appropriate for treating the volatile components, since these techniques will destroy or degrade the contaminant[1].

Table 4.2 summarizes the key soil parameters that should be measured at a site and factored into the bench- or pilot-scale performance test plan. This information also will be useful to commercial system vendors as they begin selecting and sizing the equipment for full-scale operations.

Table 4.1 (on page 4.5) shows the general effectiveness of soil washing for removing various types of chemical groups from soils. Excellent to good applicability ratings shown in this table mean the probability is high that soil wash-

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[1] See the monographs in this series, *Innovative Site Remediation Technology: Thermal Desorption*, *Innovative Site Remediation Technology: Bioremediation*, and *Innovative Site Remediation Technology: Vacuum Vapor Extraction*—Ed.

ing will be effective for removing chemicals in the group from the soil type indicated. Moderate to marginal applicability indicates situations where care must be exercised in choosing soil washing.

Because treatment performance is so closely linked to individual site characteristics, broad indicators or guidelines cannot be used to accurately predict whether soil washing will provide the desired degree of performance at any given site. The specific chemical form of a contaminant when it is released into the soil directly affects the mobility, fate, and removal of the chemical. For example, metallic forms of lead scattered on the ground as a fine particulate or dust can be much more difficult to remove from the soil than dissolved forms that might have been spilled on the ground as a liquid. Also, the length of time that a soil has been contaminated can also have a dramatic effect on the ability of a soil washing system to achieve desirable contaminant separation efficiencies. For example, over time, lead and other metals can mineralize in the soil, becoming very tightly bound to the soil matrix and virtually impossible to extract with water solutions, even with the aid of pH adjustments and chelants.

4.1.4 Application at Superfund and European Sites

Soil washing has been selected for remedial application at 23 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Superfund) National Priorities List (NPL) sites and one other lower priority CERCLA site. See tables 4.3 (on page 4.8), 4.4 (on page 4.8), and 4.5 (on page 4.9), for information about soil washing applications at Superfund sites. None of these applications involves the separation and recovery of volatile contaminants. Instead, soil washing was selected to treat soils contaminated with semivolatile organics (SVOCs), polynuclear aromatic hydrocarbons (PAHs), dioxins, pesticides, and heavy metals. The average amount of soil to be washed at these sites is nearly 34,000 m^3 (44,000 yd^3), ranging from 1,400 to 150,000 m^3 (1,800 to 200,000 yd^3). Some full-scale soil washing projects have been completed at Superfund sites, while others are in various stages of planning, design, or installation.

In developing soil washing processes several major environmental contractors in the Netherlands and in Germany progressively improved upon combinations of mining and chemical processing approaches for removing contaminants from sandy soils. In 1989, the US EPA funded an evaluation of existing soil washing technologies. Table 4.6 (on page 4.12) presents a summary of the evaluation.

Table 4.3
Superfund Project Status Summary, April, 1992

Region	Soil Washing	Status
02	Ewan Property, NJ	PD
02	CE Wiring Devices, PR	D
02	King of Prussia, NJ	C (mid Oct. 1993)
02	Myers Property, NJ	PD
02	Vineland Chemical, OU1 and OU2, NJ	D
04	American Creosote Works, FL	D
04	Cabot Carbon/Koppers, FL	D
04	Southeastern Wood Preserving, MS (Removal)	O
04	Cape Fear Wood Preserving, NC	D/I
05	United Scrap Lead/SIA, OH	D
05	Zanesville Well Field, OH	PD
05	Moss-American, WI	D
06	Arkwood, AR	PD
06	Koppers/Texarkana, TX	PD
06	South Cavalcade Street, TX	D
06	Sand Creek Industrial, OU 5, CO	D
09	FMC (Fresno), CA	PD
09	Koppers Company, Inc. (Oroville Plant), CA	D
09	Poly-Carb, NV	C
09	Sacramento Army Depot, CA	PD
10	Gould Battery, OR	I
10	Idaho Energy Lab	D
10	Naval Sub Base, Bangor, WA	PD

PD - Predesign phase
D - In Design and contractor onsite
D/I - Design completed awaiting installation
I - Being installed
O - Operational
C - Completed

Table 4.4
Remedial/Removal Superfund Sites Using Soil Washing as Part of a Treatment Train, April, 1992

Site	State	Treatment Sequence
Myers Property	NJ	Dechlorination followed by Soil Washing
Zanesville Well Field	OH	Soil Vapor Extraction followed by Soil Washing
Ewan Property	NJ	Solvent Extraction followed by Soil Washing
American Creosote	FL	Soil Washing followed by Bioremediation
Cabot Carbon/Koppers	FL	Soil Washing followed by Bioremediation
Southeastern Wood Preserving (Removal)	NC	Soil Washing followed by Bioremediation
Moss-American	WI	Soil Washing followed by Bioremediation
Koppers (Oroville)	CA	Soil Washing followed by Bioremediation
Arkwood	AR	Soil Washing followed by Bioremediation
South Cavalcade Street	TX	Soil Washing followed by Bioremediation
Sand Creek OU 5	CO	Soil Washing followed by Bioremediation
FMC (Fresno)	CA	Soil Washing followed by Bioremediation

Source: US EPA 1992a

Table 4.5

Detailed Site Information on Soil Washing Applications at U.S. Superfund Sites

Region	Site Name, State, (ROD Date)	Specific Technology	Site Description	Media (Quantity)	Key Contaminants Treated	Status	Lead Agency and Treatment Contractor (if available)	Contacts/Phone
2	Ewan Property,* NJ (09/29/89) See also Solvent Extraction	Soil washing with water only (preceded by solvent extraction)	Industrial waste dumping	Soil (22,000 cy)	Metals (Chromium, Lead, Copper, Barium)	Predesign; Stalled by negotiations and access problems	Still in negotiation	Dave Rosoff 212-264-5393 FTS-264-5393
2	King of Prussia, NJ (09/28/90)	Soil washing with water with washing agents as additives	Recycling facility	Soil, sludge, sediments (20,000 cy, combined)	Metals (Chromium, Copper, Silver)	In design; Design completion planned Summer 1993	PRP lead/Federal oversight	Gary Adamkiewicz 212-264-7592 FTS-264-7592
2	Vineland Chem. OU 1 and OU 2, NJ (09/29/89)	Soil washing preceded by dechlorination, may be followed by s/s	Pesticide manufacturing/ use/storage	Soil (50,000 cy Combined), sediments	Metals (Arsenic)	In design; Design completion planned Spring 1993	Federal lead/Fund financed	Matthew Westgate 212-264-3406 FTS-264-3406 Steve Hadel (USACe - Kansas City) 816-426-5221 FTS-897-5221
4	American Creosote Works,* FL (09/28/89) See also Bioremediation Ex Situ	Soil washing with water with surfactants as additives (followed by slurry-phase bioremediation for fines)	Wood preserving	Soil (36,500 cy)	SVOCs (PCP), Dioxins, PAHs (Creosote)	In design; Design completion planned Fall 1992; the design will be a performance spec	Federal lead/Fund financed	Madolyn Streng 404-347-2643 FTS-257-2643 Charles Logan FL 904-488-0190 Kelsey Kelton 904-488-0190
4	Cabot Carbon/Koppers, FL (09/27/90) See also, Bioremediation, Ex Situ, Bioremediation In Situ	Soil washing (followed by bioremediation of fines)	Wood preserving; Pine tar and turpentine manufacturing	Soil (6,400 cy)	SVOCs (PCP, Bis(2-ethylhexyl) phthalate, DNT, Dimethylphenol, PAHs, Metals (Arsenic, Chromium)	In design; Design completion planned Spring 1994	PRP lead/Federal oversight	Martha Berry 404-347-2643 FTS-257-2643

Table 4.5 (cont.)

Detailed Site Information on Soil Washing Applications at U.S. Superfund Sites

Region	Site Name, State, (ROD Date)	Specific Technology	Site Description	Media (Quantity)	Key Contaminants Treated	Status	Lead Agency and Treatment Contractor (if available)	Contacts/Phone
4	Southeastern Wood Preserving, MS Emergency Response (Action Memo signed 09/30/90) See also, Bioremediation Ex Situ	Soil washing (separation of sands followed by bioremediation of fines)	Wood preserving	Solids (8,000 cy of soils, sludges, and kiln ash)	SVOCs (PCP), PAHs (Creosote)	Operational; Completion planned Summer 1993	Federal lead/Fund financed; OHM Remediation Services Corp.	Don Rigger 404-347-3931 FTS-257-3931
4	Cape Fear Wood Preserving, NC (06/30/89) See also, Bioremediation Ex Situ	Water with sodium hydroxide or hydrochloric acid to adjust pH as an additive (followed by s/s)	Wood Preserving	Soil (20,000 cy)	VOCs (Benzene), PAHs (Creosote), Metals (Copper, Chromium, Arsenic)	Design completed but not installed; Currently procuring construction contractor	Federal lead/Fund financed	Jon Bornholm 404-347-7791 FTS-257-7791
5	United Scrap Lead/SIA, ON (09/30/88)	Soil washing	Battery recycling/ disposal	Soil (109,000 cy, combined), Solids (55,000 cy of battery casing chips), sediments	Metals (Lead)	In design; Design completion planned Spring 1993	Federal lead/Fund financed	Anita Boseman 312-886-6941 FTS-886-6941
5	Zanesville Well Field, OH (09/30/91) See also Soil Vapor Extraction	Soil washing (preceded by vacuum extraction)	Municipal water supply; Auto parts manufacturing	Soil (1,800 cy)	Metals (Lead, Mercury)	Predesign; PD completion planned Fall 1992; Consent Decree is expected in Fall 1992	PRP Lead/Federal oversight	Dave Wilson 312-886-1476 FTS-886-1476

5	Moss-American,* WI (09/27/90) See also, Bioremediation Ex Situ	Soil washing (followed by slurry phase bioremediation of fines)	Wood preserving	Soil (80,000 cy)	PAHs	In design; Design completion planned 1994	PRP lead/Federal oversight; Weston, Inc.	Betty Lavis 312-886-4784 FTS-886-4784
6	Arkwood, AR (09/28/90)	Soil washing (incineration of residuals)	Wood preserving	Soil (20,400 cy)	SVOCs (PCP), Dioxins	Predesign; PD completion planned Fall 1994	PRP Lead/Federal oversight	Rick Erhart 214-655-6582 FTS-255-6582
6	Koppers/Texarkana,* TX (09/23/88)	Water with a surfactant as an additive (waste water to be treated and discharged)	Wood preserving	Soil (19,400 cy)	PAHs (Benzo(a)pyrene DNAPLs, Creosote) Metals (Arsenic)	Predesign; Soil Washing project is on hold, EPA is considering relocation of the community	In negotiation	Ursula Lennox 214-655-6736 FTS-255-6735
6	South Cavalcade Street,* TX (09/26/88) See also In Situ Flushing	Water with surfactants as an additive (followed by incineration of residuals)	Wood preserving	Soil (11,000 cy)	SVOCs (Benzo(a)pyrene, Benzo(a) anthracene Chrysene), PAHs	In design; Design completion planned Winter 1994	PRP Lead/Federal oversight	Mark Fite 214-655-6715 FTS-255-6715
8	Sand Creek Industrial OU5,* CO (09/28/90)	Soil washing (followed by incineration of contaminated residual(s)	Pesticide manufacturing/ use/storage	Soil (14,000 cy)	Pesticides, Metals (Arsenic)	In design; Design completion planned Summer 1992	Federal lead/Fund Financed	Erna Acheson 303-294-1971 FTS-330-1971
9	FMC (Fresno)*, CA (06/28/91)	Soil washing followed by solidification/stabilization	Pesticide manufacturing/ use/storage	Soil (30,000 cy)	Biocides (DDT, EDS, Toxaphene, Chloradane)	Predesign; Design completion planned Fall 1992	PRP lead/State oversight	Tom Dunkelman 415-744-2395 FTS-744-2395
9	Koppers Company, Inc. (Oroville Plant), CA (04/04/90) See also, Bioremediation In Situ	Soil washing (method to be determined)	Wood preserving	Soil (200,000 cy)	SVOCs (Polychlorinated Phenols), Pesticides, Dioxins	In design; Design completion planned Spring 1993	PRP lead/Federal oversight	Fred Schauffler 415-744-2365 FTS-484-2365

* Indicates that a treatability study has been completed.

Source: US EPA 1992b

Table 4.6
Evaluation of Existing Soil Washing Technologies (1989)

Installation	Rated Throughput	Principal Operations	Particle Reject Size	Fixed or Transportable	Pollutants Treated	Refractory Pollutants	Treatment Fee per Ton	Sludge Disposal Costs per Ton	Capital Costs
Heijmans Milieutechniek b.v. Rosmalen, The Neths.	11 ton/hr	• Particle sizing • Scrubbing with detergents and oxidants • Flocculation • Precipitation	<63 µm	Transportable but fixed	Cyanides Heavy metals PCAs Mineral oil Kerosene	Cl-HCs Aromatics	$73-91 $102 at max 30% <63 µm	$136	New 33 ton/hr plant planned, $4.5 million
HWZ Bodemsan-ering Amersfoort, The Neths.	22 ton/hr	• Particle sizing • Scrubbing with detergents • Flocculation • pH adjustment • Carbon filters	<63 µm	Transportable but fixed	Cyanides Heavy metals aromatics Solvents Cl-HCs	Oily cmpds Br compds	$53 plus $2.50/ton for each % <63 µm, up to 20%	$136	$3 million
Heidemij Realisatie Arnhem, The Neths.	30 ton/hr	• Particle sizing • Froth flotation with cleaning agents • Washing	<38 µm	Fixed	Cyanides Heavy metals PCAs Oils Cl-HCs Pesticides	PAHs PCBs HCH Some heavy metals	$90-155, 2200 tons is min treated	as high as $182	$3 million
Harbauer GmbH Berlin, FRG	16.5-22 ton/hr	• Particle sizing • Low-freq. vibration with extractants • Washing • Water treatment by flotation, air stripping, ion exch. and activated carbon	<15 µm	Fixed	Organics Phenol PAH Org-Cl cmpds PCBs	Heavy metals	$136 (excludes residue disposal)	Sludge stored to date	$4.5-6 million
TBSG Industrievertretungen GmbH- Oil CREP System Bremen, FRG	44 gpm New 88 gpm plan planned	• Particle sizing • Washing with Oil CREP 1 • Solid/liquid separation	<100 µm	Mobile	Extractables HCs PAHs Extr. Hal-org.	PCBs Fl-HCs Cyanides Heavy metals	$82-109 excluding disposal of residues, 3920 cu yds min treated	$6K/day sludge treatment	Not known at this time

Source: US EPA 1988

4.2 Soil Flushing

4.2.1 General

In situ soil flushing should be considered for applications involving petroleum hydrocarbons, chlorinated hydrocarbons, metals, salts, pesticides, herbicides, and radionuclides. Current interest seems to be focusing on the use of in situ flushing for chlorinated hydrocarbons. A unique capability centers on cleaning up contaminated soil beneath structures. Many industrial sites throughout the U.S. have chlorinated hydrocarbons in the subsurface. Since excavation and other existing remediation strategies require access, in situ soil flushing offers clear advantages. Other advantages include: no soil replacement and/or disposal costs, no disruption of the ecosystem, cost advantages at greater depths, and minimized worker exposure to contaminants. Excavation can also be cost prohibitive in complex hydrogeologic environments.

In general, soil flushing is most effective in homogeneous permeable soils (e.g., sands or silty sands with greater than 10^{-4} cm/sec permeability) with low recharge capacity for metals and low adsorptive capacity for organic contaminants. Soil flushing may also be appropriate for the following applications:

- Recovery of mobile degradation products formed after soil treatment with chemical oxidizing agents. This application may be particularly appropriate if excavation presents a high safety and health hazard; and
- Enhancement of oil recovery operations. Water (sometimes containing emulsifying chemicals) is pumped into the ground, forcing a free oil phase towards recovery wells. Steam has also been used for enhanced oil recovery.

Key contaminants that can be remediated by in situ flushing are listed in table 4.7 (on page 4.14).

Organics amenable to water flushing can be identified by the magnitude of their octanol/water partitioning coefficient. Soil flushing is generally applicable to soluble organic compounds with octanol/water coefficients less than 1,000 ($\log K_{ow}<3$). Highly water soluble organics, such as low molecular weight alcohols, phenols, carboxylic acids and other organics with a coefficient less than 10 ($\log K_{ow}\leq1$) may already have been flushed from the site due to natural flushing processes. Medium solubility organics ($1000<K_{ow}>10$) that could be

Table 4.7
In Situ Soil Flushing Target Contamination Table

Target Groups	Specific Contaminants
VOCs	TCE, DCE, PCE, TCA, BTEX, Vinyl Chloride, Carbon Tetrachloride, Chloroform, Bis-2-chloroethylene, DCA, Dichloromethane
SVOCs	Benzo (a) Pyrene, Benzo (a) Anthracene, Chrysene, Phenols, Methyl Ethyl Ketone, Dichlorobenzene, Trichlorobenzene
Inorganics	Ferrous sulfate
Metals	Chromium, Lead, Arsenic, Nickel, Mercury
Petroleum Hydrocarbons	Creosote, Cresol, Pesticides (PAHs)

effectively removed from solids by water flushing include low to medium molecular weight ketones, aldehydes, aromatics, and lower molecular weight halogenated hydrocarbons such as TCE and perchloroethylene (PCE).

Soil flushing is generally applicable also to inorganic compounds with solubility >1 ppm, with soluble salts, such as the carbonates of nickel, zinc, copper, and chromates. Dilute acids, such as acetic acid or dihydrogen phosphate, or chelating agents, such as ethylene diamine triacetic acid (EDTA) or diamene tricedic pyrrolidine acid (DTPA), may be necessary to enhance inorganic solubilization and removal. Hexavalent chrome and nitrates are amenable to soil flushing because of their negative charge (easier to remove from negatively-charged clays and organic matter). Dilute acids or reducing agents could change hexavalent chrome to the trivalent form and thereby reduce its solubility and, thus, its amenability to soil flushing (but, since the chrome toxicity would be reduced by three orders of magnitude, this would reduce the need for soil flushing).

4.2.2 Soil Flushing (Enhanced Oil Recovery (EOR))

Transfer of technology from EOR and in situ mining (ISM) has the potential to substantially increase the rate of waste extraction from the ground and therefore lower costs. The EOR technology results from years of research and development. The oil and gas industry developed a number of alternative methods to recover oil that remains trapped in a particular reservoir after the conventional means of production no longer allows the particular reservoir to produce at economic rates. Many of these processes are also applicable as in situ waste recovery schemes or what might be called "unconventional soil flushing".

In general, EOR techniques involve the injection of materials that are not normally found in the soil in order to facilitate the removal of the hydrocarbon waste. The EOR processes fall in the following categories:

- gas processes;
- chemical processes; and
- thermal processes.

4.2.2.1 Gas Processes

In gas processes, gases, such as, CO_2, N_2, and CH_4, are injected at relatively high pressures in order to create a miscible mixture with the hydrocarbon. Once miscibility has been achieved, the interfacial tension (IFT) is reduced to nearly zero and the resultant mixture flows more readily through the reservoir. Because of the high pressures that are generally required, gas processes would be applicable only at relatively large depths in a confined stratum.

4.2.2.2 Chemical Processes

Three chemical processes appear to have applicability to in situ soil flushing: (1) polymer flooding, (2) surfactant flooding, and (3) alkaline flooding. Polymer and alkaline flooding have not been evaluated extensively for use in environmental applications. On the other hand, a good deal of research has been conducted on the use of surfactants to assist in the cleanup of soils that contain hydrocarbon waste.

In polymer flooding, a water-soluble polymer is added to the injected water in order to increase its viscosity. The increase in injectant viscosity will decrease the mobility ratio. This, in turn, will increase the areal sweep efficiency, E_a, and, to some small degree, the displacement efficiency, E_d, but will not increase the capillary number significantly enough to reduce the final hydrocarbon saturation to a reasonably small value.

The use of surfactants as an additive to the injected water in order to extract organic contaminants appears to be one of the most promising of in situ soil flushing techniques. In this process, a surface-active agent, a surfactant or micelle, is injected into the soil in order to reduce the IFT to nearly zero. Micelles allow the injected water and the hydrocarbon to form an emulsion that flows more readily through the soil. Once this emulsion moves to the surface, it can be broken and the hydrocarbon can be recovered. While surfactants are environmentally safe and relatively inexpensive, the proper design of an in situ cleanup system using them is complicated by factors such as adsorption, salinity of the injected water, concentration of the surfactant, and temperature.

The use of alkaline agents, instead of direct injection of surfactants is another process that may be applicable to the in situ cleanup of hydrocarbons. When in contact with certain hydrocarbons, alkaline agents, such as sodium hydroxide or sodium carbonate, can react to form surfactants. These in situ generated surfactants then act to reduce the IFT of the system. In most cases, the hydrocarbon waste that is the target must exhibit an acidic-type behavior. That is, it must contain a minimum amount of acid components.

4.2.2.3 Thermal Processes

In thermal EOR processes, heat is injected into the soil. The most common methods of adding this thermal energy are through the injection of hot water or steam. The most important mechanism in this process is the reduction of hydrocarbon viscosity because of the increased temperature. Lowering the viscosity decreases the mobility ratio to a value where the efficiencies described earlier are increased to reasonable values. The applicability of this process, therefore, is limited primarily to situations where a very heavy hydrocarbon is being recovered. The effectiveness of the technology in environmental applications is not known.

5

PROCESS EVALUATION

5.1 *Soil Washing*

5.1.1 Process Performance

The evaluation of a soil washing system usually turns upon the quality of the residuals produced. The residuals of concern are:

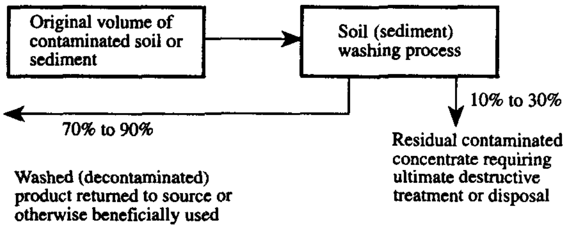
- the oversize materials, typically everything >6.4 mm (>0.25 in.);
- the coarse-grained materials, the sands produced by treatment;
- the fine-grained fraction containing the concentrated contaminants; and
- the process water.

In most soil washing applications, the principal objective is to meet the treatment standards applicable to the oversize materials and the product sands so that they may be placed back on the site without limitation. The major measure of effectiveness, therefore, is the ability to meet specified standards for the residuals that are targeted for placement back on site.

The fine-grained fraction may be either dewatered into a sludge cake for disposal off site, or subjected to additional treatment. The process water is recycled, and may or may not require treatment dependent upon the contaminants removed. At the conclusion of the project, the process water remaining in tankage will require treatment for disposal off site.

When used as a pretreatment step to other remediation processes, soil washing presents two key advantages. The first is its ability to substantially contribute to *waste minimization.* The process can concentrate 70 to 90% or more of the nonvolatile and heavy metal contaminants in a residual soil product representing only 5 to 40% of the original soil volume. The washed soil product (representing 60 to 95% of the original volume and containing from 0 to 30% of the original contamination) may be suitable for redeposition on site or for other beneficial uses (see figure 5.1). Even better removals have been achieved with volatile organic compounds (VOCs).

Figure 5.1
Processed Materials Distribution



The second advantage lies in its potential *cost-effectiveness*. For many sites, substantial remediation savings can be realized by reducing the sheer volume of contaminated soil that must be treated and disposed of by more complex and expensive methods. Costs are estimated to be $170 to $280/tonne ($150 to $250/ton) of soil for commercially-available soil washing systems, compared to $390/tonne ($350/ton) for secure landfill and $1,100/tonne ($1,000/ton) for incineration, including excavation, site support, gate rate disposal, transportation, and applicable taxes. Further savings are realized through reduced transportation costs. Tables 5.1 and 5.2 (on page 5.3) present examples of potential cost savings.

Because its treatment systems are closed and contain fugitive dusts and volatile emissions, soil washing should be viewed favorably by the public when compared with other remediation methods.

Table 5.1

Example of Potential Cost Savings of Soil Washing*

A. Site remediation costs without soil washing - 100,000 yd^3 (76,460 m^3) soil excavated and transported to off site facility 500 miles for incineration and disposal.

Excavation, staging and site management	$3,000,000
Transportation (20 yd^3 load, $3/mile)	7,500,000
Incineration ($1,000/$yd^3$)	100,000,000
Disposal of Ash (80,000 yd^3 @ $150/$yd^3$)	12,000,000
	$122,500,000

B. Site remediation costs using soil washing - 100,000 yd^3 (76,460 m^3) soil excavated and soil washed, 25,000 yd^3 (19,110 m^3) transported off site for incineration and disposal.

Excavation and site management	$3,000,000
Soil Washing	15,000,000
Transportation of Sludge Cake	1,875,000
Incineration of Sludge Cake	25,000,000
Disposal of Ash	3,000,000
	$47,875,000

*Assuming the soil requires incineration

Table 5.2

Typical Cost Comparison for a Cleanup Project

Involving 38,230 m^3 (50,000 yd^3) of soil contaminated with PCBs.
Assumes that residuals requiring further treatment or disposal are 15% of the original volume processed.

Destruction by incineration only $50,000,000	Soil pretreatment with incineration of residuals $12,250,000
Disposal in an RCRA designated landfill (50,000 yd^3) $12,500,000	Soil wash pretreatment with landfill disposal of residuals $6,625,000
Destruction by dechlorination (50,000 yd^3) $11,500,000	Soil wash pretreatment with dechlorinization of residuals $6,475,000
Solidification/stabilization with landfill storage at a separate site (50,000 yd^3) $8,000,000	Soil wash pretreatment with solidification/stabilization of residuals, landfill storage at a separate site $5,950,000

Unit Costs Used For Comparisons

	Per Cubic Yard
Incineration	$1,000.00
Landfill	$250.00
Dechlorination	$230.00
Solidification/Stabilization	$160.00
Soil Washing Pretreatment	$95.00

Soil washing is a low-cost alternative for separating wastes. Testing to date indicates the technology can remove volatile organic contaminants with 90 to 99% effectiveness, and semivolatile organics and metals with 40 to 90% effectiveness.

5.1.2 Range of Costs

The cost of soil washing is dependent upon several key variables:

- volume of the soil to be treated;
- nature of the contaminants to be removed;
- particle size distribution, particularly the volume of fines in the process stream; and
- site preparation requirements.

Although there are presently no completed full-scale soil washing operations in the U.S. from which to derive comparative cost data, estimates have been made based upon the literature. Based upon projects in the range of 23,000 to 180,000 tonne (25,000 to 200,000 ton), the estimated treatment price, including all known cost components, is in the range of $170 to $280/tonne ($150-$250/ton). Details of these estimates are set forth in table 5.3 (on page 5.5). These costs are consistent with current field pricing.

5.1.3 Key Operational Considerations

Key operational considerations for soil washing include the following:

- cleanliness or treatability of the oversize material;
- whether standard screening steps can be used to prepare soils for treatment;
- whether materials can be effectively separated; and
- whether the generated sludge volume will be within disposal and cost limitations.

5.2 *Soil Flushing*

5.2.1 Process Performance

Laboratory column and shaker studies have been very successful, demonstrating removal efficiencies of petroleum hydrocarbons, chlorinated hydrocarbons, and metals at levels above 99%. Pilot studies are reporting highly successful removals.

The removal efficiencies in the field have varied from site to site. This variability is related more to the site hydrogeology than to the contaminants of concern. The vadose zone is generally poorly understood by most investiga-

Table 5.3
Soil Washing Comparative Cost Data

	Volume (Short tons)			
	25,000	50,000	100,000	200,000
Capital Costs				
Plant Capacity	15 ton/hr	25 ton/hr	25 ton/hr	50 ton/hr
Process Time	6 months	9 months	12 months	12 months
Plant Cost ($)	3,000,000	4,500,000	4,500,000	7,500,000
		Prices expressed in $/ton		
Operating Costs				
Depreciation	40	30	15	12
MOB and DEMOB	8	4	3	1
"Normal" Site Prep	12	6	4	2
Material handling	15	15	15	15
Labor	30	25	20	15
Chemicals	15	15	15	15
Maintenance	8	6	4	2
Safety Equipment	3	3	3	3
Utilities	8	8	8	8
Process Testing	15	12	8	5
Disposal of Residuals 10% assumption	32	32	32	32
Management/Engineering Overhead and Profit	70	60	48	40
NET PRICE ($/short ton)	256	216	175	150

Assumptions:
- The "Basic" Plant consists of mechanical screening, separation, flotation, and fines handling
- Site excavation is not included, materials exist at an influent feed pad.
- The soil is predominantly sand and gravel with 20% <63 microns
- Contaminants of concern are PNAs and metals, existing in fines and sands
- The plant throughput capacity is sized to spend 1 year processing
- *Process time is 2 shifts per day, 5 days per week, one day of maintenance.*
- Summary does not include RI/FS, treatability studies, or the RD package.

tors. In addition, the State of California has taken the position that even for site-specific conditions, there is no solute transport model that is reliable.

The relationship between capillary pressure, water content, and permeability is not generally understood in the field. In addition, the complexity of some hydrogeologic settings precludes a successful soil flushing operation. Since the success rate under laboratory conditions is very high and that in the field is not, it appears that a better understanding of unsaturated flow in the vadose zone is required to successfully implement soil flushing. One study reported at the Volk Field, Wisconsin, site (US EPA 1990), showed that the field tests did not agree with the laboratory tests for the firefighter training pit soil. Heavy rains at the site, however, may have contributed to the decreased percolation and pore clogging.

Bench-scale soil flushing tests have proven to be very successful; however, field applications have not shown the same success. The problems of reduced permeability by plugging and biofouling must be overcome. In addition, soil flushing in the field may be subject to flow instabilities which result in finger flow that may not remove the contamination between the fingers. The use of supersurfactants (REMSOL) may reduce this problem. No single in situ removal or treatment technique is likely to be the most effective technique in all situations. The most cost-effective in situ remediation approach may require two or more different techniques in sequence.

5.2.2 Process Byproducts

The majority of the surfactants, polymers and gas additives are biodegradable and, consequently, the byproducts are CO_2 and water. Some alkaline/acid wastes may require pH control, with minimal measurable byproduct. The majority of the byproducts are the contaminants that are removed by the treatment process. The amount of these contaminants varies with the condition of the site.

5.2.3 Range of Costs

Because of the site specific nature of remedial techniques and the limited field application of in situ flushing, it is difficult to obtain comprehensive, detailed cost estimates of this technique at this time. The following preliminary economic evaluation of the technique by Sara Kimball is based on a process that is being developed by Eckenfelder Inc., Nashville, Tennessee (Oma, Wilson, and Mutch 1991). The estimates are based on the results of two mathematical models of hypothetical contaminated sites and represent the upper and lower estimates of remediation of an area with the characteristics listed in table 5.4.

Table 5.4
Optimum Conditions for In Situ Surfactant-Enhanced Soil Flushing

Factor	Optimum Conditions
Soil Characteristics	
Particle Size	Low Silt and Clay Content
TOC	Low, <10%
Hydraulic Conductivity	Medium to High, >10
Waste Characteristics	Hydrophobic K_{ow} = 3 or less Nonvolatile Organic
Surfactant Characteristics	Non toxic, biodegradable Soluble at Ground Water Temps Doesn't sorb to Soil HLB # matches Contaminant HLB # Effective at Low Conc., <3.0% Low-Soil Dispersion Low-Surface Tension Low CMC

From Kimball, S.L., "Surfactant-Enhanced Soil Flushing: An Overview of an In Situ Remedial Technology for Soils Contaminated with Hydrophobic Hydrocarbons," in "Hydrocarbon Contaminated Soils," Vol II, Kostecki, P.T., Calabrese, E.J., Bonazountas, M., Eds, Lewis Publishers 1992, a subsidiary of CRC Press, Boca Raton, Florida. With permission

The best case model (Equilibrium Solubility Model) is a materials-balance model based on the solubility limit of the organic contaminant(s) within the sodium docyl sulfate (SDS) surfactant. This model calculates the volume of surfactant needed to solubilize a given mass of contaminants within the soil. The surfactant is distributed at the surface. The model predicts a cost of \$103.70/m^3 (\$79.30/yd^3) of contaminated soil.

The worst case estimate is made with the Two Component Local Equilibrium Model created by Wilson and Clarke (1991). With this model, an injection and a recovery well flush a 2-dimensional aquifer with surfactant. With a surfactant flow rate of 1,950 L/min (516 gal/min), this model predicts recovery of 95% of the polychlorinated biphenyls (PCBs) and all the trichloroethylene (TCE) in 2 years. Cleanup times depend on site-specific soil and/or contaminant characteristics. This model gives an estimated remedial cost of \$214.90/m^3 (\$164.30/yd^3) of contaminated soil. Input parameters required by the model are listed in table 5.5.

Table 5.5
Modeled Example Site Parameters and Values

Parameter	Value
Contaminants	
Arochlor 1254 in heavy oil	2,000 mg/kg - Vadose Zone 200 mg/kg - Saturation Zone
TCE	200 mg/kg - Vadose Zone 20 mg/kg - Saturation Zone
Site Area	4,000 m^2 (1 acre)
Vadose Zone Depth	3 m (10 feet)
Aquifer Depth	3 m (10 feet)
Soil Density	1,700 kg/m^3
Soil Porosity	0.3
Surfactant	
Sodium Dodecylsulfate	2.5%

From Kimball, S.L., "Surfactant-Enhanced Soil Flushing: An Overview of an In Situ Remedial Technology for Soils Contaminated with Hydrophobic Hydrocarbons," in "Hydrocarbon Contaminated Soils," Vol. II, Kostecki, PT, Calabrese, E.J., Bonazountas, M., Eds., Lewis Publishers 1992, a subsidiary of CRC Press, Boca Raton, Florida. With permission.

The cost evaluation breakdown for both models is given in table 5.6 (on page 5.9). The cost for in situ flushing is considerably less than other forms of remediation. The Oma, Wilson, and Mutch (1991) study yields costs of \$1,300 to \$2,600/m^3 (\$1,000 to \$2,000/yd^3) for off-site disposal.

Direct capital costs included in the study are purchased equipment, equipment installation, instrumentation and controls, piping, and electrical. A 12% interest rate and a 7-year amortization apply to capital costs. Indirect capital costs include engineering and supervision, construction expenses, fees, and contingency.

Table 5.6

Cost Evaluation Breakdown for In Situ Surfactant Flushing of One Acre Example Site

Cost Component	Equilibrium Solubility Model (78 gal/min SDS)		Two Component Local Equilibrium Model (516 gal/min SDS)	
	Total Cost ($1,000)	Unit Cost ($/cu yd)	Total Cost ($1,000)	Unit Cost ($/cu yd)
Amortized Cap. Equip.	978	30.40	3039	94.40
Site Construction	129	4.00	129	4.00
Operations & Maintenance				
Labor	727	22.60	915	28.40
Materials	414	12.60	414	12.80
Electrical Power	132	4.10	622	19.30
Analytical	31	1.00	31	1.00
Waste Disposal	143	4.40	143	4.40
Total	2,554	79.30	5,293	164.30

- All costs are in 1990 dollars.
- Site construction cost includes labor and materials
- Site construction cost range is for excavation of PCB-contaminated soil without (lower cost) and with (higher cost) the use of sheet piling.

Reprinted from "Surfactant Flushing/Washing. Economics of an Innovative Remedial Process Including Recovering and Recycle" by K.H. Oma, D.J. Wilson, and R.D. Mutch, Jr in the Proceedings of the Fourth Annual Hazardous Material Management Conference/Central, 1991. Published by Advanstar Expositions. Copyright 1991 by K.H Oma, D.J. Wilson, and R.D. Mutch, Jr. By permission.

Included in the operation and maintenance (O&M) costs are labor, materials, electrical power, analytical work, and waste disposal. The O&M costs comprise 56.6% of the estimated total remediation cost. The O&M cost assumptions are given in table 5.6.

The following costs were not included in the remediation evaluation because they vary considerably from site-to-site:

- remedial investigation/feasibility study;
- permitting — local, state, and federal;
- administrative and legal project management;
- contractor profit; and
- contingency — usually 10 to 15% of total cost.

Capital costs for chemically enhanced solubilization (CES) are similar to those for traditional pump-and-treat (P&T), except for the initial expense of surfactant handling equipment. Operating costs are similar also, except for surfactant replacement and handling. Overall, on a life-cycle basis, CES is significantly less expensive than P&T because of the much shorter time frames and smaller volumes of water which have to be extracted and treated.

The following set of parameters can be used to compare cost and time estimates for CES with those for pump-and-treat. Assume a 3 x 30 x 30 m contaminated aquifer with a hydraulic conductivity of 10^{-4} cm/sec and a porosity of 35% containing 135,000 L of TCE (a residual dense nonaqueous phase liquid (DNAPL) saturation of 14%). For an injection-withdrawal system with 3 injection and 3 withdrawal wells, the groundwater level time across the system would be on the order of 70 days at an injection rate of 10 L/min. Approximately 21 pore volumes of a 1% surfactant solution would be needed to solubilize the TCE, based on interpretation of the data from the Borden test site. This would require 21 x 70 days, or approximately 4 years.

The equivalent time for pump-and-treat with groundwater as the solvent depends on the effective solubility of the groundwater. Normally, pumped effluents contain less than 10% of the aqueous solubility of the halogenated solvent being pumped. Thus, for TCE, the effective aqueous solubility would be on the order of 100 mg/L. This would require over 2,000 pore volumes of ground water and about 400 years to decontaminate the aquifer.

Capital costs for this example are estimated to be $200,000, including surfactants, air stripping, and carbon treatment of the offgas. Annual operating costs are estimated at $150,000 per year, including $50,000 per year for surfactants. The four-year cleanup is then estimated to cost a present value of $697,000 at a cost of capital of 8%. A similar system for P&T would cost approximately $100,000 initial capital and $100,000 annual operating cost. After 9 years with less than 3% of the TCE removed, the present value cost of the P&T system exceeds that of CES (Jackson, Fontaine, and Wunderlich 1992).

6

LIMITATIONS

6.1 Soil Washing

6.1.1 Process Limitations

Effectiveness of soil washing is highly dependent on site conditions. It is relatively ineffective on soils with high silt and clay content (i.e., more than 40% of the soil has a particle size of <63 mm (230 mesh)). It may be relatively ineffective also on soils contaminated with a high concentration of mineralized metals or hydrophobic organics. Washing additives (e.g., chelating agents, solvents, surfactants) may be tailored to the site, soil, and contaminant conditions; however, these may be hazardous, difficult to recover, and interfere with washwater treatment. If these conditions occur, process costs may be prohibitive because of the cost of treating washing fluids and replenishing additives.

Hydrophobic contaminants can be difficult to separate from soil particles into the aqueous washing fluid. Estimated aqueous distribution coefficients (K_d), also known as partition coefficients (K_p), indicate the fraction of the contaminant expected to remain on the soil particle versus the fraction of the contaminant dissolved in the water. Alternative methods can be used to estimate these values when tabulated values cannot be located. A contaminant with a high K_d (e.g., polychlorinated biphenyl (PCB) >10,000) is more difficult to wash off the soil particles using water than a contaminant with a lower K_d (e.g., trichloroethylene (TCE) = 3). Additives, such as surfactants, may be required to improve removal efficiencies. When additives are used, however, larger volumes of washing fluid may be needed.

Complex mixtures of contaminants in the soil, such as a mixture of metals, nonvolatile organics, semivolatile organics, etc., make it difficult to formulate a single suitable washing fluid that will remove all the different types of contaminants from the soil. Sequential washing steps, using different additives, may be needed. Frequent changes in the contaminant and its concentration in the feed soil can disrupt the efficiency of the soil washing process. To accommodate changes in the chemical or physical composition of the feed soil, modification of the wash fluid formulation and the operating settings may be required. Alternatively, additional feedstock preparation steps, such as blending soils to provide a consistent feedstock, may be appropriate.

High humic content in the soil makes separation of contaminants very difficult. Humus consists of decomposed plant and animal residues and offers binding sites for accumulation of both organics and metals.

A high percentage of clay and silt (e.g., more than 30 to 50%) in the soil usually indicates that soil washing will not be favored because of the amount of time and money required to treat the soil. A volume reduction process like soil washing is most cost-effective when the clean soil fraction is much larger than the more contaminated soil fraction. Performance can be limited also by weathering and aging. Mineralized or degraded contaminants cannot be easily removed.

Chelating agents, surfactants, solvents, and other additives are often difficult and expensive to recover from the spent washing fluid by conventional treatment processes, such as, settling, chemical precipitation, or activated carbon, in order to recycle it. The presence of additives in the contaminated soil and treatment sludge residuals may cause added difficulty in disposing of these residuals.

6.1.2 Reliability of Performance

As opposed to thermal processes, where the heat transfer unit (the kiln or the dryer) must be kept within limited operating ranges, soil washing is a particularly forgiving process. This is because the moving force of the process, the feed stream that is driving the soil through the system, has a broad range of acceptable influent concentrations. This advantage can be significantly diminished, however, by a broadly divergent or heterogeneous feed stream. Proper attention to treatability studies and pilot-scale tests can reduce this risk.

6.1.3 Site Considerations

Commercial power will normally be used, although in extreme circumstances, the plant can be operated with generators. Process water is required as plant makeup, supplied from commercial sources or from a local well. In remote sites, a roadway may have to be constructed before the plant can be installed. The plant itself will be placed on a properly designed operations area providing protection of uncontaminated areas and normal run-on and run-off controls.

6.1.4 Waste Matrix

The waste matrix may pose the most significant limitation on soil washing. It is often reported that soil washing is not effective over a certain percentage of fines (often cited as 30%). But this is not necessarily the case. Soil washing is a separation and treatment system. Therefore, the ability to properly remove and treat any portion of the contaminated soil should be evaluated in the context of what other options are available. For example, a project where incineration has been specified as the remedy may be substantially improved by using soil washing as part of the process train to allow for incineration of only the material really requiring that step.

6.1.5 Risk Considerations

The main risk in soil washing operations is that of inaccurate site characterization. The material encountered at the remedial site may not be like the soils studied in treatability or pilot-scale tests. Additional contaminants may be encountered, and the percentage of the fine-grained fraction may be significantly different from that expected.

6.1.6 Process Needs

Every soil washing project requires a treatability study, and, possibly, a pilot-scale study. The treatability study can be conducted in the laboratory on a batch basis. It will characterize the soil/contaminant relationship and enable evaluation of each of the unit operations considered for the full-scale process plant. In addition, it will enable development of a mass balance and process diagram so that the system can be adequately understood on an operations and cost basis. In some cases, the bench-scale treatability study must be supported by a pilot-scale study. The pilot plant studies will normally be performed in the field, on a continuous process basis. The pilot-scale study is intended to confirm the findings of the bench-scale study and provide adequate data to upgrade processes to full-scale operations.

6.2 *Soil Flushing*

6.2.1 General

One principal drawback of soil flushing is the generation of large quantities of contaminated elutriate, the mixture of water, surfactants, and contaminants that is recovered in the soil flushing process, requiring treatment. In some cases, the elutriate may be discharged to a local publicly-owned treatment works (POTW), but often on-site treatment must be devised. As with many other treatment methods, soil flushing requires that the groundwater flow pattern be well defined to ensure complete recovery of the elutriate. If not, physical barriers such as slurry walls may be required. This technique also requires access to a source of water for flushing. Typically, groundwater is extracted, treated, and recycled as the flushing solution.

Soils with pockets of low hydraulic conductivity may limit the effectiveness of flushing. This limits the ability to pass large quantities of water through the contaminated soil. Many underground storage tank (UST) sites, especially those in urban settings, do not lend themselves to flushing because of nearby pipes and underground utilities. Soil flushing will be less effective at sites where the contaminants are relatively insoluble or tightly bound to the soil. The lack of an existing water supply may also be limiting.

The use of surfactants involves several considerations. The interactions of the surfactant with the biological, physical, and chemical properties of the unsaturated zone are typically uncertain, and must be determined at each site. For example, the addition of a surfactant containing sodium may lower soil permeability due to its reactive effect on the soil/sodium adsorption ratio (US EPA 1987b), which with time would decrease the effectiveness of this technique. The groundwater geochemistry also should be assessed for troublesome, naturally-occurring constituents prior to addition of any surfactant. For example, hard water may render a surfactant ineffective. The soil may also reduce a surfactant's effect. High clay content can cause chemical adsorption of the surfactant to the soil, thereby reducing available surfactant concentrations and limiting its effectiveness. Biological effects on the surfactant may also be important. In some cases, a surfactant may biodegrade too quickly, reducing its exposure time to the contaminated soil. On the other hand, the surfactant should be degradable by the soil microbes at a slow rate so that surfactant buildup does not occur.

At the present, another limitation of soil flushing is the inability to separate the surfactant from the water, so that the surfactant can be recycled. Until the surfactant can be separated from the water, the high rates of surfactant consumption will limit the cost-effectiveness of soil flushing.

6.2.2 Reliability of Performance

Since very few test sites have been evaluated, the reliability of soil flushing is an open issue. Soil flushing as a remediation technology is in its infant stage. While water flooding has been used at several sites, the enhanced oil recovery (EOR) approaches have undergone very little testing at contamination sites. The success of EOR techniques over the past fifty years, however, suggests their probable success in soil flushing.

A limitation occurs with contaminated soils located in the vadose zone. As contaminants are mobilized by soil flushing, the soil's capacity to retain oil must be satisfied before the oil will flow through the materials. Residual adsorption capacities of soils can be in the neighborhood of 1/3 of a pore space. This can result in the loss of large volumes of free-phase oils and increases the volume of soils at residual saturation that need to be remediated.

The limitation of water flooding or primary oil recovery lies in its capability to remove only a portion of the total free-phase hydrocarbon contamination in the subsurface, leaving a substantial residual oil level in the subsurface.

6.2.3 Site Considerations

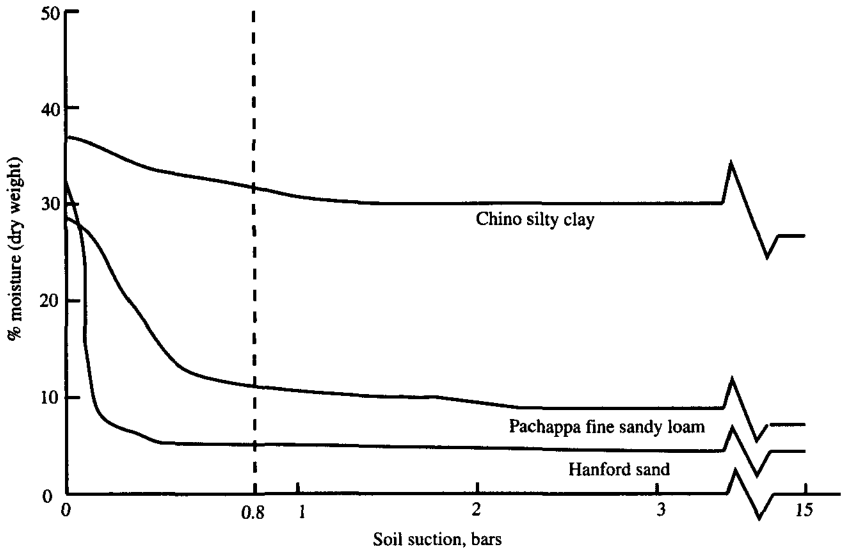
While many theories are available to describe soluble contaminant transport in ideal homogeneous media, many sites are far from ideal, involving nonhomogeneous subsurface conditions, nonuniform distribution of contaminants, or a nonaqueous phase liquid (NAPL), any of which will cause channeling and uneven treatment. In any of these conditions, it may be particularly difficult to determine whether the flushing solution has sufficiently contacted all waste material in the aquifer and whether the cleanup objectives can be achieved within the estimated flushing water volumes.

Quite often, NAPLs accumulate in the form of a floating "free-product" layer, or dense nonaqueous phase liquids (DNAPLs) may sink down to pool on top of a lower confining layer. These concentrated products must often be removed before appreciable soil flushing of soluble contaminants from the groundwater can be accomplished. The solubilization of product into the groundwater will otherwise continue as a source for quite some time. Removal of this product is based on the basic premise that the physical forces that hold large fractions of this residual product immobile can be overcome by the addition of chemical solutions to modify the pore-level environment or by the creation of sufficiently steep hydraulic gradients to recover the product in its free form.

Heterogeneities in natural geological materials make the prediction and detection of contaminant behavior in groundwater difficult in practice. Advection is normally considered on the macroscopic scale in terms of the pattern of groundwater flow. Flow patterns and flow nets in ideal uniform media are described extensively in textbooks; however, heterogeneities, such as, horizontal permeable lenses, often dominate the actual transport of contaminants and groundwater. It is not unusual to encounter lenses of 2 to 3 orders of magnitude higher permeability (K) or conductivities 100 to 1,000 times that of the surrounding media. For example, a change of silt or clay content of only a few percent in a sandy zone can have a large effect on hydraulic conductivity. These lenses exert a very strong influence on the migration patterns, dispersivity, and velocity distribution. Contaminants can move through the flow system almost entirely in these thin layers at an overall reduced travel time. Similarly, lower permeability aquatards can impair vertical groundwater and contaminant migration, particularly that of NAPLs.

Pump-and-treat as a remediation strategy is coming under close scrutiny in the U.S. because of its inability to bring the concentration levels down from below required action levels. Problems associated with pump-and-treat approaches can be related to nonideal aquifer conditions such as heterogeneity, anisotropy, and variable density. In addition, pump-and-treat programs suffer from well construction effects, including partial penetration, partial screening, and incomplete development. Anthropogenic influences such as property access, vandalism, and unknown pumpage or injection can create further problems. Issues such as physiochemical attenuation, biological transformation, and operational failures all lead to shortcomings in pump-and-treat.

Figure 6.1
Moisture Retention Curves — Three Soil Types

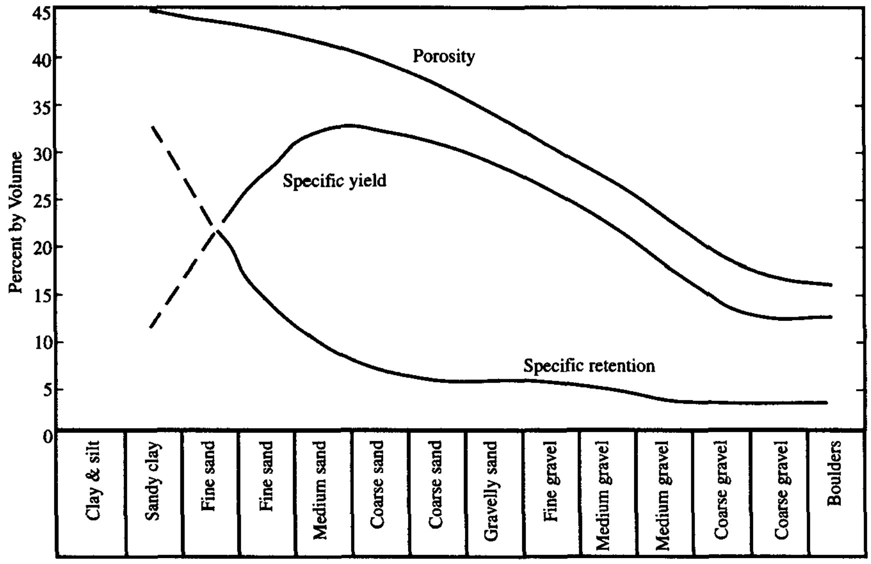


Source: Everett 1986

Site characterization requires an understanding of soil suction and percent moisture in the soils under investigation (figure 6.1). In the field, soil suction can be measured with tensiometers and then related to percent moisture through the use of water characteristic curves (Everett 1992). In order to determine when unsaturated flow takes place, the relationships between porosity, specific yield, and specific retention (figure 6.2 on page 6.8) must be understood (Everett, Wilson, and Hoylman 1984). For modeling purposes, it also must be understood that the relative permeability in the vadose zone increases dramatically over a narrow range of soil moisture pressure potentials (figure 6.3 on page 6.9). For definitive treatment of vadose zone flow and monitoring see Everett, Wilson, and Hoylman 1984 and Everett 1986 and 1992.

Figure 6.2

Variation of Porosity, Specific Yield, and Specific Retention with Grain Size



Source: Everett et al. 1984

6.2.4 Waste Matrix

The physical, chemical, or biological mechanism with which the waste is bound to the soil matrix dictates the type of remediation strategy. Wastes that are soluble and loosely held to the soil matrix are good candidates for water flooding. Those that have a high interfacial tension require EOR techniques and those that result in toxicity problems when interacting with the wash solution need to be carefully evaluated. Finally, wastes that result in plugging from fines movement, inorganic precipitation, formation of stable emulsions, or biological activity need to be measured to prevent permeability problems.

6.2.5 Risk Considerations

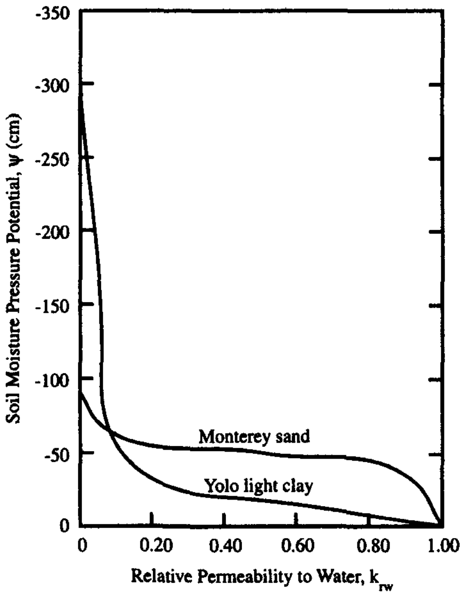
Although vadose zone models are used as a guide in many soil flushing applications, the California Water Resources Control Board has taken the position that solute transport models in the vadose zone are not reliable and that vadose zone monitoring will be required to confirm all vadose zone characterization and remediation programs.

The dispersion of solutes during transport through many types of fractured rocks cannot be described by the same relationships for homogeneous granular materials. Fractured geologic materials are notoriously anisotropic with respect to the orientation and frequency of fractures. For example, distribution coefficients are more commonly expressed on the basis of media surface area rather than mass. Little is known about predicting dispersion in fractured media. If

Figure 6.3

Relationship of Pressure Potential to Relative Permeability to Water

Soil properties: ψ versus K_{rw} (wetting curve).

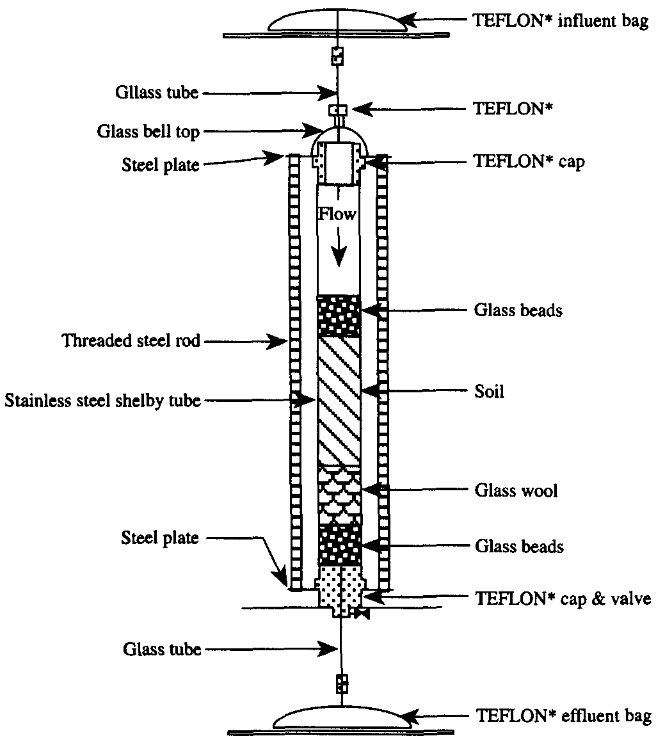


the transverse dispersivity is very large, contaminants transported along relatively horizontal flow paths can migrate deep into the flow system. Dispersivity can be established only by detailed field testing and experiments.

6.2.6 Process Needs

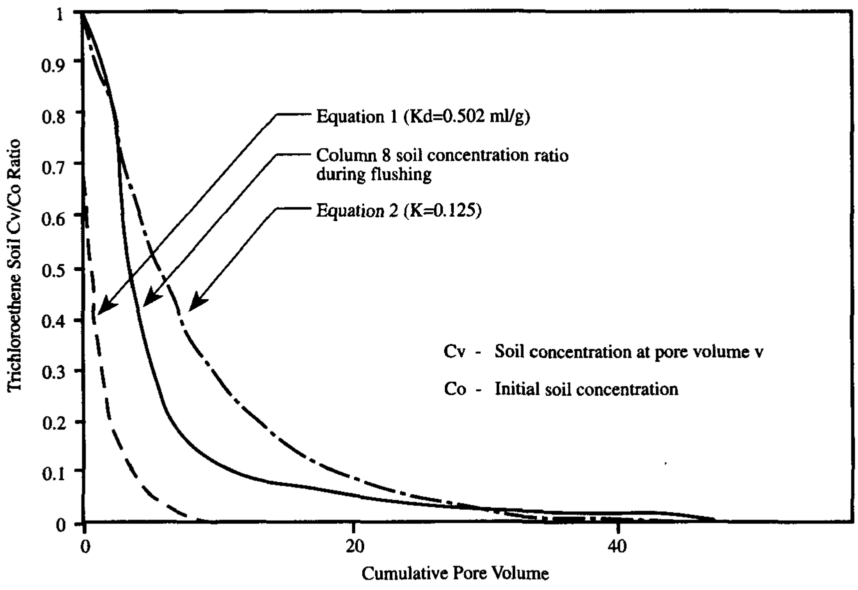
Shaker table and column bench studies (see figure 6.4) are required to determine the appropriate surfactant type, dosage, and pore volumes (see figure 6.5 on page 6.11). The bench-scale approach does appear to present a problem.

Figure 6.4
Bench-Scale Flushing Apparatus



* TEFLON™

Figure 6.5
Bench-Scale Soil Flushing Study
Actual and Simulated Trichloroethene vs. Pore Volume



The field process suffers from a lack of site characterization and flow understanding. Site characterization in the vadose zone is a complex problem (Everett, Wilson, and Hoylman 1984), and only a few companies specialize in vadose zone investigations. The problems of channeling, instabilities, and preferential flow need further technical understanding at some sites.

7

TECHNOLOGY PROGNOSIS

7.1 Soil Washing

7.1.1 Further Treatment of Fines

Most technical development will take place in the additional treatment of the fine-grained fractions. Success in this area has the potential of decreasing the amount of residual material that must be disposed of off site, reducing the unit treatment prices. Work is currently being done to develop the use of bioslurry reactors for use in further degrading the organic constituents in the fines, and in developing extraction and recovery techniques to remove inorganics. Improved extraction and recovery techniques may also enable the production of some after treatment market value from valuable materials existing as contaminants. Examples may be the recovery of metallic copper through the cementation process, the recovery of high concentration ferrous materials that may be introduced back into a steel plant through the sintering plant, and recovery of an iron-chromium complex. In some cases, both organic and inorganic treatment of the fines may be conducted, and although some sludge will result from the treatment, the volume may be only 10% of the volume of sludge cake that may be produced without further fines treatment.

Further treatment of the fines means the ability to truly recover valuable materials from the contaminant stream. In addition, the oversize materials may also have value after they have been cleaned. Examples are wood products that may be chipped and burned in a cogeneration facility for the production of electricity, scrap steel products that can be sold to steel "minimills" for producing pipe and rebar, tires that can be introduced into tire recycling facilities, and construction debris that can be crushed and used as construction grade aggregates.

7.1.2 Fixed Plant Operations

Soil washing is currently offered as a mobile treatment unit, and undoubtedly will remain available in this configuration. The European experience, however, has clearly demonstrated that fixed plant operations are more efficient and provide corresponding cost advantages. In a fixed plant, the mobilization and demobilization costs, the site set-up costs, and other costs attending mobile treatment are not incurred. More unit operations can be made available and thus provide broader treatment capability. The key barrier that will need to be addressed is the ultimate disposal of residuals that are generated in the fixed plant, particularly, the clean products. In the Netherlands, for example, the sand and oversize materials, once they have been treated to the required standard, are sold as construction-grade materials on the open market. This would require a change in current regulations in the U.S.

7.2 Soil Flushing

Soil flushing that relies on fluid movement in the subsurface has a strongly positive prognosis for sites where the depth to contamination, contaminant distribution, permeability, and permeability heterogeneities are compatible with the process. Additional research is required, however, as to such matters as, soil/water incompatibility, permeability reductions, and flushing chemical retention in the subsurface.

Recent breakthroughs in developing a "supersurfactant" reduce the concerns about soil/water incompatibility and permeability reductions. The supersurfactant developed by Sadeghi (Sadeghi et al. 1988, 1989a, 1989b; Sadeghi, Sadeghi, and Yen 1990; Sadeghi, Everett, and Yen 1992) has the ability to form a surfactant from the contaminated soil at the site. Based upon the old chemical engineering adage that "like dissolves like," the supersurfactant is capable of improving soil/water/contaminant compatibility.

Various investigators have reported that vadose zone permeability is reduced with successive water flooding (Nash and Traver 1989; Nash, Traver, and Downey 1987). Explanations of permeability reductions relate to fine-grained material transport and plugging, chemical precipitation, and micelle (surfactant) size. The REMSOL process, which produces the supersurfactant, utilizes a sonication stage that has been optimized to create a micelle size that is much smaller than the normal surfactant and consequently results in minimizing the *permeability impacts.*

The issue of chemical retention in the vadose zone and in the saturated zone must be recognized. Chemically enhanced soil flushing is applicable at many sites as a cost-effective step between water flooding and other technologies, such as, in situ passive bioremediation, that have the potential over time to lower cleanup levels. Since chemical additives may not be hazardous, their presence in the subsurface should not add to the risk. Residual contamination, however, has the potential to slowly degrade over time. Chemical retention in the saturated zone is subject to all of the problems identified with pump-and-treat systems.

The limitations discussed in Section 6.2.3 notwithstanding, pump-and-treat systems have been successful in hydraulically containing contaminated fluids at a particular site. For soil flushing activity, therefore, the principal value of pump-and-treat is to hydraulically contain the fluids as they are flushed from the system and to treat the contamination at the surface. To this extent, therefore, pump-and-treat systems are more applicable to soil flushing technologies.

It is important to realize, however, that velocity plots and capture zones of pumping systems, as represented in figure 7.1 (on page 7.4), must be understood. Clearly, the flow rates within the boundary of the capture are substantially different than the downgradient stagnant area represented in figure 7.1 (on page 7.4). The hydrodynamic isolation (dead spots) within well fields need to be understood.

Typically, a concentration/time plot of contamination residual, as represented in figure 7.2 (on page 7.5), shows that after pumping cessation, the residual concentration increases. As a part of a soil flushing operation, however, the source of contamination in the vadose zone will have been removed, and as such, this contaminant level rebound should not occur.

Soil flushing must, however, be effective in removing contaminants which have diffused into low permeability sediments. In addition, it must be able to desorb contaminants from sediment surfaces. Further, liquid-liquid partitioning of immiscible contaminants must occur in order to mobilize the pollutants of concern. The permeability variations which can affect the success of soil flushing are represented in figure 7.3 (on page 7.5).

Figure 7.1

Cross-Sectional and Three Dimensional Conceptualizations of Capture Zone vs. Cone of Depression

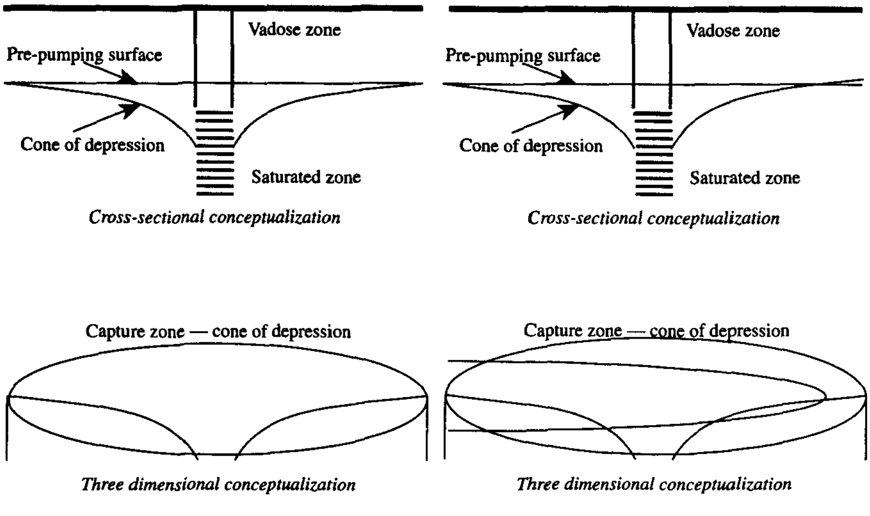


Figure A. Stagnant aquifer conditions

Figure B. Mild natural gradient

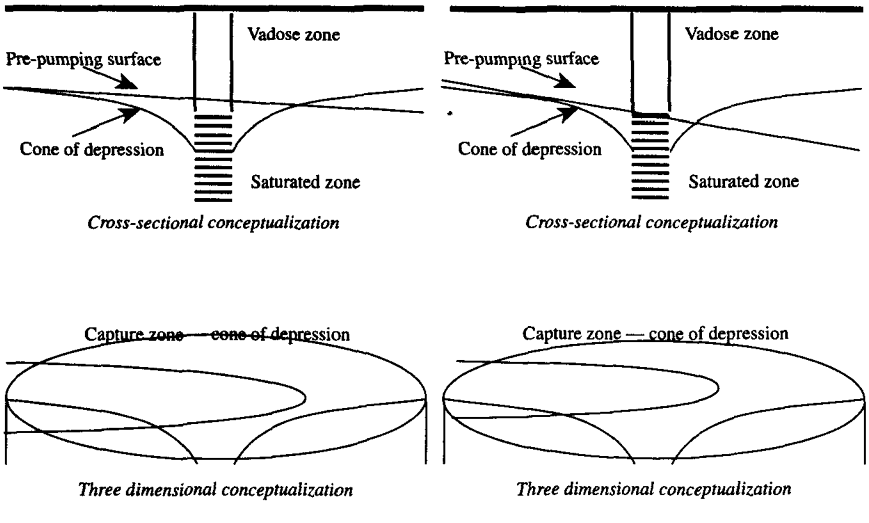


Figure C. Moderate natural gradient

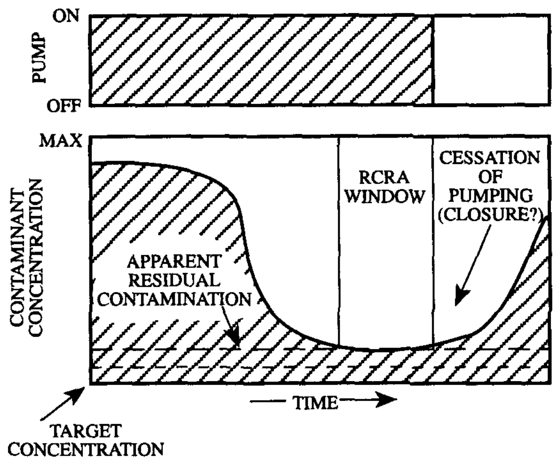
Figure D. Steep natural gradient

Based upon. US EPA 1989

Figure 7.2

Contaminant Level Increases After Remediation Stops

Contaminant Levels May Rebound When Pump-and-Treat Operations Cease, Because of Contaminant Residuals.

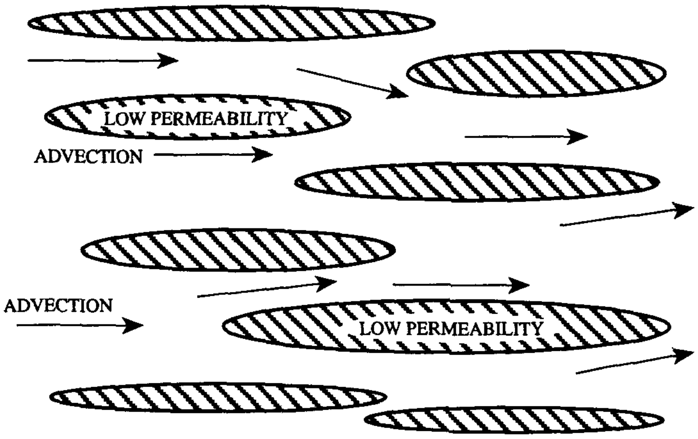


Based upon: US EPA 1989

Figure 7.3

Permeability Variations Limit Remediations

High-Permeability Sediments Conduct Most of the Flow; Low-Permeability Sediments Act As Leaky Contaminant Reservoirs



APPENDIX A

List Of Vendors and Contacts

Soil Washing Vendors

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Bio-Recovery System, Inc.
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Biotrol, Inc.
11 Peavey Road
Chaska, MN 55318
Phone: 612-448-2515

Canonie Environmental Services Corp.
94 Inverness Terrace East, Suite 100
Englewood, CO 80112
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Flo Trend System, Inc.
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Onsite-Offsite, Inc./Battelle PNL
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APPENDIX B

Soil Washing Case Histories

Case 1

Project Performance Date:	January 1992 — October 1992
Project Name:	King of Prussia Technical Corporation Site
Location:	Winslow Township, Camden County, N.J.
Key Contaminants:	Chromium, Copper, and Nickel
Technical Team:	Alternative Remedial Technologies, Inc. (ART) (A Joint Venture of Geraghty & Miller, Inc. and Heidemij Realisatie of the Netherlands)
Point of Contact:	Michael J. Mann, P.E. Phone: (813) 264-3571

Project Summary. This National Priorities List (NPL) site is known as the King of Prussia (KOP) Technical Corporation site. The ten-acre site is in a rural area approximately 48 km (30 miles) southeast of Philadelphia. The site was operated for approximately three years with the intention of converting industrial sludges into materials that could be marketed as construction-grade materials. That plan did not materialize, and, over the operational period, about 57 MM L (15 MM gal) of sludges were transported and treated at the site. The Remedial Investigation identified soil and groundwater contamination, a Feasibility Study was completed, and the Potentially Responsible Parties (PRP) Group chose to take the lead responsibility in remediating the site. The Record of Decision (ROD) specified soil washing as the remedial technology to be used to treat the source materials. Five key contaminants were identified in the soils, and treatment standards were established.

The PRP Group took a strong, proactive approach to working with the U.S. EPA Region II and the New Jersey Department of Environmental Protection (NJDEP) to implement the requirements of the ROD. It was clear that substantial time and money could be saved by taking action and completing the requirements. Additionally, because an aggressive approach could move forward on a pace faster than the consent order required, the regulators were interested in being part of an effort that posted a possible early construction completion. With that goal, several contractors performed initial soil evaluations, and it became clear that several distinct subsources exist at the site: lagoons with pure sludge, lagoons with sludge and soil-like material, and an area of natural soils with sludge intermittently disposed. Additionally, it was found that the soil matrix, in terms of its particle size distribution, was a good candidate for volume reduction activities, with about 10-15% fines.

Soil Washing Treatability Study. Alternative Remedial Tecnologies was selected to perform a detailed treatability study in accordance with the Comprehensive Environmental Response Compensation Liability Act (CERCLA) guidance document. The treatability study first defined the particle size and contaminant relationships for each source area, examined the nature of the particle and soil relationships using Scanning Electron Microscopy/Electron Probe Microanalysis. It was found in this first phase, that the contaminants were primarily bound in the fine-grained fraction of the soils, but, that in some cases, several of the coarse-grained fractions also exceeded the treatment standards. Next, bench-scale work was conducted to specifically evaluate screening, separation, and treatment steps that could be used in the configured full-scale treatment plant.

Process Equipment and Configuration. During this phase, mechanical screening to 500 μm (30 mesh), hydrocycloning, gravity separation, flotation, dewatering, sludge handling and processing testing were performed and documented. After the unit operations were selected, the combined treatment train was operated on a sequential batch basis in the laboratory in what was called a process simulation run. The results of this study provided the basis for development of a system mass balance and design/operational parameters.

Results of Treatability Study. As a result of the treatability study it was concluded that soil washing, as proposed and configured in the report, could meet the requirements of the ROD.

Soil Washing Demonstration Run. To confirm the findings of the treatability study and to provide additional assurance to all parties, it was proposed and accepted to perform a Demonstration Run on actual KOP site materials at the full-scale Heidemij plant located at Moerdijk, The Netherlands. First, approvals were obtained from the United States Environmental Protection Agency (U.S. EPA) and the Dutch equivalent organization (VROM). The project team (PRP's, U.S. EPA, the soil washing contractor, and the consultant) developed a detailed plan, excavated representative soils totalling 180 tonne (200 ton), packaged the material in "Super Sacks", loaded the material into transportation containers, and shipped the material to the Port of Rotterdam. There, the material was downloaded to the plant and prepared for the demonstration.

Process Equipment and Configuration. The Heidemij plant is a Treatment, Storage, and Disposal Facility (TSDF) equivalent with an annual treatment capacity of approximately 70,000 tonne (80,000 ton). The plant consists of all the unit operations to be used at the KOP site and was configured in exactly the same manner as proposed in the KOP treatability study. The treatment included feed preparation, loading, wet screening, hydrocyclone separation, surfactant addition, flotation and dewatering of the sand fraction, and sedimentation, thickening, and dewatering of the fines. Three process residuals — oversize material, sand, and a dense sludge cake — were produced, staged, examined, sampled, and analyzed. The oversize sand products are intended for placement back onsite and were analyzed for the target contaminants. The sludge cake will be disposed at a hazardous waste landfill and was analyzed to confirm compliance with applicable land disposal restrictions. The process plant is now in the design process. The team will move to the KOP site in early 1993 when full-scale operations will begin.

Results of the Demonstration Run. The demonstration run was extremely successful in meeting the stated objectives of confirming that the soil washing plant, configured as recommended in the KOP treatability study, can effectively treat KOP soils in compliance with the ROD requirements.

Full-Scale Operations. Prior to full-scale operations, a pilot run was performed on 1,000 tons of composited site soils. The pilot-run was successful and cleanup levels below the ROD-specified standards were reached. Record of Decision standards are:

- Chromium — 483 mg/kg
- Copper — 3,571 mg/kg
- Nickel — 1,935 mg/kg

Full-scale operations began on June 28, 1993 and ran until mid-October, 1993. During the operation of the soil washing facility, clean soils were returned to the site as backfill. The contaminated fraction was disposed of at an appropriate disposal facility. The site was then revegetated and returned to its natural condition.

Case 2

Project Performance Date: October 1989
Project Name: MacGillis and Gibbs Site
Location: New Brighton, Minn.
Key Contaminants: PAH's, PCP, Cu, Cr, As
Technical Team: Biotrol, Inc.
11 Peavey Road
Chaska, Minn. 55318
Phone: (612) 448-2513 Fax: (612) 448-6050
Point of Contact: Mr. Dennis Chilcote, President, Biotrol, Inc.

Project Summary. A SITE Program demonstration of the soil washing technology developed by Biotrol, Inc., was carried out. The demonstration showed that the contamination in the bulk of the soil can be greatly reduced. The contaminants were concentrated in a much smaller volume of soil fines than could be successfully treated biologically.

Process Equipment and Configuration. The overall operation consisted of three units — the soil washing process, a fixed-film bioreactor to treat process water prior to recycling, and a slurry bioreactor to treat the residuals from the soil washing process.

Treatment Standards and Results. Since this was a demonstration, there were no treatment standards. Removal of pentachlorophenol during soil washing ranged from 87 to 89%. For polynuclear aromatic hydrocarbons (PAHs), the removal ranged between 83 and 88%. The bioreactor removed 91 to 94% of the pentachlorophenol in the influent washwater. Removal efficiencies in the slurry bioreactor increased 90%.

Cost Information. Based on the results of this demonstration, the cost to treat one ton of soil (18 tonne/hr (20 ton/hr)), including water treatment, slurry biodegradation, and incineration of woody debris, was estimated at $168.00.

Case 3

Project Performance Date: September 1991 through June 1992
Project Name: U.S. Army Corps of Engineers, Saginaw, Mich.
Location: Saginaw, Mich.
Volume: 450 tonne (500 ton)
Key Contaminants: PCBs
Technical Team: Bergmann USA
Point of Contact: Richard Traver, Program Director
Bergmann USA

Project Summary. Bergmann USA was invited to present an overview on river and harbor sediment treatment technology to the joint U.S. EPA and Army Corps of Engineers' (ACOE) Assessment and Remediation of Contaminated Sediments (ARCS) Work Group in March, 1991. Bergmann was contracted by Jim Galloway, ACOE, Detroit, to conduct a Pilot Sediment Washing Demonstration on the Saginaw River Project. In-house, bench-scale treatability evaluations were performed, followed by the design and fabrication of a 5-10 ton/hr pilot-scale Bergmann USA field demonstration sediment washing plant to effectively separate contaminated fines from coarse fractions of river dredge sediments. This plant was placed into operation in October 1991 a mile and a half off-shore aboard a 37 m x 10 m (120 ft x 33 ft) ACOE dredge support barge for the processing of approximately 450 tonne (500 ton) of PCB-contaminated soil.

Preliminary results indicate a reduction of 91% of the initial polychlorinated biphenyl (PCB) concentration with only .2 mg/kg of PCBs remaining in the "clean" coarse >74 μm (>200 mesh) fraction. The <74 μm (<200 mesh) fines were enriched to a level of 14 mg/kg PCBs, and the humic fraction (leaves, twigs, roots, grasses, etc.) contained 24 mg/kg of PCBs. These materials are scheduled for biodegradation during the Spring/Summer of 1992.

This system was evaluated by the Superfund Innovative Technology (SITE) Program in May and June, 1992 by SAIC, Inc., working with Jack Hubbard, of the EPA Hazardous Waste Engineering Research Laboratory in Cincinnati. Preliminary analytical test results will be available in July, 1992 followed by the Applications Analysis Report in August, 1992 and the Technology Evaluation Report in February 1993.

This 9 tonne/hr (10 ton/hr) plant processed approximately 180 tonne (200 ton) of PCB-contaminated dredge sediments prior to winterization. An additional 270 tonne (300 ton) of material was washed during the May through June, 1992 evaluation period.

Case 4

Project Performance Date:	January 1992 to September 1992
Project Name:	Toronto Harbour Commission's (THC) Soil Recycling Demonstration Project
Location:	Toronto, Ontario, Canada
Volume:	4,000 tonne (4,400 ton)
Key Contaminants:	Cadmium, Arsenic, Copper, Lead, Mercury, Zinc, Nickel, Oil and Grease, PAH's
Technical Team:	THC, SNC, Inc., Bergmann USA, Bodemsaneling Nederland, B.V. (BSN)
Point of Contact:	Dennis Lang, Director of Engineering Toronto Harbour Commission Phone: (416) 863-2047 Fax: (416) 863-4830

Project Summary:

- demonstration project costing $8,000,000, entirely privately funded;
- demonstration integrated soil washing, metal extraction by chelation, and organics reduction by aerobic bioremediation in upflow air reactors;
- two soil washing processes evaluated; Bergmann USA's chemical attrition scrubbing system at 4.5 to 9 tonne/hr (5 to 10 ton/hr), and BSN's high-pressure wash system at 50 ton/hr at a wash plant in Holland; and
- objective was to treat soil so that cleaned soil can be reused on industrial land and metals removed can be recycled.

Process Equipment and Configuration:

- BSN wash system tested by shipping three 320-tonne (350-ton) bagged samples to Holland for washing. Residual soil returned in bags; residual slurry with concentrated contaminants returned in 2,600 170-L (45-gal) drums for metal removal and bioremediation;
- Bergmann USA leased a 4.5 to 9 tonne/hr (5 to 10 ton/hr) demonstration soils unit which was located on site; and
- Process – soil wash for volume reduction, then metals reduction, and then organics reduction by bioremediation.

Treatment Standards and Results:

- Objective was to meet Ontario Ministry of The Environment standards for cleaning soil for industrial use;

- Soil wash systems effectively cleaned coarse (>6 mm (>0.2 in.)) and intermediate streams (0.063 to 6 mm (0.002 to 0.2 in.)) to industrial standards;
- Metal extraction process can remove metals to meet residential and agricultural standards; and
- Bioremediation process can reduce oil and grease to industrial levels.

Cost Information:

- Total project cost $8,000,000 (Canadian); and
- Estimate a 45 tonne/hr (50 ton/hr) commercial-scale treatment plant would cost about $25,000,000 and would charge $175/tonne ($160/ton) to clean soil.

Case 5

Project Performance Date:	December 1991 — Ongoing
Project Name:	Bruni Soil Washing Project
Location:	Bruni, Tex.
Volume:	12,000 m^3 (16,000 yd^3) (15,000 tonne (16,000 ton))
Key Contaminants:	Uranium and Radium
Technical Team:	Scientific Ecology Group (SEG) and Westinghouse Science and Technology Center
Point of Contact:	C. P. Keegan Scientific Ecology Group 1501 Ardmore Blvd., 3rd Floor Pittsburgh, PA 15221 Phone: (412) 247-6255

Project Summary. Bruni, Texas was the site of a Westinghouse in situ uranium mining operation between 1975 and 1981. Borings containing uranium and radium ore were left on the surface during the drilling of over 1,000 wells. Additionally, solution spills during plant operations added uranium and radium to the soil. Over the years, uncontaminated soil built up over the contaminated soil in a nonuniform manner.

The characteristics of this site are particularly difficult for the application of soil washing: fresh water supplies are limited to 150 L/min (40 gal/min), the area is semiarid and humid, and the clay content of the soil is very high (between 40 and 60%). In addition, contaminated root hairs from site vegetation and ion exchange resins from solution spills must be removed from the soil.

The SEG Soil Washing System arrived on the Bruni Site in December, 1991. Assembly, start-up and calibration were completed in March, 1992, and production began. Processing rates were increased until the rated capacity of 18 tonne/hr (20 ton/hr) was achieved. Over 7,000 tonne (8,000 ton) were successfully processed as of August 1, 1992. Processing at Bruni and demobilization are scheduled for completion by the end of 1992.

Process Equipment and Configuration. The patented soil washing process is based upon commonly-available mineral treatment equipment and processes. It consists of several unit operations tied together in an integrated process to wash and separate soil components from contaminating materials and to separate the contaminants from each other. It does this through a combination of particle separation by size and density and by chemical extraction using environmentally-acceptable extraction solutions. The general process can be modified to fit the needs of a particular site by changing the extraction solution chemistry and particle separations. The almost infinite combinations of soil and contaminant characteristics made the use of a treatability study mandatory, but the flexibility inherent in the soil washing process allows a wide degree of latitude in its application.

In the SEG Soil Washing System, the excavated soil is first processed to remove large rocks and debris, which are cleaned for return to the site. The soil is then processed in a rotating drum to sort and prewash the soil. The large fraction is washed with leachate solution to remove the fines, rinsed with water, and returned to the site. The remaining contaminated soil is then processed using mineral processing equipment in which the soil contacts with the leachate solution and the resins and root hairs are separated from the soil for disposal. The washed soil is then rinsed, monitored, and returned to the site. The leachate is further treated and sent to the leachate make-up tanks for reuse.

The SEG Soil Washing System is permanently mounted on three trailers. Auxiliary equipment, such as, the feed hopper and conveyors, is transported on additional trailers. The system is therefore mobile for rapid transport, mobilization, and demobilization.

Treatment Standards and Results. Table B.1 shows the average contamination levels at the Bruni site and the limits established by the Texas Department of Health:

Table B.1
Treatment Standards for the Bruni Soil Washing Project

Contaminant	Average Soil Contamination Level	Above Background	Required Levels Background
U	70 ppm	42 ppm (30 pCi/g)	1 ppm
Ra	6 pCi/g	5pCi/g(5 x 10^{-6} ppm)	1 pCi/g

From a volume standpoint, the uranium is to be removed to parts per million levels and the radium is to be removed to parts per trillion levels. Generally, the concentration of contamination on the site is one to five times the acceptable levels.

The terms for the lease of the Bruni site property require that when returned to the landowner, the land must be capable of sustaining the growth of buffalo grass, a prominent local vegetation in the Bruni area. The soil must therefore remain fertile after processing.

Bruni Results. Essentially 100% of the soil is being recovered as clean soil. The uranium and radium are extracted in the resin and zeolite columns. The uranium can be stripped and used by uranium processors and is therefore not a waste stream. The zeolite, resins and root hairs are the waste streams requiring disposal. Incineration of the resins and root hairs in the SEG incinerator at its Oak Ridge, Tennessee facility will reduce their volume by over 100:1.

The average concentration of uranium in the clean soil to date is 20.7 ppm and the average concentration of radium in the clean soil, including background, is 5.9 pCi/g. Laboratory testing of processed soil showed that it is capable of sustaining buffalo grass growth.

Cost Information. Soil washing prices generally range 25-75% below packaging, hauling and burying. The cost is a function of the contaminants, the soil type, the cleanup limits, the available utilities, etc.

Additional advantages of soil washing are:

- sometimes possible to separate a mixed waste into a radioactive and hazardous component;
- final solution to contamination on-site;
- allows free-release of treated soil;
- significantly reduces the amount of waste requiring disposal;
- reduces disposal cost;
- processing performed on site;
- flexible process meets the specific needs of various sites;
- no damage to the environment;
- closed-cycle process guarantees no air or water pollution;
- quick site remediation with 18 tonne/hr (20 ton/hr) capacity mobile system;
- in some cases, concentrated metal removed from the soil can be sold as a useable product; and
- reduces liability.

Case 6

Project Performance Date:	1987 — 1988
Project Name:	Poly-Carb Site
Location:	Wells, Nev.
Key Contaminants:	Phenol and Creosol
Technical Team:	CH2M Hill/EPA Region 9
Point of Contact:	Mr. Bob Mandel, EPA Region 9 Phone: (415) 744-2290

Project Summary. Soils contaminated with phenol and creosol were placed in a double-lined, half-acre leach field. The leach field extraction system contained a water supply, an irrigation system to distribute water onto the soil, a leachate collection system above the top liner, a holding tank, disposable granular activated carbon (GAC) cartridges, and necessary pumps.

Process Equipment and Configuration. Contaminated soils were treated in a "passive" soil washing system. Clean water was spray irrigated onto the waste, collected as leachate, treated and reused.

Treatment Standards and Results. Soil leaching reduced phenol concentrations in the soil by 99.9% and lowered creosols by 99.7%. Influent phenol concentrations averaged 980 mg/kg and after treatment were less than 1 mg/kg.

Case 7

Project Performance Date:	August 1990
Project Name:	Union Pacific Railroad
Location:	Pocatello, Idaho
Size:	11 Recovery Wells
Key Contaminants:	Nonaqueous phase liquids (NAPLs)
Technical Team:	Kennedy, Jenks, and Chilton
Point of Contact:	Ann Williamson, EPA Region 10 Phone: (206) 553-1090

Project Summary. Upper-aquifer groundwater was extracted from eleven wells at 75 L/min (20 gal/min) each. The recovered groundwater was treated and discharged to the Pocatello Publicly Owned Treatment Works. Clean water was injected into the infiltration galleries located within the capture zone. The reinjected water assisted in mobilizing contaminants that could then be collected by the recovery well.

Process Equipment and Configuration. The process equipment included the recovery wells, the treatment system, and the infiltration galleries. The treated water was enhanced with in-line oxygen and nutrients to stimulate biodegradation during the soil flushing process.

Treatment Standards and Results. The system involved the recovery and treatment of approximately 439 MM L/yr (116 MM gal/yr) for five years. Clean water was used for the flushing.

Cost Information. The cost estimate for the project, including capital and operation and maintenance (O&M), was $1,191,000.

Case 8

Project Performance Date: 1988 - 1990
Project Name: Private Wood Treating Site - Pilot Test
Location: Western U.S.
Key Contaminants: Polynuclear aromatic hydrocarbon (PNA), compounds and carrier oils
Technical Team: CH2M Hill and Surtek
Point of Contact: Tom Sole, CH2M Hill, Denver, Colo.
Phone: (303) 771-0900

Project Summary. This privately-owned former wood-treating site contains over 400,000 m^3 (500,000 yd^3) of PNA-contaminated alluvial deposits with significant dense non-aqueous phase liquids (DNAPLs) and a floating free-product layer. Contaminants are contained by underlying impermeable shale, a perimeter bentonite slurry wall, and a negative hydraulic gradient.

The soil volume and proximity to residences preclude excavation and on-site treatment. The PNA concentrations limit the effectiveness of pump-and-treat remedies. These conditions encourage the use of in situ technologies, such as primary oil recovery and soil flushing.

Process Equipment and Configuration. The field test was conducted in a 3.6-m (12-ft) deep test cell isolated from the surrounding alluvium by a 8.2 x 8.2 m (27 x 27 ft) sheet-pile wall. Alluvial sediments graduated from fine sands, silts, and clays at the surface to coarse sands and fine gravels at the base. The lower three feet of alluvium was saturated by a waste wood-treating oil. The density and viscosity of the oil were approximately 1.04 g/cm^3 and 54 cp, respectively.

Delivery and recovery of the soil-washing solutions were accomplished using 10.16-cm (4-in.) horizontal drain lines spaced 4.6 m (15 ft) apart in parallel and located at the alluvium-bedrock contact.

Above-ground process facilities required to complete the pilot included:

- tankage and controls for storage and regulated delivery of the soil-washing solution;
- pumps for recovery of fluids from the alluvium; and
- reactors for treatment of the produced fluids.

A summary of the sequence used in the pilot test is presented in table B.2 (on page B.14). A pore volume is defined as the volume of liquid required to saturate the cell and was estimated at 19,000 L (5,000 gal).

The first step was to cycle water between the recovery and delivery drain lines and to displace all of the mobile free-phase oil. Recovery of oil and water

Table B.2
Delivery Sequence and Volumes

Sequence	Delivered Fluid	Volume (gallons)	Volume (pore volumes)
Waterflooding	Water	144,000	28
Soil Flushing	Polystep A-7^R	10,000	2
	Makon-10^R	10,000	2
	Water	10,000	2
	Makon-10^R	10,000	2
Reconditioning	Water	150,000	30

phases from the alluvium was accomplished using a dual drain recovery concept. The primary purpose of the waterflood or primary oil recovery sequence was to remove all mobile oil so the efficacy of soil flushing could be gauged under conditions where only immobile, residual oil remained.

The second phase of the pilot test was to deliver 100,000 L (30,000 gal) of soil washing solutions consisting of a mixture of alkaline agents, polymer, and surfactants. The composition of the soil washing solution was determined in the laboratory studies described earlier and is presented in table B.3 (on page B.15). Two different soil washings were used in the pilot test. Based on the laboratory tests, it was believed that optimal results could be obtained by using the Polystep A-7^R initially to produce reusable wood-preserving oil, followed by the Makon-10^R system to achieve lower cleanup levels.

Included in the delivery phase was 38,000 L (10,000 gal) of water delivered after the first 76,000 L (20,000 gal) of soil-washing solution had been delivered. The intermediate water cycle kept fluids moving while the arrival of more soil-washing solution was awaited.

The final phase of the test involved flooding the cell with water to displace the mobilized oil and soil-washing solution remaining in the alluvium.

Treatment Results And Conclusions. It was concluded that in situ soil flushing could play an important role in recovery of waste wood-treating oils at the site.

A total of 7,200 L (1,900 gal) of PNA-contaminated oil was removed from the test cell. On average, primary oil recovery was able to reduce oil concentration from 93,000 to 15,500 mg/kg, and in situ soil flushing further removed the oil to achieve a final concentration of 5,100 mg/kg, or a 94% reduction overall.

The test primarily used petroleum industry methods for the recovery of free-phase, non-aqueous hydrocarbons. More aggressive soil adsorption and viscos-

Table B.3

Soil Washing Solutions

	Makon-10^{R} System		Polystep A-7^{R} System	
	Compound	Concentration	Compound	Concentration
Alkaline	Na_2CO_3 $NaHCO_3$	0.825 by wt 0.65% by wt	Na_2CO_3 $NaHCO_3$	0.1% by wt 0.72% by wt
Polymer	Xanthan Gum Biopolymer	1,050 mg/L	Xanthan Gum Biopolymer	1,050 mg/L
Surfactant	Makon-10^{R}[a]	1.4% by wt	Polystep A-7^{R}[b]	1% by wt
pH	9.2		10.2	
Viscosity	54 cp		54 cp	

[a] Ethoxylated nonylphenol

[b] Sodium dodecyl benzene sulfonate

ity, or in situ bioremediation were recommended to lower cleanup levels further.

The removal of pore space oil also increased the soil bulk permeability from 15 to 30 Darcy. Soil flushing solution enhancement chemicals were 61 to 99% recovered.

Key questions still to be answered include the following:

- Is the permeability of the contaminated porous media sufficient to effectively deliver and recover fluids to and from the subsurface?
- Can delivery and recovery systems be constructed that will effectively move the soil-washing solutions through contaminated portions of the subsurface?
- Using the identified delivery and recovery system, can the soil-washing solution and mobilized oils effectively be contained and recovered? and
- Can conventional oil and water separation techniques be effective on the oily emulsions that can result from enhanced flushing solutions?

Once these questions are answered, the next step is to select a soil-washing solution. This step should be done in the laboratory, using materials from the site. Issues to be resolved in the laboratory include the following:

- Does the solution effectively mobilize residual oil?

- To what degree are the components of the soil-washing solution consumed by the subsurface materials, and how does this consumption affect economic feasibility?
- Are unfavorable reactions leading to inorganic leaching or formation plugging likely to occur? and
- What is the most practical approach to managing the fluids produced in a field application?

The final step in evaluating in situ soil washing as a cleanup approach should be a small-scale field demonstration. Through a field demonstration, preliminary evaluation of these issues can be confirmed, design data for larger-scale applications can be developed, and accurate estimates of full-scale cost can be made.

Case 9

Project Performance Date: 1988 to present
Project Name: United Chrome Products
Location: Corvallis, Oreg.
Area: 8-acre shallow aquifer plume
Key Contaminants: 19,000 ppm of Hexavalent Chromium
Technical Team: CH2M Hill
Point of Contact: Randy Pratt, CH2M Hill

Project Summary. The United Chrome Products site is a former industrial hard-chrome plating facility sited on approximately eight acres just north of the Corvallis Airport Facility. Operations and waste management practices resulted in hexavalent chromium (Cr(VI)) contamination of surface water, soils, and groundwater. The local subsurface is characterized by two water-bearing zones separated by a silty-clay aquitard. The upper zone consists mostly of silt and is the primary zone of contamination. The contaminant extended about 90 m (300 ft) downgradient from the source areas with Cr(VI) concentrations up to 19,000 mg/L. The deep aquifer consists of a sand and gravel mixture that is capable of supplying potable water for commercial and residential use. The deep aquifer plume extends about 100 m (400 ft) downgradient from the source area with Cr(VI) concentrations up to 223 mg/L. The selected remedy consisted of the installation of two infiltration basins and one infiltration trench, along with a series of shallow wells to extract groundwater from the upper zone and an on-site treatment facility to remove chromium prior to Publicly Owned Treatment Works (POTW) discharge.

Process Equipment and Configuration. Two open-bottom infiltration basins and one infiltration trench were constructed to release water to the subsurface flushing Cr(VI) from soils in the vadose zone to the water table for recovery by adjacent extraction wells. The flushing process also provides a source of groundwater recharge for the upper zone extraction wells to replace approximately half of the water removed by pumping. Water is discharged into each basin through an outlet controlled manually or by a float valve that maintains the water level at a relatively constant depth. Precipitation recharge contributes another 30% of the pumped volume.

The success of the basins is demonstrated by a 100% to 200% increase in extraction gallons for adjacent wells and concurrent decrease of up to 95% in Cr(VI) concentrations. The infiltration trench increases extraction well yields along the longitudinal axis of the plume and operates primarily during the summer and early fall months to provide supplemental recharge as decreased precipitation and underflow reduce the amount of water available for extraction. Another important benefit of the trench is the high groundwater velocities created by the increased hydraulic head. This condition should accelerate removal of contaminated groundwater from wells in this vicinity.

The water used for basin and trench inflows has been obtained from the City drinking-water system. In the future, groundwater extracted from deep aquifer remediation may be used to supplement this source.

Treatment Standards and Results. The extraction and treatment system has been in operation for three years, during which time approximately 37 MM L (9.7 MM gal) of contaminated groundwater containing 12,125 kg (26,732 lb) of hexavalent chromium Cr(VI) have been removed. To accelerate removal of Cr(VI) from contaminated soils and to provide supplemental recharge for the upper zone, 20 MM L (5.2 MM gal) of city-supplied water have been recharged through two infiltration basins and one infiltration trench.

Evaluation of site operations data indicates the 100,000-gal extraction system has reduced the magnitude of Cr(VI) concentrations present in the upper zone, has prevented off-site migration of the contaminant plume, and reduced discharges of contaminated groundwater to local surface drainage ditches. Hexavalent chromium concentrations have been reduced from an overall average of 1,923 mg/L in August 1988 to 87 mg/L in June 1991. Maximum groundwater concentrations have been reduced from over 19,000 to 530 mg/L. Four of 23 extraction wells and 10 of the 11 monitoring wells tested in April 1991 were below the site cleanup goal of 10 mg/L Cr(VI).

Cleanup Trends. Monitoring data indicate that remediation progress is highly variable with cleanup rates influenced primarily by the well location and volume of water that can be flushed through a given area. This results from a variable distribution of contaminant mass in the upper zone. Extraction wells in the vicinity of the infiltration basin have yielded the largest volume of groundwater and exhibit the greatest overall decrease in Cr(VI) concentration.

The average concentration of chromium in extracted groundwater for the combined well flows has decreased dramatically from 1,923 mg/L to 87 mg/L. The rate of decline has decreased in recent months and is beginning to exhibit an asymptotic or "tailing" effect. This condition is also present at individual well locations and may result from any one or combination of contaminant transport and geochemical processes occurring in the subsurface. The processes include:

- Variable length contaminant flow paths – Contaminated water at the perimeter of a well capture zone must travel a greater distance (at lower velocity) to reach the extraction point;
- Diffusion of Cr(VI) from fine-grained sediments – Localized variations in the rate of groundwater flow arise in heterogenous settings because of the interlayering of high and low permeability sediments. Pumping induces rapid flushing of the high permeability zones; however, contaminants are removed very slowly by diffu-

sion from the low permeability zones. The rate of diffusion is dependent primarily on the concentration gradient present between the two zones. Low permeability sediments can act as leaky contaminant reservoirs;

- Hydrodynamic isolation – Localized areas of velocity stagnation (zero flow) often develop between pumping wells. These zones can only be remediated by modifying existing flowline patterns by changing the location of pumping wells, or by altering pumping rates among existing wells; and
- Desorption of Cr(VI) from soil particles and dissolution of solid phase Cr(VI) – Both of these processes frequently result in the slow release of contaminants, often at concentrations well below their chemical equilibrium levels. This condition results in extraction of large volumes of high concentration water, unless the pumping approach is modified to account for these effects.

As the total mass of recoverable Cr(VI) in the subsurface is reduced, the influence of these processes becomes more apparent. Because these processes are not well understood, accurate prediction of future remediation progress is increasingly difficult.

Cleanup Duration. The time required to attain the remediation goal of 10 mg/L in the upper-zone groundwater is directly related to the time required to remove a pore volume of contaminated groundwater.

A pore volume is defined as the volume of contaminated groundwater present within the pore spaces (water-filled voids) of aquifer material bounded by the contaminant plume boundary. At the United Chrome site, a single pore volume has been estimated to contain 9.8 MM L (2.6 MM gal) of water (within the 10 mg/L concentration contour). The time required to remove a pore volume is simply the pore volume (gal) divided by the total pumping rate (gal/min). At a sustained rate of 40 L/min (10 gal/min), a pore volume at United Chrome is extracted every six months. However, due to the highly variable well yields at the site, some areas are flushed more rapidly than others, resulting in reduced cleanup rates at low water yield areas of the site.

Uncertainties about sediment heterogeneity, distribution of contaminant mass, variable groundwater extraction rates, and seasonal weather patterns that limit groundwater availability make it difficult to estimate the time frame required to achieve the remediation goals. Cleanup time estimates have ranged from 5 to 15 years to attain the goal of 10 mg/L at different times.

Evaluation of monitoring data collected during three years of system operation has identified several operational procedures and monitoring schedules that should be modified. These changes may increase Cr(VI) recovery per gallon of groundwater extracted and will permit a reduced level of effort in terms of data gathering requirements necessary to establish extraction system performance. These recommendations include:

- Infiltration Basin Operations – The basins have flushed most of the soluble chromium from vadose zone soils. Removal of solid phase hexavalent chromium ($BaCrO_4$) and soluble Cr(VI) may require longer contact times to generate higher Cr(VI) concentrations per gallon extracted. Operation of the basins should be modified to increase contact time between infiltration water and solid phase Cr(VI) and/or sorbed Cr(VI). The basins should also be used to deliver recharge water to other areas within the extraction well network;
- Extraction System Operations – Aggressive operation of wells adjacent to the infiltration basins initially resulted in the removal of significant mass, but the high pumping rate may have created short circuiting and resulted in the production of large volumes of low concentration water, while also decreasing the amount of recharge available to other wells. Operation of marginally producing wells should be reduced or discontinued; and
- Monitoring Schedules – Increased confidence in system operations and aquifer response to pumping will permit a reduction in the monitoring frequency and number of monitoring locations. Monitoring activities in the upper zone will also be modified to gather data on the hydraulic interaction between the upper zone and deep aquifer once deep aquifer groundwater extraction begins.

Cost Information. The cost estimates compare each alternative in terms of annual and present value costs and cost per pound of Cr(VI) removed. The cost estimates indicate that treatment costs, presently estimated at $88/kg ($40/lb) of Cr(VI) removed for the first 11,000 kg (25,000 lb) will double to $176/kg ($80/lb) of Cr(VI) removed as Cr concentrations drop in the later phases of operation.

APPENDIX C

Guide for Conducting Treatability Studies Under CERCLA: Soil Washing

Section 121 (b) of CERCLA mandates that EPA should select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and that EPA should prefer remedial actions in which treatment that "permanently reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants is a principal element." Treatability studies provide data to support treatment technology selection and remedy implementation and should be performed as soon as it is evident that insufficient information is available to ensure the quality of the decision. Conducting treatability studies early in the remedial investigation/feasibility study (RI/FS) process should reduce uncertainties associated with selecting the remedy, and provide a sounder basis for the ROD. Regional planning should factor in the time and resources required for these studies.

This fact sheet provides a summary of information to facilitate the planning and execution of soil washing remedy selection treatability studies in support of the RI/FS and the remedial design/remedial action (RD/RA) processes. This fact sheet follows the organization of the "Guide for Conducting Treatability Studies Under CERCLA: Soil Washing", Interim Guidance, EPA/540/000/000A September 1991. Detailed information on designing and implementing remedy selection treatability studies for soil washing is provided in the guidance document.

INTRODUCTION

There are three levels or tiers of treatability studies: remedy screening, remedy selection, and remedy design. The "Guide for Conducting Treatability Studies Under CERCLA: Soil Washing Remedy Selection" discusses the remedy screening and remedy selection levels.

Remedy screening studies are designed to provide a quick and relatively inexpensive indication of whether soil washing is a potentially viable remedial technology. Soil washing remedy screening studies should not be the only level of testing performed before final remedy selection. Remedy selection and remedy design studies will also be required to determine if soil washing is a viable treatment alternative for a site. The remedy selection evaluation should provide an indication that reductions in contaminant concentrations or in the volume of contaminated soil will meet site-specific cleanup goals. It will also produce the design information required for the next level of testing. Remedy design studies may be needed to optimize process design.

TECHNOLOGY DESCRIPTION AND PRELIMINARY SCREENING

Technology Description

Soil washing is a physical/chemical separation technology in which excavated soil is pretreated to remove large objects and soil clods and then washed with fluids to remove contaminants. To be effective, soil washing must either transfer the contaminants to the wash fluids or concentrate the contaminants in a fraction of the original soil volume, using size separation techniques. In either case, soil washing must be used in conjunction with the other treatment technologies. Either the washing fluid or the fraction of soil containing most of the contaminant, or both, must be treated.

At the present time, soil washing is used extensively in Europe and has had limited use in the United States. During 1986-1989, the technology was one of the selected source control remedies at eight Superfund sites.

The determination of the need for and the appropriate level of treatability studies required is dependent on the literature information available on the technology, expert technical judgment, and site-specific factors. Several reports and electronic data bases exist that should be consulted to assist in planning and conducting treatability studies as well as help prescreen soil washing for use at a specific site. Site-specific technical assistance is provided to Regional Project Managers (RPMs) and On-Scene Coordinators (OSCs) by the Technical Support Project (TSP).

Prescreening Characteristics

Prescreening activities for the soil washing treatability testing include interpreting any available site-related field measurement data. The purpose of prescreening is to gain enough information to eliminate from further treatability testing those treatment technologies which have little chance of achieving the cleanup goals.

The three most important soil parameters to be evaluated during prescreening and remedy screening tests are the grain size distribution, clay content, and cation exchange capacity. Soil washing performance is closely tied to these three factors. Soil with relatively large percentages of sand and gravel (coarse material >2 mm in particle size) respond better to soil washing than soils with small percentages of sand and gravel. Larger percentages of clay and silt (fine particles smaller than 0.25 mm) reduce soil washing contaminant removal efficiency. In general, soil washing is most appropriate for soils that contain at least 50 percent sand/gravel, i.e., coastal sandy soils and soils with glacial deposits. Soils rich in clay and silt tend to be poor candidates for soil washing. Cation exchange capacity measures the tendency of the soil to exchange weakly held cations in the soil for cations in the wash solution, which will be more strongly bound to the soil. Soils with relatively low CEC values (less than 50 to 100 meq/kg) respond better to soil washing than soils with higher CEC values. Early characterization of these parameters and their variability throughout the site provides valuable information for the initial screening of soil washing as an alternative treatment technology.

Chemical and physical properties of the contaminant should also be investigated. Solubility in water (or other washing fluids) is one of the most important physical characteristics. Reactivity with wash fluids may, in some cases, be another important characteristic to consider. Other contaminant characteristics such as volatility and density may be important for the design of remedy screening studies and related residuals treatment systems. Speciation is important in metal-contaminated sites. Specific metal compounds should be quantified rather than total metal concentration for each metal present at the site.

There is no steadfast rule that specifies when to proceed with remedy screening and when to eliminate soil washing as a treatment technology based on a preliminary screening analysis. A literature search indicating that soil washing may not work at a given site should not automatically eliminate soil washing from consideration. On the other hand, previous studies indicating that pure chemicals will be effectively treated using soil washing must be viewed with caution. Chemical interactions in complex mixtures frequently found at Superfund sites or interactions between soil and contaminants can limit the effectiveness of soil washing. An analysis of the existing literature, coupled with the site characterization, will provide the information required to make an "educated decision." However, when in doubt, a remedy screening study is recommended.

Technology Limitations

Many factors affect the feasibility of soil washing. These factors should be addressed prior to the selection of soil washing, and prior to the investment of time and funds in further testing. A detailed discussion of these factors is beyond the scope of this document.

THE USE OF TREATABILITY STUDIES IN REMEDY SELECTION

Treatability studies should be performed in a systematic fashion to ensure that the data generated can support the remedy evaluation and implementation process. A well-designed treatability study can significantly reduce the overall uncertainty associated with the decision but cannot guarantee that the chosen alternative will be completely successful. Care must be exercised to ensure that the treatability study is representative of the treatment as it will be employed (e.g., the sample is representative of the contaminated soil to be treated) to minimize the uncertainty in the decision. The method presented below provides a resource-effective means for evaluating one or more technologies.

There are three levels or tiers of treatability studies: remedy screening, remedy selection, and remedy design. Some or all of the levels may be needed on a case-by-case basis. The need for, and the level of, treatability testing required are management decisions in which the time and cost necessary to perform the testing are balanced against the risks inherent in the decision (e.g., selection of an inappropriate treatment alternative). Figure 1 shows the relationship of three levels of treatability study to each other and to the RI/FS process.

Remedy Screening

Remedy screening is the first level of testing. It is used to establish the ability of a technology to treat a waste. These studies are generally low cost (e.g., $10,000 to $50,000) and usually require hours to days to complete. The lowest level of quality control is required for remedy screening studies. They yield data enabling a qualitative assessment of a technology's potential to meet performance goals. Remedy screening tests can identify operating standards for investigation during remedy selection or remedy design testing. They generate little, if any, design or cost data, and should never be used as the sole basis for selection of a remedy.

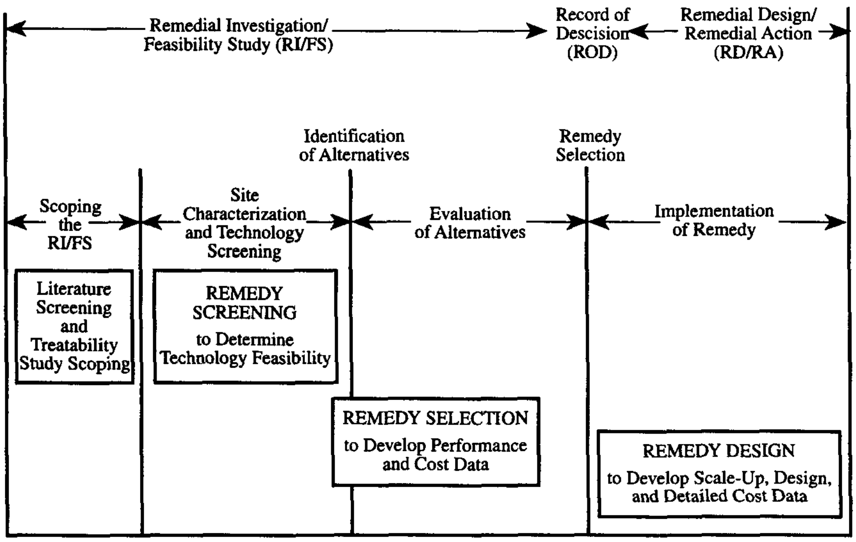
Remedy screening soil washing treatability studies are frequently skipped. Often, there is enough information about the physical and chemical characteristics of the soil and contaminant to allow an expert to evaluate the potential success of soil washing at a site. When performed, remedy screening tests are jar tests. However, remedy selection tests are normally the first level of treatability study executed.

Remedy Selection

Remedy selection testing is the second level of testing. Remedy selection tests identify the technology's performance for a site. These studies have a moderate cost (e.g., $20,000 to $100,000) and require several weeks to complete. Remedy selection tests yield data that verify that the technology can meet expected cleanup goals, provide information in support of the detailed analysis of alternatives (i.e., seven of the nine evaluation criteria), and give indications of optimal operating conditions.

The remedy selection tier of soil washing testing generally consists of laboratory tests which provide sufficient experimental controls such that a semi-quantative mass balance can be achieved. Toxicity testing of the cleaned soil is

Figure 1
The Role of Treatability Studies in the RI/FS and RD/RA Process



typically employed in the remedy selection tier of treatability testing. The key question to be answered during remedy selection testing is how much of the soil will this process treat by either particle size separation or solubilization to meet the cleanup goal. The exact removal efficiency needed to meet the specified goal for the remedy selection test is site-specific. In some cases, pilot-scale testing may be appropriate to support the remedy evaluation of innovative technologies. Typically, a remedy design study would follow a successful remedy selection study.

Remedy Design

Remedy design testing is the third level of testing. It provides quantative performance, cost, and design information for remediating an operable unit. This testing also produces remaining data required to optimize performance. These studies are of moderate to high cost (e.g., $100,000 to $500,000) and require several months to complete. For complex sites (e.g., sites with different types or concentrations of contaminants in different areas or with different soil types in different areas), longer testing periods may be required, and costs will be higher. Remedy design tests yield data that verify performance to a higher degree than the remedy selection and provide detailed design information. They are performed during the remedy implementation phase of a site cleanup.

Remedy design tests usually consist of bringing a mobile treatment unit onto the site, or constructing a small-scale unit for nonmobile technologies. Permit exclusions may be available for offsite treatability studies under certain conditions. The goal of this tier of testing is to confirm the cleanup levels and treatment times specified in the Work Plan. This is best achieved by operating a field unit under conditions similar to those expected in the full-scale remediation project.

Data obtained from the remedy design tests are used to:

- Design the full-scale unit
- Confirm the feasibility of soil washing based on target cleanup goals
- Refine cleanup time estimates
- Refine cost predictions.

Given the lack of full-scale experience with innovative technologies, remedy design testing will generally be necessary in support of remedy implementation.

REMEDY SELECTION TREATABILITY STUDY WORK PLAN

Carefully planned treatability studies are necessary to ensure that the data generated are useful for evaluating the validity or performance of a technology. The Work Plan, which is prepared by the contractor when the Work Assignment is in place, sets forth the contractor's proposed technical approach for completing the tasks outlined in the Work Assignment. It also assigns responsibilities and establishes the project schedule and costs. The Work Plan must be approved by the RPM before initiating subsequent tasks. A suggested organization of the Work Plan is provided in the "Guide for Conducting Treatability Studies Under CERCLA: Soil Washing."

Test Goals

Setting goals for the treatability study is critical to the ultimate usefulness of the data generated. Goals must be defined before the treatability study is performed. Each tier of treatability study needs performance goals appropriate to that tier.

Remedy screening tests are not always performed for soil washing processes. If remedy screening tests are performed, an example of the goal for those tests would be to show that the wash fluid will solubilize or remove a sufficient percentage (e.g., 50 percent) of the contaminants to warrant further treatability studies. Another goal might be to show that contaminant concentrations can be reduced in the >2 mm soil fraction by at least 50 percent, as compared to the original soil concentrations, using particle size separation techniques. These goals are only examples. The remedy screening treatability study goals must be determined on a site-specific basis.

Achieving the goals during this tier should merely indicate that soil washing has at least a limited chance of success and that further studies will be useful. Frequently, such information is available based on the type of soil and contaminant present at the site. Based on such information, experts in soil washing technology can often assess the potential applicability of soil washing without performing remedy screening.

The main objectives of the remedy selection tier of testing are to:

- Measure the percentage of the contaminant that can be removed from the soil through solubilization or from the >2 mm soil fraction by particle size separation.
- Produce the design information required for the next level of testing, should the remedy selection evaluation indicate remedy design studies are warranted.
- The actual goal for removal efficiency must be based on site- and process-specific characteristics. The specified removal efficiency must meet site cleanup goals, which are based on a site risk assessment or on the applicable or relevant and appropriate requirements (ARARs).

Experimental Design

A jar test is the type of remedy screening test that can be rapidly performed in an onsite laboratory to evaluate the potential performance of soil washing as an alterative technology. Such studies should be designated to maximize the chances of success at the remedy screening level. The object of this guidance document is not to specify a particular remedy screening method but rather to highlight those critical parameters which should be evaluated during the laboratory test.

Contaminant characteristics to examine during remedy screening include solubility, miscibility, and dispersibility. Properties of organic contaminants are generally easier to evaluate than those of inorganic contaminants. Inorganics, such as heavy metals, can exist in many compounds (e.g., oxides, hydroxides, nitrates, phosphates, chlorides, sulfates, and other more complex mineralized forms), which can greatly alter their solubilities. Metal analysis typically provide only total metal concentrations. More detailed analyses to determine chemical speciation may be warranted.

The liquid used in the jar test is typically water, or water with additives which might enhance the effectiveness of the soil washing process. To save time and money, chemical analyses should not be performed on the samples until there is visual evidence that physical separation has taken place in the jar tests. Jar tests can yield three separation fractions from the original soil sample. These include a floating layer, a wastewater with dispersed solids, and a solid fraction. Chemical analysis can be performed on each fraction.

When performing the jar test, observe if any floating materials can be skimmed off the top. Observe whether an immiscible, oily layer forms, either at the top or the bottom, indicating release of an insoluble organic material. Observe and time the solids settling rate and depth. Sand and gravel settle first, followed by the silt and clay. The rate and the relative volume of the settling material will provide some indication of the particle size distribution in the waste matrix and the potential for soil washing as a treatment alternative. Further evidence can be gained by analyzing the settled and filtered wash water for selected indicator contaminants of concern. If simple washing releases a large percentage of these contaminants into the wash water, then soil washing can be viewed favorably and more detailed laboratory and bench tests must be conducted.

Variations on the jar tests can include the addition of surfactants, chelants, or other dispersant agents to the water; sequential washing; heated water washing versus cold water; acidic or basic wash water; and tests that include both a wash and a rinse step. The rinse water and fine soil fraction (<2 mm particle size) should be separate from the coarse soil fraction (>2 mm particle size) using a #10 sieve. No attempt should be made during jar tests to separate the soil into discrete size fractions; this is done at the bench-scale tier of testing. Normally, only the coarse soil fraction should be analyzed for contamination. In general, at least a 50 percent reduction in total contaminant concentration in the >2 mm soil fraction is considered adequate to proceed to the remedy selection tier. The separation of approximately 50 percent of the total soil volume as clean soil also indicates remedy selection studies may be warranted.

To reduce analytical costs during the remedy screening tier, a condensed list of known contaminants must be selected as indicators of performance. The selection of indicator analytes to track during jar testing should be based on the following guidelines:

- Select one or two contaminants present in the soil that are most toxic or most prevalent.
- Select indicator compounds to represent other chemical groups if they are present in the soil (i.e., volatile and semivolatile organics, chlorinated and nonchlorinated species, etc.)
- If polychlorinated biphenyls (PCBs) and dioxins are known to be present, select PCBs as indicators in the jar tests and analyze for them in the washed soil. It is usually not cost-effective to analyze for dioxins and other highly insoluble chemicals in the wash water generated from jar tests. Check for them later in the wash water from remedy selection tests.

Remedy selection tests require that electricity, water, and additional equipment are available. The tests are run under more controlled conditions than the jar tests. The response of the soil sample to variable washing conditions is fully characterized. More precision is used in weighing, mixing, and particle size separation. There is an associated increase in QA/QC costs. Treated soil particles are separated during the sieve operations to determine contaminant partitioning with particle size. Chemical analyses are performed on the sieved soil particles as well as on the spent wash waters. The impact of process variables on washing effectiveness is quantified. This series of tests is considerably more costly than jar tests, so only samples showing promise in the remedy screening phase (jar test) should be carried forward into the remedy selection tier. If sufficient data are available in the prescreening step, the remedy screening step may be skipped. Soil samples showing promise in the prescreening step are carried forward to the remedy selection tier.

A series of tests should be designed that will provide information on washing and rinsing conditions best suited to the soil matrix under study. The RREL data base should be searched for information from previous studies. To establish percent of contaminant removal, particle size separation, and distribution of contaminants in the washed soil, the following should first be studied: 1) wash time, 2) wash water-to-soil ratio, and 3) rinse water-to-wash water ratio. Following those studies, the effect of wash water additives on performance should be evaluated.

Several factors must be considered in the design of soil washing treatability studies. A remedy selection design test should be geared to the type of system expected to be used in the field. Soil-to-wash water ratios should be planned using the results from the jar tests, if jar tests were performed. In general, a ratio of 1 part of soil to 3 parts of wash water will be sufficient to perform remedy selection tests. The soil and wash water should be mixed on a shaker table for a minimum of 10 minutes and a maximum of 30 minutes. The soil-to-wash water ratio and mix times presented here are rules of thumb to be used if no other information is available.

Another factor to consider is the variability of the grain size distribution. Gilsen Wet Sieve devices are recommended for remedy selection studies. Ro-Tap or similar sieve systems may also be used. Such devices will enhance the completeness and reproducibility of grain size separation. However, they are messy, expensive, and very noisy when in operation. An alternative choice is to complete a series of four to six replicate runs under exactly the same set of conditions to obtain information on the variability of the grain size separation technique. Variability in the separation technique can be evaluated by comparing sieve screen weights across runs and soil contaminant data for the same fractions from each run. By identifying the range of variability associated with repeated runs at the same conditions, estimates can be made of the variability that is likely to be associated with other test runs under slightly different conditions.

Normally, only the wash water and the soil particles captured by the sieve screen need to be analyzed for contaminants. Experience has shown that little additional contaminant removal is likely to be found in the rinse water. Rinsing is important and must be included in the procedure since it improves the efficiency of the grain size separation/sieving process. Rinsing separates the fine from the coarse material. This can result in a cleaner coarse fraction and more contaminant concentrated in the fine fraction. Contaminant concentration in the rinse water may be determined periodically (e.g., 10 percent of the samples) to evaluate the performance of the wash solution. However, very little contamination is typically dissolved in the rinse solution. Therefore, analyses of the rinse solution may have limited value in verifying wash solution performance.

Initially, only the coarse soil fraction and the wash water should be analyzed for indicator contaminants. If the removal of the indicator contaminants confirms that the technology has the potential to meet cleanup standards at the site, additional analyses should be performed. All three soil fractions and all wash and rinse waters must be analyzed for all contaminants to perform a complete mass balance. The holding time of soil fractions in the lab before extraction and analysis can be an important consideration for some contaminants.

The decision on whether to perform remedy selection testing on hot spots or composite soil samples is difficult and must be made on a site-by-site basis. Hot spot areas should be factored into the test plan if they represent a significant portion of the waste site. However, it is more practical to test the specific waste matrix that will be fed to the full-scale system over the bulk of its operating life. If the character of the soil changes radically (e.g., from clay to sand) over the depth of contamination, then tests should be designed to separately study system performance on each soil type.

Additives such as oil and grease dispersants and chelating agents can aid in removing contaminants from some soils. However, they can also cause processing problems downstream from the washing step. Therefore, use of such additives should be approached with caution. Use of one or a combination of those additives is a site-by-site determination. Some soils do not respond well to additives. Surfactants and chelating agents may form suspensions and foams with soil particles during washing. This can clog the sieves and lead to inefficient particle size separation during screening. The result can be the recovery of soil fractions with higher contamination than those cleaned by water alone. Such results can make the data impossible to understand. Additives can also complicate the rinse water process that might follow the soil washing. Recent studies have shown that counter-current washing-rinsing systems, incorporating the use of hot water for the initial wash step, offer the best performance in terms of particle size separation, contaminant removal, and wastewater management (treatment, recycling and discharge).

SAMPLING AND ANALYSIS PLAN

The Sampling and Analysis Plan (SAP) consists of two parts - the Field Sampling Plan (FSP) and the Quality Assurance Project Plan (QAPjP). A SAP is required for all field activities conducted during the RI/FS. The purpose of the SAP is to ensure that samples obtained for characterization and testing are representative and that the quality of the analytical data generated is known. The SAP addresses field sampling, waste characterization, and sampling and analysis of the treated wastes and residuals from the testing apparatus or treatment unit. The SAP is usually prepared after Work Plan approval.

Field Sampling Plan

The FSP component of the SAP describes the sampling objectives; the type, location, and number of samples to be collected; the sample numbering system; the necessary equipment and procedures for collecting the samples; the sample chain-of-custody procedures; and the required packaging, labeling, and shipping procedures.

Field samples are taken to provide baseline contaminant concentrations and material for the treatability studies. The sampling objectives must be consistent with the treatability test objectives. Because the primary objective of remedy screening studies is to provide a first-cut-evaluation of the extent to which specific chemicals are removed from the soil or concentrated in a fraction of the soil by soil washing, the primary sampling objectives should include, in general:

- Acquisition of samples representative of conditions typical of the entire site or defined areas within the site. Because this is a first-cut evaluation, elaborate statistically designed field sampling plans may not be required. Professional judgment regarding the sampling locations should be exercised to select sampling sites that are typical of the area (pit, lagoon, etc.) or appear above the average concentration of contaminants in the area being considered for the treatability test. This may be difficult because reliable site characterization data may not be available early in the remedial investigation.

- Acquisition of sufficient sample volumes necessary for testing, analysis, and quality assurance and quality control.

The sampling plan for remedy selection will be similar. However, because a mass balance is required for this evaluation, a statistically designed field sampling plan will be required.

Quality Assurance Project Plan

The Quality Assurance Project Plan should be consistent with the overall objectives of the treatability study. At the remedy screening level the QAPjP should not be overly detailed.

The purpose of the remedy selection treatability study is to determine whether soil washing can meet cleanup goals and provide information to support the detailed analysis of alternatives (i.e., seven of the nine evaluation criteria). An example of a criterion for this determination is removal of approximately 90 percent of contaminants. The exact removal efficiency specified as the goal for the remedy selection test is site-specific. The suggested QC approach will consist of:

- Triplicate samples of both reactor and controls
- The analysis of surrogate spike compounds in each sample
- The extraction and analysis of a method blank with each set of samples
- The analysis of a matrix spike in approximately 10 percent of the samples.

The analysis of triplicate samples provides for the overall precision measurements that are necessary to determine whether the difference is significant at the chosen confidence level. The analysis of the surrogate spike will determine if the analytical method performance is consistent (relatively accurate). The method blank will show if laboratory contamination has had an impact on the analytical results.

Selection of appropriate surrogate compounds will depend on the target compounds identified in the soil and the analytical methods selected for the analysis.

TREATABILITY DATA INTERPRETATION

The information and results gathered from the remedy screening are used to determine if soil washing is a viable treatment option and to determine if additional remedy selection and remedy design studies are warranted. A reduction of approximately 50 percent of the soil contaminants during the test indicates additional treatability studies are warranted. Contaminant concentrations can also be determined for washing water and fine soil fractions. These additional analyses add to the cost of the treatability test and may not be needed. Before and after concentrations can normally be based on duplicate samples at each period. The mean values are compared to assess the success of the study. If the remedy screening indicates that soil washing is a potential cleanup option then remedy selection studies should be performed.

In remedy selection treatability studies, soil contaminant concentrations before soil washing and contaminant concentrations in the coarse fraction after soil washing are typically measured in triplicate. A reduction of approximately 90 percent in the mean concentration indicates soil washing is potentially useful in site remediation. A number of other factors must be evaluated before deciding to proceed to remedy design studies.

The final concentration of contaminants in the recovered (clean) soil fraction, in the fine soil fraction and wastewater treatment sludge, and in the wash water are important to evaluating the feasibility of soil washing. The selection of technologies to treat the fine soil and wash water wastestreams depends upon the types and concentrations of contaminants present. The amount of volume reduction achieved is also important to the selection of soil washing as a potential remediation technology.

TECHNICAL ASSISTANCE

Literature information and consultation with experts are critical factors in determining the need for and ensuring the usefulness of treatability studies. A reference list of sources on treatability studies is provided in the "Guide for Conducting Treatability Studies Under CERCLA" (EPA/540/2-89-058).

It is recommended that a Technical Advisory Committee (TAC) be used. This committee includes experts on the technology who provide technical support from the scoping phase of the treatability study through data evaluation. Members of the TAC may include representatives from EPA (Region and/or ORD), other Federal Agencies, States, and consulting firms.

OSWER/ORD operate the Technical Support Project (TSP) which provides assistance in the planning, performance, and/or review of treatability studies. For further information on treatability study support or the TSP, please contact:

Groundwater Fate and Transport Technical Support Center
Robert S. Kerr Environmental Research Laboratory
(RSKERL), Ada, OK
Contact: Don Draper
FTS 743-2200 or (405) 332-8800

Engineering Technical Support Center
Risk Reduction Engineering Laboratory (RREL),
Cincinnati, OH
Contact: Ben Blaney
FTS 684-7406 or (513) 569-7406

FOR FURTHER INFORMATION

In addition to the contacts identified above, the appropriate Regional Coordinator for each Region located in the Hazardous Site Control Division/Office of Emergency and Remedial Response or the CERCLA Enforcement Division/ Office of Waste Programs Enforcement should be contacted for additional information or assistance.

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