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INNOVATIVE SITE REMEDIATION TECHNOLOGY

DESIGN & APPLICATION

Volume 3

Liquid Extraction Technologies

Prepared by the American Academy of Environmental Engineers under a cooperative agreement with the U.S. Environmental Protection Agency

INNOVATIVE SITE REMEDIATION TECHNOLOGY: DESIGN AND APPLICATION

LIQUID EXTRACTION TECHNOLOGIES

Soil Washing
Soil Flushing
Solvent/Chemical

One of a Seven-Volume Series

Prepared by WASTECH®, a multiorganization cooperative project managed by the American Academy of Environmental Engineers® with grant assistance from the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the U.S. Department of Energy.

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This monograph was prepared under the supervision of the WASTECH® Steering Committee. The manuscript for the monograph was written by a task group of experts in chemical treatment and was, in turn, subjected to two peer reviews. One review was conducted under the auspices of the Steering Committee and the second by professional and technical organizations having substantial interest in the subject.

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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.

Qualified reviewers were recruited from the Waste Group of the Technical Council. It was determined that the monograph is technically sound and publication is endorsed.

American Society of Civil Engineers

The American Society of Civil Engineers, established in 1852, is the premier civil engineering association in the world with 124,000 members. Qualified reviewers were recruited from its Environmental Engineering Division.

ASCE has reviewed this manual and believes that significant information of value is provided. Many of the issues addressed, and the resulting conclusions, have been evaluated based on satisfying current regulatory requirements. However, the long-term stability of solidified soils containing high levels of organics, and potential limitations and deficiencies of current testing methods, must be evaluated in more detail as these technologies are implemented and monitored.

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Hazardous Waste Action Coalition

The Hazardous Waste Action Coalition (HWAC) is the premier business trade group serving and representing the leading engineering and science firms in the environmental management and remediation industry. HWAC's mission is to serve and promote the interests of engineering and science firms practicing in multi-media environment management and remediation. Qualified reviewers were recruited from HWAC's Technical Practices Committee. HWAC is pleased to endorse the monograph as technically sound.

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Soil Science Society of America

The Soil Science Society of America, headquartered in Madison, Wisconsin, is home to more than 5,300 professionals dedicated to the advancement of soil science. Established in 1936, SSSA has members in more than 100 countries. The Society is composed of eleven divisions, covering subjects from the basic sciences of physics and chemistry through soils in relation to crop production, environmental quality, ecosystem sustainability, waste management and recycling, bioremediation, and wise land use.

Members of SSSA have reviewed the monograph and have determined that it is acceptable for publication.

Water Environment Federation

The Water Environment Federation is a nonprofit, educational organization composed of member and affiliated associations throughout the world. Since 1928, the Federation has represented water quality specialists including engineers, scientists, government officials, industrial and municipal treatment plant operators, chemists, students, academic and equipment manufacturers, and distributors.

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INTRODUCTION

This monograph covering the *design, applications, and implementation* of Liquid Extraction Processes — Soil Washing, Soil Flushing, and Solvent/ Chemical, is one of a series of seven on innovative site and waste remediation technologies. This series was preceded by eight volumes published in 1994 and 1995 covering the description, evaluation, and limitations of the processes. The entire project is the culmination of a multi-organization effort involving more than 100 experts. It provides the experienced, practicing professional with guidance on the innovative processes considered ready for full-scale application. Other monographs in this design and application series and the companion series address bioremediation; chemical treatment; stabilization/solidification; thermal desorption; thermal destruction; and vapor extraction and air sparging.

1.1 Liquid Extraction Technologies

1.1.1 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.

1.1.2 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, water with chemical additives, 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 also effective 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 thorough 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 often amenable to soil flushing.

1.1.3 Solvent/Chemical Extraction

Solvent/chemical extraction (SCE) is an ex-situ separation and concentration process in which a nonaqueous liquid reagent is used to remove organic and/or inorganic contaminants from wastes, soils, sediments, sludges, or water. The process is based on well-documented chemical equilibrium separation techniques used in many industries, such as oil extraction from soy beans, supercritical decaffeination of coffee, and separation of copper from leaching fluids.

Solvent/chemical extraction can be differentiated from soil washing in that soil washing involves the use of dilute aqueous solutions of detergents or chelating agents to remove contaminants through dissolution, abrasion, and/or physical separation, whereas SCE relies on the action of concentrated chemical agents.

Solvent/chemical extraction typically produces a treated fraction and a concentrated contaminated fraction, which requires further treatment to recover, destroy, or immobilize the contaminants. It may concentrate contaminants by a factor as high as 10,000:1 (although a concentration between 50:1 is much more common), thereby, significantly reducing the volume of material requiring further treatment or producing a concentrated stream for materials recovery.

1.2 Development of the Monograph

1.2.1 Background

Acting upon its commitment to develop innovative treatment technologies for the remediation of hazardous waste sites and contaminated soils and groundwater, the U.S. Environmental Protection Agency (US 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, multi-disciplinary 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, providing for the Academy to manage a project 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 multi-organization 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, the Soil Science Society of America, and the Water Environment Federation, together with the Academy, US 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 initial monographs began in earnest in January, 1992, and the original eight monographs were published during the period of November, 1993, through April, 1995. In Spring of 1995, based upon the reception by the industry and others of the original monographs, it was determined that a companion set, emphasizing the design and application of the technologies, should be prepared as well. Task Groups were identified during the latter months of 1995 and work commenced on this second series.

1.2.2 Process

For each of the series, 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. The Steering Committee then appointed a task group composed of 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.

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 US 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 members of the Committee supplemented by 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.

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.

1.3 Purpose

The purpose of this monograph is to further the use of innovative soil washing, soil flushing, and solvent/chemical extraction 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 these technologies.

1.4 Objectives

The monograph's principal objective is to furnish guidance for experienced, practicing professionals, and users' project managers. This monograph, and its companion monographs, are 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.

1.5 Scope

The monograph addresses innovative liquid extraction technologies 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 Liquid Extraction Task Group to briefly review the technologies and discuss their design and applications. Actual case histories were reviewed and included as appropriate.

The monograph's primary focus is site remediation and waste treatment. To the extent the information provided can also be applied elsewhere, it will provide the profession and users this additional benefit.

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 that they are essential to understand the applications and limitations of the technologies described:

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

1.6 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, post-publication 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.

1.7 Organization

This monograph and others in the series are organized under similar outlines intended to facilitate cross reference among them and comparison of the technologies addressed.

SOIL WASHING

2

APPLICATION CONCEPTS

2.1 Scientific Principles

2.1.1 Background on the Development of Soil Washing

Dutch Experience. Soil washing seems to have started as an environmental remediation technology in The Netherlands around 1982 or 1983. The Netherlands has experienced significant economic and industrial development over the past 300 years, resulting in contamination at about 10,000 Superfund-equivalent sites. Yet, The Netherlands has a land area of only about 38,850 km^2 (15,000 mi^2)(about the size of Florida) and is the most densely populated country in Europe. Because of the scarcity of land, the treatment of contaminated soils to avoid land disposal is very important. Soil management in The Netherlands has been a central factor in the successful development of the country.

Remedial response at some of the first high-profile sites was undertaken by a consortia of contractors and environmental companies. Nearly all remediation activity in The Netherlands is controlled and paid for by the government. The consortia interfaced directly with the responsible government entities to begin work on treating soil to make significant volume reductions in contaminated material and reuse "clean" products that met specified treatment standards. At about the same time these efforts got underway, the Dutch government published treatment standards that could be applied to any soil cleanup in The Netherlands. These standards, now modified several times, have come to be known as the Dutch A/B/C levels. The standards, which are based on a risk assessment of approximately 50 common organic and inorganic elements and compounds, define what are known as action-level concentrations ("C" level), limited reuse concentrations ("B" level), and unrestricted reuse concentrations ("A" level). Implementation of this system made it possible for technology developers and contractors to develop, test, and invest in treatment units that could meet the targeted treatment levels. The "B" level of treatment quickly became a primary performance level since the "clean" products, typically an aggregate and a sand, could be reused in a limited manner after confirming that the appropriate concentrations had been attained for the target contaminants. The limited product reuse is generally as a construction-grade material for use as a roadway sub-base, as clean backfill in construction projects, or as material incorporated into concrete and asphalt products.

Early soil washing projects in The Netherlands were not spectacular successes. The first project was undertaken at a subsite of the famous "Dutch Love Canal" at Lekkerkirke, near The Hague. The soil was contaminated with several contaminants including arsenic, cyanide, a wide range of carcinogenic polynuclear aromatic compounds (PNAs), and pesticides. Not only were the contaminants difficult to treat, the concept of soil washing had not been tested. The general concept initially was that the soil would be prescreened to remove only the heaviest oversize material and then treated with acids and surfactants to solubize the target contaminants and remove them as a high-concentration wastewater. It was expected that this approach would leave behind a clean soil and allow further treatment of the wastewater by traditional methods. It did not work that way. Although some of the top companies were involved in this development, the project was a soil washing treatment failure. Most of the material was eventually incinerated or landfilled.

The breakthrough in the development of soil washing in The Netherlands came with a simple "paradigm shift." During early development of the technology, the central view had been that the treatment should focus on the contaminant(s). It was assumed that if the contaminant was understood, a method of dissolving, removing, or destroying it could be identified. The important shift took place when it was discovered that the initial focus should be on the soil. If the soil and its representative fractions could be better understood, then treatment for the removal or destruction of the contaminants could be effected. This shift in thinking led to the recognition that soil washing could draw upon the proven experiences of the mining industry. It also led to the development of a remedial technology that today represents the central treatment approach in The Netherlands and Germany.

Current soil washing systems are based upon innovative uses of proven mining equipment and processes. Soil washing is similar to mining in that mining projects treat large volumes of ore to recover small amounts of product relative to the feed. The valuable product is recovered, and the waste ores, or tailings, are disposed. Soil washing is "reverse mining" in that large amounts of feed soil are processed to generate a large volume of clean tailings that can be reused or replaced on-site as backfill. The concentrates are the contaminants that are removed and disposed.

2.1.2 Fundamental Concepts

Soil washing is an ex-situ, physical/chemical separation technology using both particle separation and extraction processes to reduce contaminant concentrations. Water is the primary extracting medium. In the soil washing process, a large fraction of the feed soil is treated to specified levels while the contaminants are concentrated in the wash water or in a smaller fraction of the feed soil. The concentrate, in either the water or soil, is then further treated or disposed. The clean soil can be returned to the site of origin as clean backfill without the need for long-term controls or monitoring.

Soil washing consists of prescreening of the excavated soil to remove debris, treatment of the bulk soil, management of clean product, and the further treatment or disposal of a much smaller volume of concentrate. There are many potential arrangements for treatment unit operations, some of which will be discussed in this chapter. It is important to understand that the treatment steps used in soil washing are not always the same. They are often modified based on the soil and contaminants to be treated. Soil washing systems can draw on more than 20 possible unit operations. These may be used in different configurations from site to site and from contractor to contractor. Soil washing also interfaces easily with other technologies such as extraction, thermal destruction, biological treatment, or stabilization, in configurations known as "treatment trains."

2.1.2.1 Concentration of Contaminants in the Fines

Soil is often composed of gravel, sand, and "fines", which are technically defined as soil particles with an average size of less than 0.063 mm. There is a general view that contaminants in soil are always concentrated in the fines, and that this must be true for soil washing to be applicable. This view is not always correct. The USDA system of soil classification (Agricultural Handbook No. 436 — Soil Taxonomy) defines clay (<0.002 mm), silt (0.002-0.050 mm), sand (0.050-2 mm), and gravel (2 mm-3 in.).

Contaminants that have come in contact with soils as a result of spills, accidents, or long-term releases will generally accumulate on the fines because of the very large surface area and complex electrical and chemical charges present in this fraction. The fines fraction has a surface area 10,000 times greater than the other soil fractions combined. However, this rule of thumb does not mean that other soil fractions may not be contaminated at levels that exceed the treatment standards. Each fraction (the gravel, sand, and fines) must be analyzed to determine where and how the contaminants reside in the various portions of the soil matrix.

If contaminants in all soil fractions exceed the treatment standard, this does not eliminate soil washing as an option. It simply means that the treatment must address each fraction. The soil matrix/contaminant approach allows the engineer/contractor to identify unit operations that may be applied to the specific treatment problems posed by each fraction. If the oversize fraction (gravel) is contaminated, mechanical screening or density separation may be appropriate. The screened soil is then prepared for treatment by separating the sand stream and the fines stream. The sand can then be treated using attritioning, floatation, or density techniques. The fines can be consolidated, treated, or disposed.

Soil washing unit operations, like those in mining, have an optimum particle-size range in which they perform best. The challenge to the engineer in treating contaminated soil is to match the optimum treatment unit operation to the appropriate contaminated soil fraction.

2.1.2.2 Volume-Reduction Potential

Soil washing has an excellent ability to reduce the amount of soil that must be treated or disposed in a remediation project. The goal of soil washing, as applied in an on-site situation, is to separate and treat portions of the feed soil so that it meets treatment standards and can be placed back on the site as "clean" soil without monitoring, capping, or other long-term controls. Soil washing may also be implemented in a fixed-site mode, in which clean soils are utilized as construction materials not backfilled on the remediated site. The "volume reduction," expressed as a percentage, is defined as the mass of soil (in tons) returned to the site, divided by the mass of feed soil processed in the soil washing treatment unit. The amount of soil or debris removed in the prescreening step is normally excluded from this calculation.

The following example is based on a site where 27,216 tonne (30,000 ton) of material is excavated. The excavated material is screened through several steps to remove debris, cobbles, construction waste, and other similar objects. The average particle size of soil fed to a soil washing plant is less than 2 in. In this example, 4,536 tonne (5,000 ton) are removed through the prescreening step, leaving 22,680 tonne (25,000 ton) as feed to the treatment plant. As a result of treatment, 18,144 tonne (20,000 ton) are returned to the site after confirmation that the treatment standards have been achieved. The volume reduction is 18,144tonne/22,680 tonne (20,000 ton/25,000 ton) = 80%.

There is a common misconception that soil washing is not viable unless the entire feed soil is rendered clean. It is important to recognize, however, that if volume-reduction measures can be performed at a cost much lower than the final remedy, soil washing as a volume-reduction step makes sense.

A good example of this situation can be illustrated by a site where the fines mass constitutes 50% of the total feed soil (a relatively high level), and the contaminants of concern require incineration. Closer investigation reveals that the contaminants are concentrated in the fines, and that mechanical screening and separation could achieve a 40% volume reduction for $110/tonne ($100/ton), compared to a cost of $1,099/tonne ($1,000/ton) for incineration. Clearly, soil washing as a volume-reduction tool makes sense in this situation.

2.1.2.3 Treatment or Disposal of Concentrates

Serious difficulty arises when any technology is expected to treat 100% of the feed soils to levels attaining all of the treatment standards. The development of remediation approaches unfortunately supports this misconception. Landfilling has developed because it is based on a very simple proposition. If waste is analyzed and shown to meet the waste-acceptance criteria, the waste can be disposed in the landfill. Incineration can make the promise that if the waste meets the feed criteria, incineration can destroy 99.9999% of the hazardous organic constituents. If heavy metals are also contained in the incinerator feed soil, incineration is no longer an option. This “either-or” thinking does not allow the use of more cost-effective approaches that require multiple-step planning and treatment.

Soil washing can be viewed most accurately as a soil pretreatment, often rendering significant volume reductions, but also producing a small mass of soil with contaminant concentrations ranging from 3 to 10 times the bulk soil concentration. The soil concentrates must be evaluated to determine whether further treatment is feasible and cost-effective. The concentrated contaminants are after in the fines, the most difficult fraction to treat. State-of-the-art techniques often cannot fully treat this concentrated contaminant mass, or, if they can, the cost may be prohibitive. The cheapest method in many instances is to consolidate the fines and dewater the soil concentrate into a sludge cake that can be disposed at an appropriate on-site, off-site hazardous or nonhazardous waste landfill. Of course, the waste must be "profiled," must meet the land disposal unit's waste-acceptance criteria, and must not trigger any of the land disposal bans. Even with this approach, disposal of the sludge cake will often be the highest individual component of the overall cost of a soil washing remedy. Thus, it makes good sense to determine what, if any, treatment can be applied to reduce the volume of concentrated soil that must be disposed.

The remaining concentrated soil can then be evaluated based upon the specific contaminants of concern and available, applicable technologies. The most common options are direct land disposal of the sludge cake, acid extraction of heavy metals, bioslurry degradation of organics, and stabilization of concentrated soil that contains metals and organics.

2.1.2.4 Complications

There are some potential complications that should be assessed when evaluating the use of soil washing for a particular project. Some of the most common concerns are presented below:

- *The Fines Fraction Seems Too Large.* Conventional wisdom is that soil with greater than 30% fines (less than 0.063 mm) is not a viable candidate for soil washing. This is not necessarily so. A full evaluation and fair comparison of applicable technologies should include the methods for handling various factions, the treatment method proposed for the fines concentrate, and the cost-effectiveness comparison to other available alternatives.

- *Fines are Difficult to Treat.* Treating the fines is the most difficult treatment challenge in soils remediation. Contaminants in this fraction are often bound into the lattice structure of the fines, tightly held by chemical and electrical forces, and oxidized to even more stable conditions. The ability to remove these contaminants must be confirmed in a rigorous treatability study. More important, reviewing the laboratory findings must take into account problems that may occur when operations are scaled up. Nevertheless, difficulties in treating the fines should be viewed as another step toward a complete solution, and, one that, although difficult, should not negate the value of the volume-reduction potential.
- *Other Fractions are Also Contaminated.* Frequently, it is found that contaminants in the sand and/or the oversize fraction also exceed the required treatment standards. This does not mean soil washing will not work. The nature and mode of contamination in these other fractions must also be evaluated so that a treatment process plan can be defined.
- *Whole Soils Make Treatment Very Difficult.* Systems that attempt to take the whole feed soil into a specific treatment unit are often bound for failure. Mining and mineral processing engineers learned long ago that treatment, removal, and concentrating processes work best within a rather narrow range of particle sizes. The challenge is to prepare the feed stream to provide the optimized particle-size range each treatment operation.

2.1.3 Soil Characterization

An important step in soil washing is the initial characterization of the site and the soil to be treated. This does not mean that more time should be spent on the remedial investigation (RI), nor does it mean that hundreds more samples are required. In fact, most RI reports do not present the information required for soil washing or other treatment technologies. Only limited information is needed, but it must be collected and evaluated with treatment in mind.

2.1.3.1 Background Understanding of How a Site was Contaminated

It is important to understand how the site was contaminated. This information can usually be determined from existing records, reports, and contact with site personnel. This knowledge will assist the process engineer in speculating as to the form of the contaminant on the affected soils. One example is a steel mill that has soil contaminated with heavy metals. It is likely that mill tailings and slag were disposed on the grounds, leading to a first estimate that the soil contains free slag and particulate metals. At an electroplating shop, heavy metals in the soil might be expected to include metal hydroxide sludges because of the operations conducted there. The metals could be bound in a lime precipitated mass. The difference in the treatment approach is very significant. Spills of mobile liquids on the ground around the plant can be expected to form a possible coating on the sand and eventually become bound up in the fines. Understanding the basics of the plant's operation or how wastes were disposed in the affected area can be very helpful in the first conceptualization of the problem.

2.1.3.2 Sample Collection and Evaluation

The soil washing process engineer should make use of existing data and information to the maximum extent possible. The nature and extent of the contamination at a site is usually well documented. Information that is often missing includes the bulk location, the heterogeneity of the waste, the layering or pocketing of hot spots, and a physical view of how the waste is distributed in the soil.

The soil washing process engineer can find out about previous site characterization efforts from the client or the consulting engineer. With that information, conclusions can be drawn regarding the distribution of wastes within the soils at the site. The site may be one large area with relatively similar situations throughout, or there may be several subsites where the wastes or the soil types are very different. Based upon this assessment, specific locations can be identified where "representative" samples may be collected.

Most RIs have been performed using borings as the method of choice to collect soil samples. While this is useful for many applications, it is not useful for technology process evaluations. Borings can give misleading indications regarding the soil and the manner in which the contaminants are disposed within the soil. If the auger hits rocks or cobbles, refusal can result in missing hotspots that lie only slightly deeper. Visual indications of the actual waste distribution are almost totally lost. For these reasons, it is recommended that test pits be used instead of borings. Test pits are open excavations usually installed to depths of 0.61 to 3.05 m (2 to 10 ft). The removed material is usually staged near the excavation site while observations are made and soil is collected. The test pit provides a very good visual picture of the subsurface conditions while offering flexibility in choosing soil to be taken as sample material. Appropriate safety practices must be followed if persons enter pits over 1.5 m (5 ft) deep. The test pits can be sized as required to obtain a good view of the actual remediation situation. Sample material is collected and packaged in containers for shipment to the designated laboratory. Treatability study materials are exempt from permitting requirements for quantities up to 10,000 kg (22,046 lb).

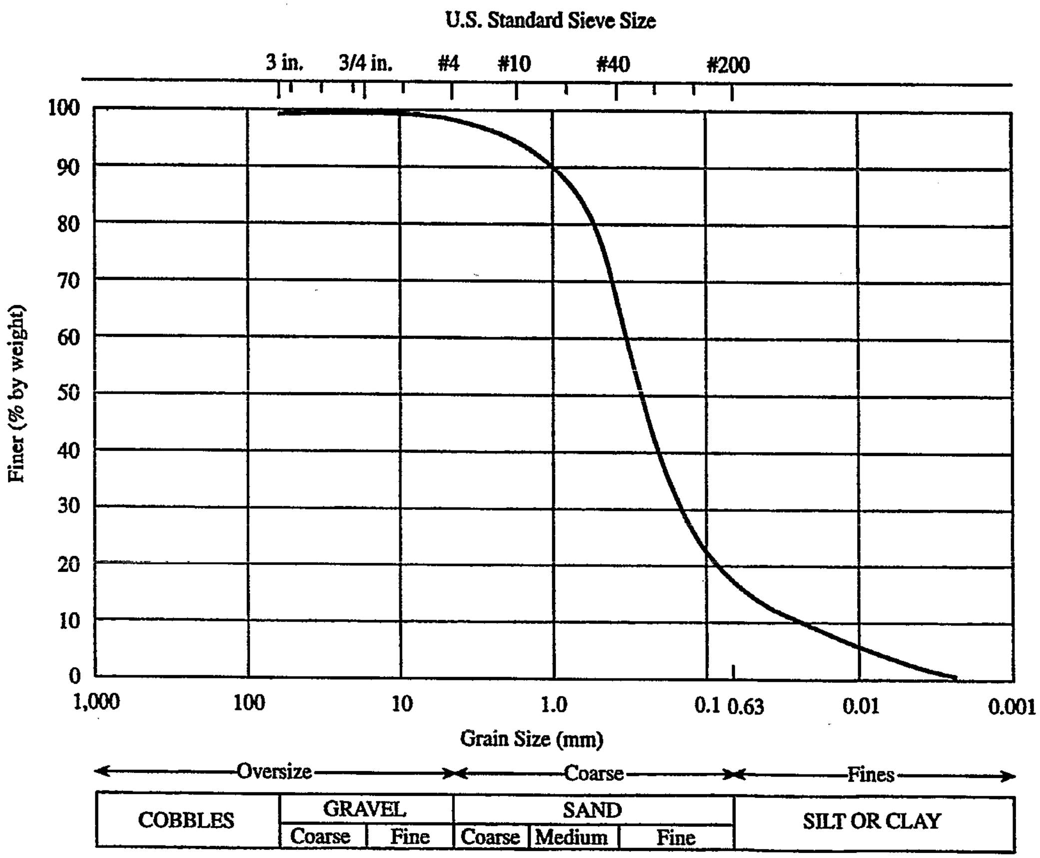
2.1.3.3 Particle-Size Distribution by ASTM Method D422

The first step in the sample evaluation is to perform a particle distribution analysis. This is done by conducting a sieving study in accordance with American Society for Testing and Materials (ASTM) Method D422 (ASTM 1963). The sieving is performed on wet material, and the water from the sieving process is retained for analysis. Generally, 8 to 11 sieves are used, ranging in size from 2 mm to 0.075 mm (200 mesh) on the bottom. After sieving, the materials retained on each sieve are dried and weighed. The data are plotted on a standard particle-size form. Results of a particle-size distribution analysis are reported on a 100% dry solids (ds) basis. Field-excavated soils are typically 80 to 85% dry solids; dewatered gravel is 95% ds; dewatered sand about 90% ds; and sludge cake 45 to 55% ds.

2.1.3.4 Chemical Analysis of Materials Retained on Sieves

To correlate the distribution of the contaminants of concern to the soil matrix, split samples of the materials retained on each sieve are forward to a chemical laboratory for analysis. The quality of data required at this stage will depend upon the ultimate use of the results. In most cases, Contract Laboratory Program (CLP) level analytical procedures are used, but extensive quality is not required. Based upon the US EPA's treatability study guidance documents (US EPA 1991), a Level III product is normally acceptable.

Figure 2.1
Particle-Size — Common Distribution



2.1.3.5 Important Conclusions that Need to be Drawn

The first evaluation of the initial data will focus on soil type. The most frequent inquiry can be answered by testing the percentage of soil mass in the fines fraction. As seen in Figure 2.1, the ASTM interface between the fine sand and the clays and silts is 0.063 mm (63 µm). All materials with an average particle size <63 µm are generically referred to as fines. Particles with an average size between 63 µm and 2 mm are referred to as coarse particles or sands. All particles >2 mm are referred to as oversize. The oversize fraction may contain a wide range of particle sizes. It often is useful to break out another working category of soil particle size. Since most treatments plants process soils with an average size of <2 in., material in the oversize fraction that is >2 mm but <2 in. is referred to as the "process oversize." All material >2 in. is generally referred to as the "gross oversize." However, these cut points are not fixed. Some sites may have a lot of construction debris, such as broken concrete rubble. In these cases, it may make sense to define another fraction as that containing material >8 in. (This is normally the largest size for a fixed-bar grizzly screen.) Other sites may require a lower cut point for defining the fines fraction. (Hydro-cyclones can make process separations as low as 20 microns.) While the individual cut points may vary, the important concept is that three or four fractions (fines, sand, oversize, and/or gross oversize) must be measured and predicted relative to their mass percentage contribution. The particle-size distribution analysis can determine how much material must be handled, separated, and treated in the process. As seen in Figure 2.1, the natural soil particle-size distribution curve will have a reversed-S shape, with 5 to 30% of the soil generally in the fines fraction. This is considered to be natural soil and a good candidate for soil washing. There is nothing fixed about the upper limit of the percentage of fines. The selection of a volume-reduction/treatment approach must be based upon the merits of the site and the other remedial options available. However, because sludges generally have a matrix of nearly 100% fines and there is no separation leverage, sludges are not normally considered good candidates for soil washing.

In addition to evaluating the soil matrix, it is necessary to assess the contaminants and their concentrations. The chemical analytical data that were derived from analysis of the materials retained on each of the sieves is plotted or overlaid on the particle-size distribution curve. Useful ways of doing this are shown in Figures 2.2 and 2.3. In Figure 2.2, the data are superimposed on the particle-size distribution curve, making it easy to identify which fractions exceed the treatment standards.

Figure 2.2
Isolate the Target Fractions

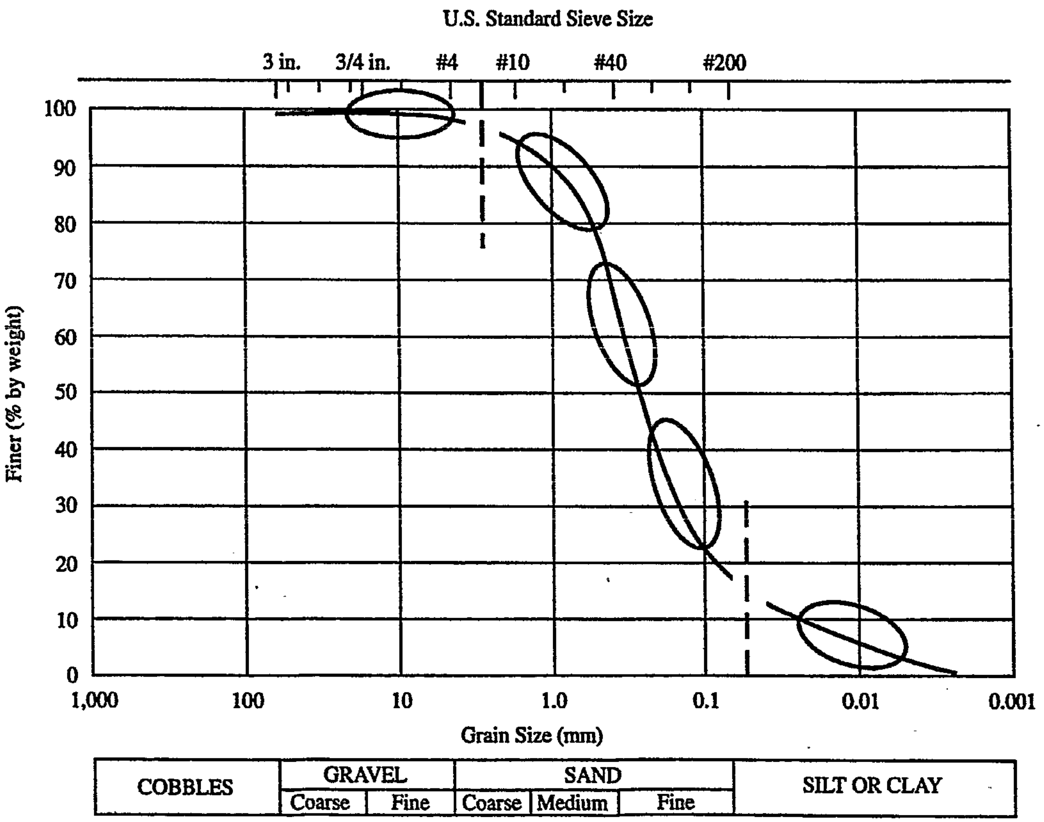
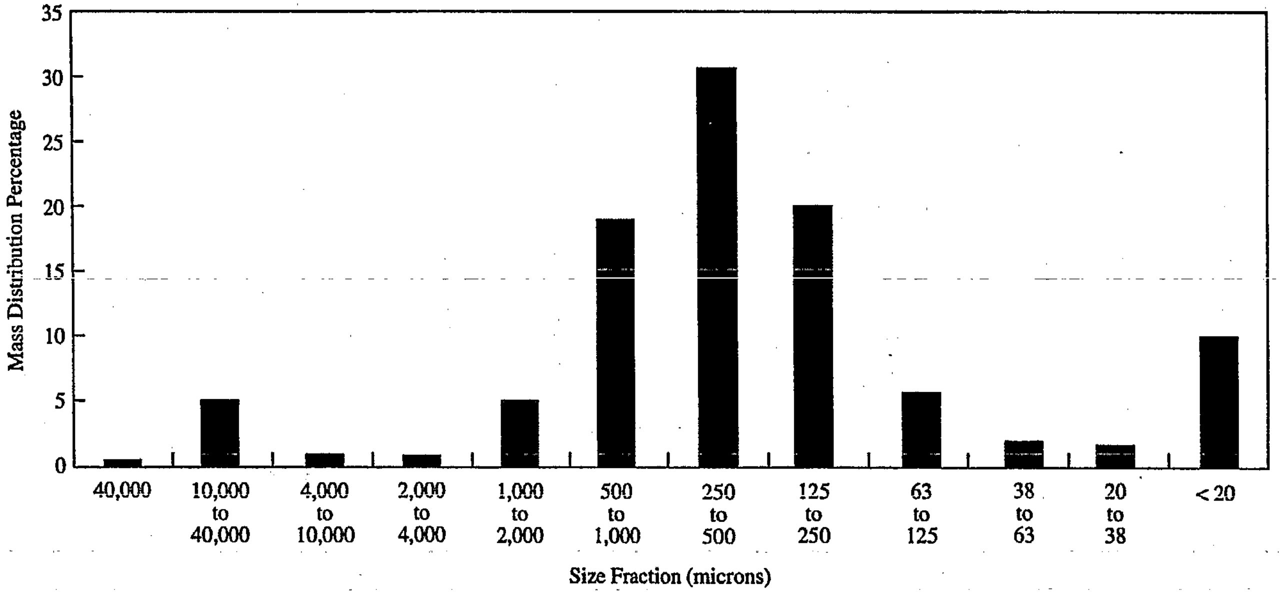


Figure 2.3
Particle-Size Distribution



2.1.4 Contaminant Occurrence

Once the concentrations of the contaminants of concern are quantified by soil fraction, additional investigation must be performed to determine the form, or modes, of contamination in each fraction.

2.1.4.1 Modes of Contamination

The mode of contamination refers to the form and species of the contaminant and how it is associated with the three key soil fractions, namely, the oversize, sands, and fines. The five primary modes of soil contamination are free contaminants, particulates, coatings, bound contaminants, and soluble material. Lead provides a simple example. Lead is a common contaminant that can exist in the five modes. In the following example, lead is the contaminant of concern at a small-arms firing range that is undergoing remediation. It is encountered in various modes in the fractions that are being prepared as the soil is screened to remove the gravel and separate the sands from the fines.

Free lead will be found in the oversize fraction as expended bullets and lead slag. The bullets are discrete, visually identifiable, and can be easily separated from the gravel fraction. The lead concentration in an individual piece of bullet or slag will be extremely high, but on a mass basis, probably does not represent a high percentage of the total soil mass. Mechanical screening techniques are likely to be appropriate for the removal of this type of free lead.

Particulate lead will be encountered within the sand fraction. Particulates are defined in this sense as discrete constituents ranging in size from 75 to 150 µm. Particulate matter in this fraction may exist in a free state commingled with the sand particles or lightly bound to the surface of a sand particle. This is a common situation encountered in mining applications. It will prompt the process engineer to consider attritioning, flotation, and gravity separation techniques. These unit operations will be discussed more fully later in this chapter.

Sand will also contain coatings of lead (sometimes referred to as "smears"). This occurs when a bullet fired into a sand berm thermally transfers and coats some of the sand particles encountered at the bullet's surface. The coating on the affected sand particles may be partial or complete. In either case, the coating significantly changes the relative density of the particle. Thus, the process engineer may consider using this density difference to separate the coated particles from the natural sands.

Bound contaminants refer to complexed species that are held by ionic, van der Waals, or other electrical charges in or on the lattice structure of the fines. The contaminants can exist in many species, such as oxides, carbonates, or sulfates. The speciation of the contaminants can be determined chemically and observed visually through the use of scanning electron microscopy (SEM). SEM, coupled with electron micro-probe quantitation can actually identify the contaminant and determine its concentration. Then, micrographs (photos) of the specific observations can be studied. The bound contaminants exist in the fines fraction and, as mentioned earlier, represent the most difficult treatment challenge. Treatment options for this fraction will be discussed later in this chapter. In the firing range example, bound lead will most commonly exist in the oxide form and tends to be removable by acid-extraction techniques.

The contaminants of concern also exist in soluble forms, but this is less of a concern for treatment than is commonly thought. In most cases, at the U.S. Department of Energy (DOE), the U.S. Department of Defense (DoD) sites and others being remediated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) or the Resource Conservation and Recovery Act (RCRA), the soils being remediated have been exposed to the environment in an uncontrolled situation for a long time. The soluble constituents have usually been mobilized by rainfall, entered into surface and groundwaters and been transported away from the soil remediation site. Some soluble contaminants have the ability to reabsorb or be converted, such as Cr^{3+} to Cr^{6+}. Contaminants of concern that remain at the site tend to be held in the soils in one of the modes discussed above. Nevertheless, the soluble form must also be evaluated by the process engineer. Soluble species that can commonly be of concern are volatile organic compounds and organic pesticides. Should the soluble component be of concern, sidestream wastewater treatment systems must be considered. In the firing range example, lead is not particularly soluble and will not tend to reconcentrate in recycle waters. The dredging of contaminated sediments can result in anaerobic sediments becoming aerobic, resulting in the oxidation and mobilization of metals.

2.1.4.2 Concentrations and Impacts

Raw soil concentrations of the contaminants of concern can be helpful in evaluating the suitability of this technology. Very high feed concentrations often mean that a very high mass of the contaminant can be removed, but that very low treatment standards may not be attainable. Very low feed concentrations may mean that low contaminant mass removal is possible, but that very low treatment standards may be attainable.

Soil washing projects will generally be controlled by treatment standards that are stated in the Record of Decision (ROD), legal administrative orders, or other legal requirements. The ability to meet the specified treatment standards for the fraction of the soil that is to be defined as "clean" will be the determining factor in the volume reduction that can be obtained, and thus, the relative success of the use of the technology. Therefore, the evaluation of the soils will be based first and foremost on the ability of the treatment arrangements to meet the treatment standards. In some cases, however, the treatment standards that have been calculated through risk assessment models are not practical or achievable in the real world. This is frequently observed in determining levels for pesticides or using background concentrations as standards.

2.1.4.3 Removal Efficiencies

In some cases, it is practical to think in terms of the removal efficiency of target contaminants. In the wastewater industry, for example, treatment requirements are often reflected in a removal of 90% of the biological oxygen demands. In soil washing, removal efficiencies may vary from 50 to 99% or greater, depending upon the mode of contamination and the feed concentration.

In a situation where a very low (and possibly impractical) treatment standard has been specified in a ROD or legal order, and a reasonably high removal efficiency can be demonstrated, it may be possible to petition for a modified treatment standard.

2.1.5 Soil Matrix/Contaminant Relationship

Understanding the soil matrix/contaminant relationship is essential in evaluating sites and their suitability for solid washing. This information will form the basis for decisions regarding the process-flow arrangement and the resultant costs. The evaluation will indicate which fractions are contaminated to levels above the treatment standards and which processes may be required. Finally, the assessment will provide information regarding the quality and quantity of residuals.

2.1.5.1 Bar Chart Representation

The soil matrix/contaminant information is normally presented graphically, either on the standard ASTM-D422 Form or in a bar chart. An example of the ASTM form is shown in Figure 2.1. An example of the bar chart method is shown in Figure 2.3.

2.1.5.2 "Treatability" by Fraction

The soil washing process engineer must make several decisions based upon the graphic and measured information presented. If free contaminants exist in the gravel fraction, the engineer will further evaluate the nature of the contamination and begin to consider additional treatment or study steps. If no free contaminants are present, the gravel fraction can be removed by mechanical screening. It is then staged, analyzed, and upon confirmation that it meets the treatment standard, be placed back on the site. Evaluation of the coarse fraction (the sands) will also dictate treatment requirements. At about 30% of all sites, the sand fraction may not be contaminated, thus allowing simple separation. If the sand is contaminated, as is the case at 70% of the sites, treatment approaches must be considered. Similarly, contaminant levels in the fines fraction must be assessed for possible treatment or disposal at an off-site facility.

2.1.5.3 Volume-Reduction Potential

Soil washing is part of an overall soil remediation strategy. Soil washing does not have to solve the entire soil treatment problem. The volume-reduction potential, measured as the portion of the soil that can be returned directly to the site after simple separation and/or treatment of selected fractions, should not be overlooked. When the soil washing portion costs less than landfilling, a volume reduction of 50% may be very cost-effective even when combined with off-site disposal at a landfill.

2.1.5.4 Screening Study Evaluation

The process of conducting particle-size distribution and chemical analyses of the sieved fractions as described above, can be referred to as a *soil washing screening study*. This screening study can be used as a "go/no go" evaluation to decide whether more extensive testing is justified. Several important questions can be answered with this basic information.

- *Is the soil matrix a good candidate for separation?* The particle-size distribution curve will provide a good insight. If the fines represent less than 30% of the soil, the site is probably a good candidate. If the soil is 30 to 50% fines, it is probably a marginal candidate, unless other remedial alternatives are limited or are very expensive (e.g., incineration).
- *Do any fractions already meet the treatment standards?* If a fraction of significant mass already meets the treatment standards, then separation of that fraction, which is less costly, can solve a significant portion of the remediation problem.
- *Does it appear that at least the sand and oversize fractions can be treated?* If fractions exceed the treatment standards but appear to be treatable, the situation is also promising.
- *What is the cost of soil washing at this site?* To prepare a preliminary cost estimate, the process engineer will need to know the volume to be treated, the soil matrix/contaminant information, the operating conditions and general requirements at the site, and the final disposition of the fines concentrate. (Disposal at a hazardous waste landfill is the default selection.)
- *How do soil washing costs compare to other viable alternatives?* To determine whether soil washing makes sense, the process engineer must speculate as to what other options can be utilized at the site. These remedial selections are based upon experience and must address the volumes, treatment standards, and capabilities for treatment.

If the answers to the preceding questions are positive, soil washing deserves further consideration. In this case, a more detailed treatability study will be required wherein each of the proposed unit operations are tested, a complete process-flow diagram prepared, mass balances calculated, and pricing refined.

2.1.6 Treatability Studies

Treatability studies are modeled principally after the US EPA's *Guidance for the Conduct of Treatability Studies* (US EPA 1991). The document provides a generic approach to studies and should be used as a guideline, not a definitive requirement. It provides a good overview of the technology and outlines the approach to be taken in using treatability testing to evaluate a soil washing remedy. The key steps include:

- establishing the data quality objectives;
- selecting a contracting mechanism;
- issuing a work assignment;
- preparing a work plan;
- preparing the sampling and analysis plan;
- preparing the health and safety plan;
- conducting required community relations activity;
- complying with regulatory requirements;
- performing the treatability study;
- analyzing and interpreting the results; and
- reporting the results.

2.1.6.1 Essential Information

The treatability study must address the collection, compositing, and use of the feed soil, with convincing arguments that it is representative of the site to be remediated. Taking only "hot-spot" samples to prove that the most highly-contaminated soil can be treated is not effective since this will not be the material actually treated. This kind of biased study will lead to misleading results and inflated costs. The study must define the soil matrix and the relationship of the contaminants to the specific fractions that will be treated in the proposed system. A process-flow diagram must be presented in detail with the corresponding mass balance that adequately accounts for the soil mass, the contaminant mass, and the water mass. The chemical data should be prepared under reasonably good quality assurance (QA) procedures that correspond at least to Level III as presented in US EPA's *Guidance* (US EPA 1991). (Level III generally requires use of off-site analytical laboratories, using detection limits similar to the CLP, and methods similar to, but not exactly the same as, the CLP methodology. Rigorous quality assurance/ quality control (QA/QC) procedures are used, but a very detailed deliverable package is not required.) It may also be helpful to consider using screening tools that may be used in a full-scale implementation to begin making some correlation with the developed data. These screening tools may include field x-ray fluorescence (XRF), field gas chromatography (GC), or various colorimetric tests.

These data and their evaluation should be presented with a cost estimate that addresses all the elements of the remedial task, not just selected items, so that the decision maker has a fair understanding of all cost elements to be encountered.

2.1.6.2 Limited-Need Information

An example of information that may not be needed for standard application is the extensive speciation of target contaminants when the process design does not require the information. For example, if concentrated sludge cake is going to be disposed in a hazardous waste landfill, there is not much value in determining the form of contaminants. What will be required are the data needed to meet the landfill's waste-acceptance criteria, such as the total concentration and Toxicity Characteristic Leachate Procedure (TCLP) analyses for the targeted contaminants.

Yet, determining the forms of contaminant occurrence is important in designing a system. Sequential extraction and scanning electron microscopy are inexpensive and go a long way to define treatment requirements.

2.1.6.3 Information That is Not Needed

Generic guidelines often try to fit all technologies or treatment philosophies under one umbrella. However, each step included in the guidelines may not be needed in all applications. This is certainly the case for soil washing. For example, when physical separation is used for soil containing sand and gravel, it is not necessary to evaluate the soil's cation exchange capacity if the separation data and the soil matrix/ contaminant information show that the sand and gravel meet the treatment standards. Nor is it necessary in this case to define the number of "wash stages" or the temperature of the wash.

2.1.7 Limitations of Treatability Study Data

Treatability studies are important. Few, if any, soil washing projects have ever been performed without them. However, these studies must be viewed in the proper context.

Treatability studies deal with small volumes of soil that commonly range from 4.5-45 kg (10-100 lb). A treatability study does not measure the performance potential of a treatment system. It attempts to model the performance based upon the experience of the contractor or technology developers. Thus, it is important to factor this experience level into the overall assessment of the validity of the results presented.

The mass balances for treatability studies conducted with small volumes of soil often will not "close." This means that the soil mass, and most often the contaminant mass, cannot be accounted for mathematically through the individual treatment steps. A treatability study is essentially a batch-type evaluation of each treatment step. The product from step 1 is treated in step 2, and so on through the system. The feed soil and product soil from each step must be analyzed for the target contaminants to determine feed and product concentrations. For small quantities of soil, the analytical replicability of data is very wide. Thus, analyses of the same sample can vary as much as 100% and still meet CLP analytical criteria. In this situation, the calculated mass balance does not close, and reviewers can mistakenly conclude that contaminants were "lost" in the study process. In the mining industry, mass balances of this type are understood to be semi-quantitative; those that close to 50% or greater are generally acceptable. For this reason, a treatability study can only imply a treatment validation and often cannot confirm it.

Equipment cannot be observed in operation during a treatability study. Because of the difficulty in linking a successful treatability study to a full-scale remediation, the contractor or technology developer will normally consider a pilot-scale study or a demonstration of the site soils of concern on an existing commercial plant. Pilot studies generally involve a continuous-process system made up of the unit operations defined in the process-flow diagram. Pilot studies have been conducted on as little as 91 tonne (100 ton) of soil, generating the oversize, sand, and fines fractions. The benefits of actually generating these products and allowing the client(s) regulators to observe the operation, see the operating crew, and measure/analyze the products, cannot be overemphasized. In general, the larger the volume treated in a pilot study, the better. To save money and obtain regulatory benefit, the pilot study can be defined as an interim remedial action or the introductory step of a full-scale remediation. It is important to understand that the unit treatment prices for a pilot study will differ from those encountered in a full-scale project, because the cost is apportioned among the small number of tons treated in a pilot study.

2.2 Potential Applications

Soil washing has a broad range of potential applications. Yet, like any technology, it is not right for all situations. The purpose of this section is to define and discuss appropriate soil washing applications and areas where limitations must be considered.

2.2.1 Soil Types

The physical soil characteristics are the first considerations in determining whether soil washing is the appropriate technology for a project. The following paragraphs identify several common soil types and discuss how their characteristics may help or hinder soil washing.

Predominantly Sand and Gravel Soils. This class of soils will have <10% of the soil mass in the fines fraction, 60 to 80% of the mass in the sand fraction, and 10 to 30% in the oversize fraction. This is the *ideal* soil for soil washing and should result in significant volume reductions. This is a common coastal soil found on both coasts of the United States.

Predominantly Clay and Silty Soil. This class of soil will have >70% of the soil mass in the fines fraction, with the remaining 30% (or less) divided among the sand and gravel fractions. This represents the *most difficult* soil matrix for soil washing because very little volume-reduction leverage can be attained, and the contaminants bound in the fines will be difficult to treat.

Sand and Gravel Soils with Some Clay and Silt. This class of soils typically will have from 10 to 30% of the soil mass in the fines fraction, with the balance of the material in the oversize and fines fraction. This soil type represents the *most common* soil matrix for soil washing. This soil type requires a screening study and probably a treatability study. A soil in this class may or may not be a good candidate for soil washing, depending upon the contaminant concentration and occurrence, and competing remedial alternatives.

Sand and Gravel with Significant Clay and Silt. This class of soil has 30 to 50% of the soil mass in the fines fraction, with the balance in the sand and gravel fractions. This soil type represents the *most marginal* soil matrix for soil washing. The process engineer may be inclined to dismiss this soil type. Yet, evaluation may reveal that the contaminant situation is not particularly difficult to treat with soil washing or that the competing remedial alternatives are very expensive. Soils in this class should not be ruled out based on the soil matrix alone.

Slags. Slags may be composed of ore wastes or process wastes from steel or aluminum production. Slag is generally an oversize product >2 mm, but it also contains secondary sand and fines constituents from contact or processing breakdown. The slags are interesting because the contaminants are usually bound in the slag itself. The fines may actually be the clean product, in which case treatment will focus on processing the oversize fraction.

Mill/Mine Tailings. Mill and mining tailings may have characteristics similar to a wide range of soil types. Depending upon the ore or the process, the material may be primarily coarse-grained, as in the case of gold or uranium mining, or it may be made up primarily of fines as in the case of coke battery wastes. Tailings at least merit a screening study to determine the mode of contamination.

Heavy Organic Soils. Heavy organic soils refer to soils that contain natural, not synthetic, organics, such as high levels of peat or other soil organics. These soils can be very difficult to treat and are not particularly good candidates for soil washing since the natural organics will foul screens, interfere with separations, and even concentrate the target contaminants.

Sediments. Sediments in this context refer to materials dredged from rivers, lakes, canals, and harbors. Sediments are often thought to consist predominantly of fine-grained materials, but in reality can often contain as much as 50% coarse-grained materials. Sediments with 30% of the mass in the coarse fraction is rather common. Since water-bottom sediments are encountered in very large volumes, the ability to make physical separations and recover even 30% of the soil mass can be extremely attractive.

2.2.2 Contaminants and Mixtures

A number of contaminant types and combinations pose challenges in soil remediation. This section identifies the most common contaminant types and their potential for treatment through soil washing. All of these types are amenable to soil washing.

Hydrocarbons. Typical hydrocarbon contamination problems are caused by spills from underground storage tanks, transport equipment, or from plant operations. Hydrocarbons, including gasoline, diesel fuel, and JP-4, have been routinely removed by various treatment companies on projects in the U.S. and Europe. Heavier products, such as No. 6 Bunker "C" fuel oils, are much more difficult to treat because they are more viscous.

Metals. Heavy metals are good candidates for treatment using soil washing. The metals will tend to present themselves in many forms and species. A screening study will indicate whether the soil matrix/contaminant relationship is suitable for this technology. In most cases, excellent removals can be expected. The most common metals for which soil washing has been proved to be effective include lead, arsenic, chromium, nickel, cadmium, zinc, and mercury.

PNAs. Polynuclear aromatic compounds (PNAs) have also been removed effectively by experienced soil washing contractors. Common PNAs include naphthalene, anthracene, phenanthrene, fluoranthrene, chrysene, and benzo(a)pyrene. PNAs tend to be found as particulate material in the sand fraction, coatings on the oversize, and bound materials in the fines.

Metals and PNAs. Metals and PNAs can be treated in the same soil washing process stream. Soil washing, in fact, is the only remedial technology that can treat organics and inorganics in the same pass through the treatment system.

Pesticides. Some pesticides have been shown to be effectively treated using soil washing. Pesticides seem to exist as particles and adsorbed materials in the sand fraction, with some bound in the fines and some that may be soluble. Sidestream wastewater treatment may be necessary with this waste stream.

PCBs. Polychlorinated Biphenyls (PCBs) have been shown to exist in soils in a manner similar to PNAs. Oily constituents may result in coatings on the sand, while degraded components may be bound in the fines. Feed concentrations in the range of 200 to 500 mg/kg can be reduced to less than 5 mg/kg if the conditions are reasonably favorable.

LLRW. Low level radioactive wastes (LLRWs) exist in many forms and result from many different operations. Most experience regarding treatment of these contaminants has come from bench-scale and pilot-scale studies performed at DOE weapons sites and ore processing sites managed under the Formerly Utilized Sites Remedial Action Program (FUSRAP). The most common contaminants include uranium, radium, and thorium. Some work sponsored by the DOE, particularly at the Idaho National Engineering Laboratory (INEL), and the Hanford facility in Washington State, has addressed cesium.

VOCs. Volatile organic compounds (VOCs), particularly benzene, toluene, xylene, and ethylbenzene, are commonly encountered at remedial action sites. Although soil washing systems can remove these contaminants, the technology is not the first choice if VOCs are the only contaminants to be treated. However, if VOCs are part of a more amenable feed stream, soil washing techniques can provide excellent removals. Examples include VOCs mixed with metals and/or PNAs.

2.2.3 Types of Sites Encountered

Chemical Plants. This class of sites is very diverse and can contain almost any media and contaminant combination. Contaminant sources typically encountered at chemical plants may include landfills, lagoons, spills, excavated and staged soil, and contaminated fill. Almost any contaminant can be encountered.

Refineries. Refineries contain many sources of contaminants that may require remediation, including operating tanks and process units, lagoons, storage tanks, land disposal units, and spilled materials. Contaminants are usually hydrocarbon-based VOCs and semivolatile organic compounds (SVOCs), sometimes commingled with heavy metals.

DoD Facilities. DoD facilities for the Army, Navy, Air Force, and Marines are most commonly contaminated by hydrocarbons in soils and groundwater that resulted from spills and operations. Many specialty facilities, however, handled a wide range of materials and wastes associated with ammunition production and storage, maintenance activities, and training. Remediation projects at DoD sites address combined wastes, including organics, PCBs, heavy metals, mercury, Her Majesty's Explosive/Royal

Division Explosive (HMX/RDX), and pesticides. Explosives are nitro aromatics and include TNT and chemical agents and unexploded ordnance (UXOs).

DOE Sites. DOE sites are primarily affected by past activities associated with nuclear weapons manufacturing. Large volumes of soil at these sites have been contaminated with low-level radioactive wastes, primarily uranium, plutonium, cesium, cobalt, and strontium, as well as organics, metals, and mixed wastes.

Harbors and Rivers. Sediments dredged during maintenance and remediation activities at ports and harbors constitute a relatively new source of contaminated materials. The soil matrix of these sediments is predominantly composed of fine-grained materials. The contaminant mix usually contains a wide range of organics, heavy metals, PCBs, pesticides, and even dioxins and furans.

2.2.4 Limitations

Soil washing can make a major contribution to reducing the volume of contaminated material and treating contaminated soil, but it also has limitations. The term soil washing implies that there is, in fact, soil to be treated. In this context, "soil" refers to a distribution of oversize, coarse, and fine-grained particles. If the target feed material consists solely of fines (e.g., a typical sludge), soil washing is less applicable since there is no leverage to separate the coarse and fine-grained materials. There is generally no accepted level representing a level of fines content above which soil washing does not work. The acceptable upper limit fines in the soil will have to be determined based on competing alternatives and economic comparisons. If it is assumed that the only competing technology is excavation and disposal at a hazardous waste landfill, then for a project involving 22,680 tonne (25,000 ton) of material, the costs of soil washing would equal those of landfill disposal if the target material were composed of about 35% fines.

The key limitations associated with soil washing may arise if:

- The soil matrix is not supportive of separation and treatment because the fines concentration is too high or excessive amounts of naturally-occurring organic materials are present in the soil.
- The mode of contamination does not support removal from the soil matrix. One practical example is a coating on sand particles that cannot be removed.

- The feed concentrations are too high and/or the treatment standards are too low. Realistic removal efficiencies vary from 70 to 99% of the contaminant mass. A reasonable range of removal efficiency is 80 to 95%. When 99.9% removal efficiency is required to meet the treatment standard, practical use of the technology is doubtful.
- The comparative economics are not favorable. The most common limitation in the use of soil washing is based upon the comparative cost of other approaches. Soil washing must be more cost-effective than competing treatment technologies, including containment and disposal remedies.
- Political decisions eliminate the treatment alternative. This may occur in some cases because of local opposition to placing treated soil back on the site.

2.3 *Treatment Trains*

A treatment train generally refers to multiple technologies used in serial or parallel fashion to treat a particular feed stream. Soil washing is particularly viable in treatment train arrangements because of its intrinsic capability to prepare soils in fractions that are more amenable to further treatment.

2.3.1 Primary, Secondary, and Tertiary Treatment

Soil washing is not a fixed process in the sense that it always uses certain unit operations in a prescribed order. Many unit operations are available in soil washing and can be configured in many ways depending upon the soil matrix/contaminant situation.

In the wastewater industry, treatment plants are commonly categorized as primary, secondary, and tertiary treatment plants. A primary plant might consist only of a clarifier and a discharge weir. Secondary systems include an activated sludge process with chlorination. A tertiary plant might add carbon polishing. Primary systems have relatively low removal efficiencies, but also have very low capital and operating costs. Secondary systems have improved removal efficiency, but at a higher cost. Tertiary systems can achieve the highest possible removal efficiency, but at much higher costs.

Soil washing systems may also be configured in a manner analogous to wastewater treatment plants. Primary soil washing systems consist of primary screening and separation. These might be used if the oversize and sand fractions do not exceed the treatment standards. Primary systems might be referred to as "straight separation" systems since they separate the sand and gravel, concentrate the contaminants in the fines and produce a sludge cake that can be disposed without further treatment. The unit operations are limited and removal efficiencies are not very high, but the sand and gravel meet the required treatment standards. Unit costs are very low with this approach.

Secondary soil washing treatment consists of the primary treatment process described above, with additional treatment of the sand fraction. This approach might be used in a situation where the gravel meets the treatment standard upon separation, but the sand and the fines do not. The sand may be treated using attritioning, froth flotation, and spiral concentration. The fines are simply consolidated and dewatered into a sludge cake that can be disposed off-site. The treatment efficiencies are improved, but the unit treatment cost is higher than "straight separation."

Tertiary soil washing treatment consists of primary and secondary treatment, with additional treatments of the fines fraction using bioslurry or extraction processes to remove contaminants from this final fraction. The removal efficiencies are very good, but the unit costs are the highest encountered.

Primary, secondary, and tertiary systems are all soil washing systems, although they look quite different and will have significantly different costs. The selection of the most cost-effective system will be based upon the soil matrix/contaminant relationship and the treatment levels demanded at the specific site.

2.3.2 Unit Operations Approach

There is no fixed arrangement of treatment steps that must be employed for a system to qualify as soil washing. Many treatment techniques can be used. This often contributes to a misunderstanding of soil washing since the process must be tailored to each application based upon the soil matrix/contaminant relationship. Specific treatment steps that may be used are referred to as unit operations. Some of the unit operations frequently used in soil washing are briefly described below.

2.3.2.1 Prescreening

Prescreening is performed to remove gross oversize product(s) and to prepare a feed to the soil washing plant. Debris removal can be conducted by the excavation equipment. Very large debris can be staged separately.

"Grizzlies" are either fixed or vibrating bar screens with a typical cut point of 8 in., 6 in., or 4 in. Most screening units are mobile. Material larger than the selected cut point is rejected off the top of the screen, and material below the cut point falls though the screen.

Trommel screens are mobile, rotating screens that can make a cut in the range of 1 to 4 in. They are particularly useful in further treating the underfall of a grizzly since they can prepare a separated product with relatively little misplacement (when material from one product stream ends up in another product stream due to equipment inefficiencies or changes in operations or feed conditions). Any product larger that the cut point comes off the end of the trommel while product smaller than the cut point drops through the screen, usually onto a conveyor belt for staging.

2.3.2.2 Feed Screening

Feed screening is required to prepare soil to the size range that will support downstream treatment steps. It usually involves removal of the gravel fraction from the sand and fines.

Mechanical screens are available in many designs. They may either be fixed or vibrating, and generally are single- or double-decked. The "decking" refers to the screen itself, made of a long-wearing synthetic material ranging in size from 2 to 20 mm.

Wet mechanical screens feature a series of water spray heads that wet the feed soil and assist in cleaning the gravel. They can be used to prepare a slurry of the sand and fines for pumping application.

2.3.2.3 Separation

Separation techniques are physical operations generally used in soil washing to prepare the sand and fines for further treatment. Separation techniques need to be highly efficient and will be measured by the misplacement of one fraction in the other. Less than 5% misplacement can be attained consistently with the right techniques.

Fines screens can be used, but they are typically limited to about 500 µm. Fines screens can be of standard design, but because of the small decking slots, they must present a very large surface area to manage the flow. Curved screens (or sieve bends) can also achieve reasonably low cut points.

Separators can be used to separate coarse and fine-grained materials at selected cut points, but are more frequently used to control the dry solids concentration in the unit underflow.

Hydrocyclones are physical separation devices. They are slightly different from other separators in that they are vented and are designed to produce a coarse product in the underflow, and a fine product and water in the overflow, at a very precise separation point, often within a selected cut point of +/- 0.003 mm.

2.3.2.4 Sand Treatment

Treatment will normally be performed on the separated sand stream since the unit operations will perform more effectively within a specific size range.

Attritioning cells (sometimes referred to as high-intensity scrubbers) will drive the feed soil to its natural particle size and are used to breakdown soils. The attritioned product can be separated again to get the coarse and fine particles in the right stream.

Density separation can be used to separate particles that have different densities but approximately the same particle size. Typical units are spiral concentrators or multi-gravity separators.

Froth flotation units are frequently used with the support of specialized surfactants to remove particulate or free contaminants from the sand fraction.

Dewatering of the sand is provided by vibrating sand dewatering screens. Normally the water fraction is recovered for reuse in the treatment facility.

2.3.2.5 Fines Treatment

Treatment of the fines fraction will vary widely depending upon the soil, the contaminants, and the contractor. As of this writing, three primary techniques are being used.

- Dewatering of a consolidated sludge fraction in preparation for off-site disposal at an appropriate landfill.
- Extraction using acids and chelates for removal, and sometimes recovery, of the target contaminants.
- Bioslurry degradation of the separated slurry to transform organic contaminants in the fines fraction.

2.3.3 Linking Soil Washing to Other Technologies

The real power of this technology to emerges when the separation and treatment capabilities of soil washing are linked to other technologies in what is referred to as a treatment train. Some of the current technologies that can be effectively linked to soil washing are:

- *Stabilization.* Reagents or additives can be added to various soil washing streams, mixed in existing or additional treatment units, and dewatered using filter presses or centrifuges that are already provided with the system. This technique may be most appropriate to stabilize the sludge cake to meet TCLP standards for placement on-site or disposal off-site.
- *Low Temperature Thermal Treatment (LTTT).* Soil washing can reduce the quantity of the feed stream to the LTTT unit and better prepare the feed stream for LTTT relative to concentration, soil characteristics, and moisture content.
- *Vitrification.* Soil washing makes an excellent first treatment step for applications involving low-level radioactive waste by achieving volume reductions and concentrating contaminants into a small fraction that can be easily and effectively fed to a vitrification unit.

3

DESIGN DEVELOPMENT

3.1 Remediation Goals

The remediation goals established for any specific project form the basis for determining the applicability of any remedial technology. The ability of soil washing to treat a broad range of contaminants, particularly its ability to treat organics and inorganics in the same process stream, makes this technology broadly applicable.

3.1.1 Proven Performance

Table 3.1 lists the contaminants most commonly treated with soil washing and the reasonably achievable treatment levels (the "B" level) under the Dutch ABC standards (described in Section 2.1.1). Although the Dutch system has been recently revised, the "ABC" levels became widely known and used. The B level can be thought of as an industrial use level. Although these are the most commonly encountered contaminants, the list is not intended to show all contaminants that can be treated with soil washing. In the United States regulatory system, the treatment standards will be determined by the completion of a site-specific risk assessment. The B levels are very helpful, however, in making a first estimate of the resulting treatment level.

The most extensive database of performance information comes from soil washing experience in The Netherlands and Germany, where the B levels are routinely achieved, and in many cases, the "A" level (an unrestricted use level) can be reached. The performance results of soil washing projects in the United States are presented in Chapter 5, Case Histories.

Table 3.1
Achievable Treatment Levels for Contaminants Commonly Treated with Soil Washing

Contaminant	Dutch "B" Level (mg/kg)
Metals	
Chromium	250
Nickel	100
Zinc	500
Arsenic	30
Cadmium	5
Mercury	2
Lead	150
Organics	
Total Polynuclear Aromatics (PNAs)	20
Carcinogenic PNAs	2
PCBs	1
Pesticides (various)	< 1
Petroleum Hydrocarbons (TPH)	100

3.1.2 Reliability

The reliability of a soil washing system in attaining the required treatment standards is entirely dependent upon the quality of the information used to design the plant, and the ability of the contractor to operate the plant and respond to changing conditions. Because an experienced contractor will manage the feed soil for the unit, reliable production can be attained in actual field practice.

3.1.3 Regulatory Acceptance

Soil washing is well accepted by the US EPA. Nearly 30 RODs involving soil washing have been approved by the agency's headquarters and regional offices. The USEPA's National Risk Management Research Laboratory (NRMRL) has been funded to evaluate, develop, and support new technologies, one of which is soil washing. Many states also have support soil washing as a development.

DOE has undertaken a strong advocacy program through the EM-40 Technical Connections Program and through the EM-50 Office of Technology Development. These programs have been implemented with support from Argonne National Laboratory and Sandia National Laboratory. These efforts have resulted in a significant commitment to soil washing at DOE's Hanford (Richland, Washington) facility and Fernald, Ohio facility and in the agency's Formerly Utilized Remedial Action Program (FUSRAP).

The U.S. Department of Defense has also undertaken major soil washing evaluation activities in each branch of the military. Significant activities promoting the use of soil washing for specific applications are being undertaken, including the U.S. Army Environmental Center in Aberdeen, Maryland, the U.S. Air Force Center for Environmental Excellence at Brooks AFB in San Antonio, Texas, U.S. Navy's Naval Facilities Engineering Support Activity in Port Hueneme, California, and the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

The combined result of these activities is that soil washing has become acceptable to regulators and government entities, but always with the requirement that the application be properly planned and managed.

3.1.4 Public Acceptance

Public acceptance of soil washing is also favorable. Soil washing has the very positive attributes of being able to treat soil, remove contaminants, and allow the reuse of soil and other resources possibly recovered from the site. There are few or no emissions problems related to the technology, and the installation is a temporary one that remains only for the duration of the project. Because soil washing can meet the required treatment standards, the site is available for development or redevelopment without any additional long-term controls.

Some problems with public acceptance might be encountered, but they are generally similar to those related to the use of any on-site treatment technology. Concerns that can be expected and should be addressed in a mitigation plan can include noise levels during operation, movement and control of haul trucks on- and off-site, and the perception that no treatment level is acceptable and, therefore, no treated product should be placed back on the site. Overall, however, soil washing is considered a benign process and is viewed enthusiastically.

3.2 Design Basis

3.2.1 Design Information

The basic information required to design a soil washing system is discussed in the following sections.

3.2.1.1 Physical Characteristics of the Soil

The first type of information required to design a soil washing system is a quantitation of the soil's physical characteristics. The soil characteristics can be readily assessed by performing a particle-size distribution analysis in accordance with ASTM Method D422 (ASTM 1963). This quantitation is performed by a wet sieving technique to weigh the mass of soil sample retained on each of 12 to 14 screens. The mass retained on each screen is dried, weighed, and plotted to construct the particle-size distribution curve. It is important to remember that results shown on this curve are on a dry weight basis. Thus, the dry weight result must be adjusted when discussing field soil conditions.

The particle-size curve information yields the first process insights for the engineer designing a treatment system. Three soil fractions are generally separated or considered for treatment: the "oversize" fraction consisting of particles with an average diameter >2 mm; the "sand" fraction consisting of soil particles <2 mm but >0.074 mm (200 mesh), and the "fines" fraction consisting of clays and silts with an average particle size <0.074 mm (200 mesh).

The particle-size distribution information is first used to determine the mass of soil in each of the three specified fractions. This information enables a first estimate of the size of unit operations to be used in the treatment of each fraction and as an estimate of residuals that will be generated through various treatment steps.

In general, the oversize material is the easiest to treat, the sand is moderately difficult, and the fines are most difficult. This rule of thumb gives the designer a sense of the degree of difficulty presented by the target soil and enables a preliminary project cost estimate.

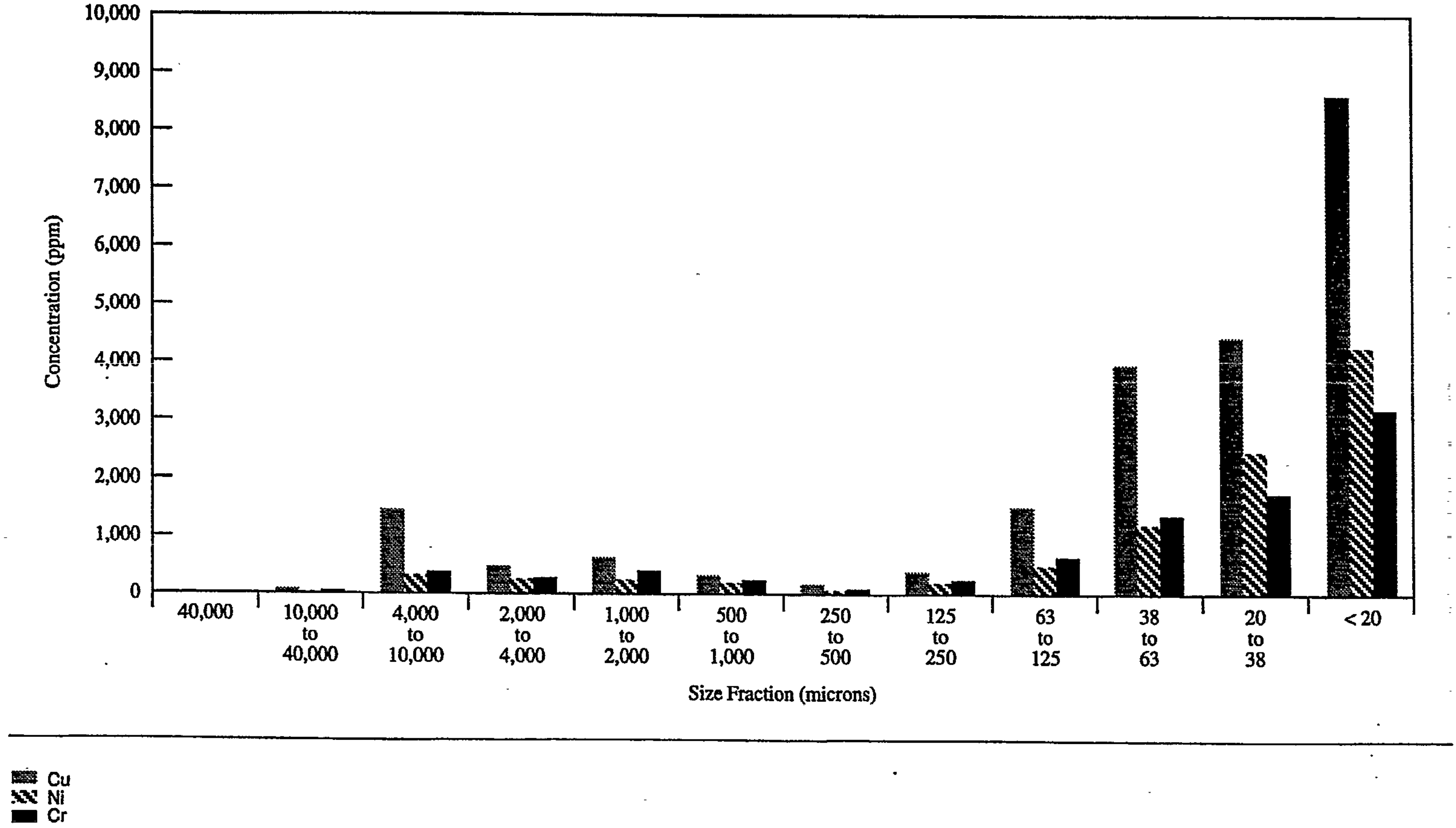
3.2.1.2 Contaminant Occurrence

The term *contaminant occurrence* is used to encompass both the form and quantity of target contaminants in specific samples. Quantitation of contaminants in the soil matrix is easy. The soil retained on each sieve during the particle-size distribution analysis is sent to a laboratory for chemical analysis. The results of the laboratory quantitation are plotted on the particle-size curve to identify the contamination by fraction. This can be represented graphically using a bar chart as shown in Figure 3.1. This information is very important to the soil washing system designer because it defines which fractions require treatment and which fractions may not. This information can also be presented in a tabular manner and expanded to show the portion of the total contaminant load that exists in each fraction.

The form of the contaminants in each fraction is also very important since it will suggest the treatment unit operation best suited to effect removal. There are five forms that the contaminant (or contaminant mix) may take in the soil:

- *Free.* Examples of contaminants in this form include bullets at a firing range or lead slag at a burn pit.
- *Particulate.* Contaminants in this form include material existing as free particulate within the sand fraction or particulate that is lightly bound to the surface of the sand. Lead is a good example of a contaminant that can exist in either of these forms.
- *A Coating.* In this form, the contaminant has covered the sand particle. Polynuclear aromatic compounds (PNAs) from a coal gasification process are a good example of this contaminant form.
- *Complexed or Bound.* These are contaminants that have oxidized in the field to form oxides, carbonates, or sulfates and are bound into the dense matrix of the fines.
- *Soluble.* Contaminants in this form have a relatively high solubility and still exist in the soil matrix. While many elements/molecules have a measured high solubility, it is often found that the highly-soluble fractions migrate away from the site and into the groundwater. Thus, it is relatively unusual to encounter this form of contamination in ex-situ soil remedial applications.

Figure 3.1
Concentration vs. Particle-Size



The form of the target contaminants can be identified by visual and microscopic techniques. The methods may be very simple or as sophisticated as using color-enhanced scanning electron microscopy, but the identification is very important in designing an efficient treatment system.

The form that the contaminants take in each of the process fractions leads directly to concepts for treating each. For example, free material like slag can be removed by mechanical screening. Separation of the sand and the fines can prepare the soil matrix for more effective treatment. Particulate material in the sand may be removed using the inherent density differences in the contaminant and the sand, or by attritioning followed by froth flotation. Complexed contaminants may be amenable to biodegradation if they are organics or extraction/chelation techniques if they are heavy metals. Soluble contaminants that still exist in the matrix can be treated in the process recycle water with standard wastewater treatment techniques.

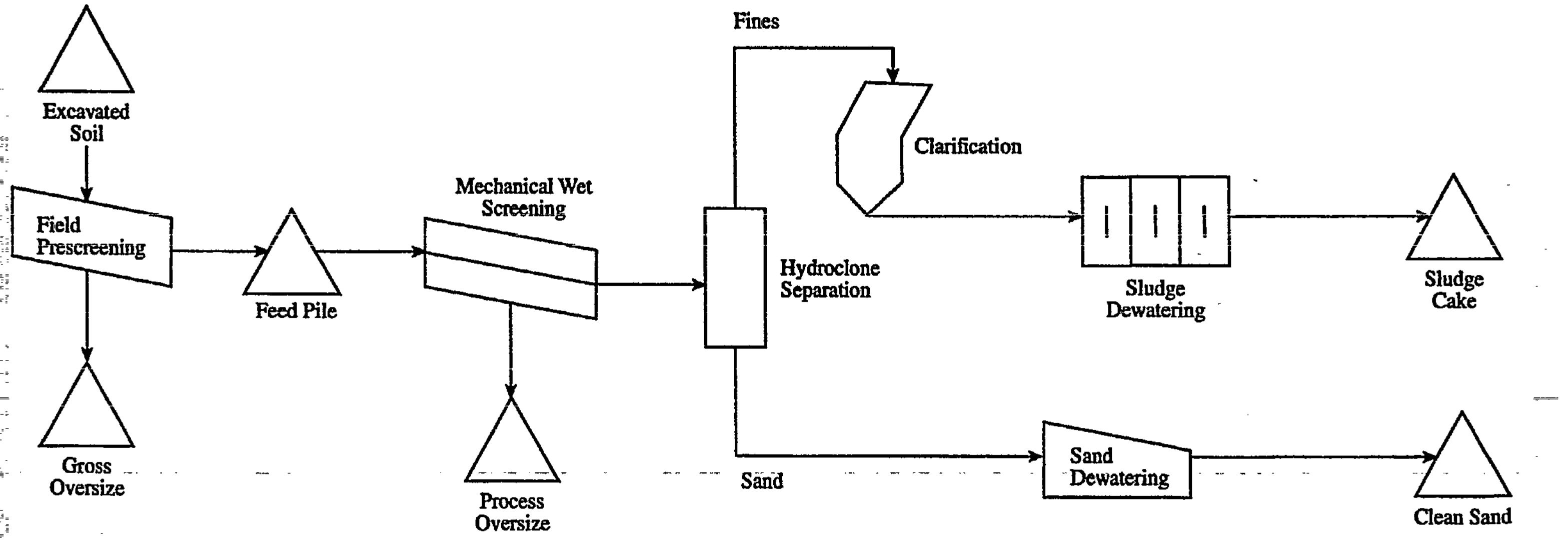
By determining contaminant occurrence, the remedial designer knows the characteristics of the soil matrix that must be handled and the concentration, form, and fraction in which the contaminants reside.

3.2.1.3 Level of Treatment

The level of treatment is a concept that is frequently misunderstood, misdirected, or not discussed. The level of treatment refers to the extent to which the soil matrix will be treated and what portion of the feed material will meet the treatment standard. A soil washing system may provide simple treatment that results in a fairly low volume reduction, or it may provide very complex treatment and result in high volume reductions. The factors that determine which approach to be used are cost and effectiveness for the specific site in question. Four levels of treatment are commonly encountered.

Simple Separation. Simple separation systems may be appropriate when the oversize and sand fractions already meet the treatment standards and only the fines fraction does not. In this situation, a system might include mechanical screening to remove the oversize fraction, separation of the sand and fines, dewatering of the sand, and consolidation and dewatering of the fines. The dewatered fines are then in a sludge cake form that can be disposed at an appropriate off-site landfill. A simple separation schematic is shown in Figure 3.2.

Figure 3.2
Simple Separation



Simple Separation Plus Sand Treatment. In this case, the oversize fraction meets the treatment standards, but the sand and the fines fractions do not. This situation encourages the designer to remove the oversize material using mechanical screening and separate the sand and fines fraction for treatment. Depending upon the form of the contaminants in the fines, attritioning, density devices, and/or froth flotation may be selected. In this case, the fines, exceeding the treatment standards, will be consolidated into a sludge cake and disposed off-site. The sand and oversize meeting the treatment standards remain on-site. A simple separation and sand treatment schematic is shown in Figure 3.3.

Simple Separation Plus Sand Treatment and Fines Treatment. This scenario involves a an uncontaminated oversize fraction and contaminated sand and fines and for either liability or cost reasons, volume-reduction requirements drive the treatment of the fines fraction. This level of treatment is the most sophisticated and will generally include the approaches mentioned above in addition to bioslurry degradation of organics in the fines or an extraction/chelation system for the removal of heavy metals. An example of such a system is shown in Figure 3.4.

Special Cases (Oversize Problems). Although many "rules of thumb" can be applied in soil washing, there are special cases that must be evaluated on the basis of the soil matrix/contaminant relationship. One special problem that can be encountered is that the oversize material is contaminated. This situation can arise if gravel is coated with a tar material, if there is slag about the same size as the gravel, or in a particularly complicated situation such as mobile contaminant (e.g., Cs-137) actually migrates into micro fractures in the gravel or ion exchanges with natural cations occur, leaving a contaminated oversize. These special situations are difficult, but often can be resolved. The solution may involve crushing, grinding, jigging, and combined processes. The use of such complicated approaches will be dictated by comparative cost considerations.

3.2.1.4 Site Conditions

The soil washing design must include the supporting infrastructure for the plant, and for the materials handling that must be accomplished to excavate, prescreen, and stage feed materials to the treatment unit. The site conditions that must be considered for the treatment plant include the location of the site, the layout of the plant and materials staging areas, the subsoil

Figure 3.3
Simple Separation plus Sand Treatment

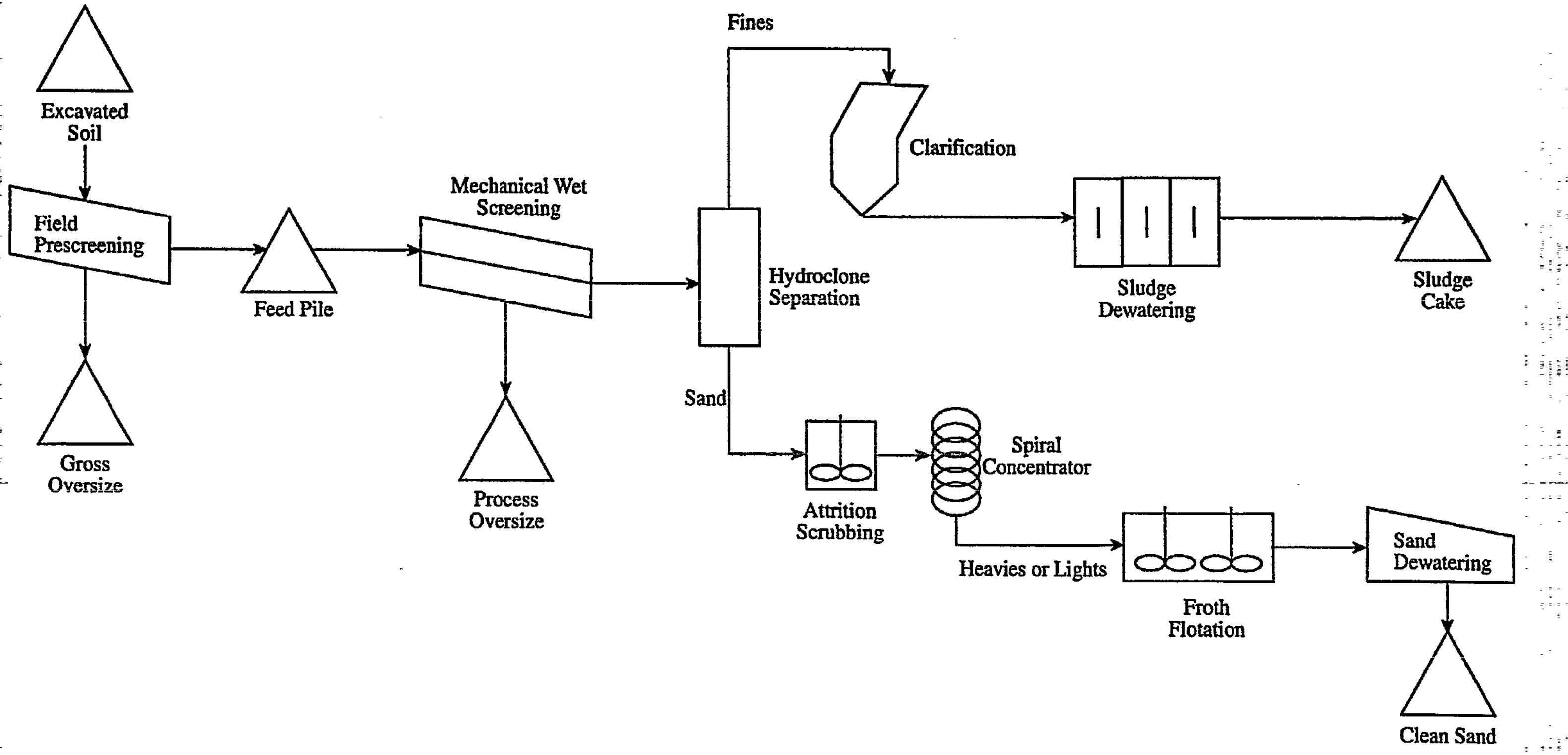
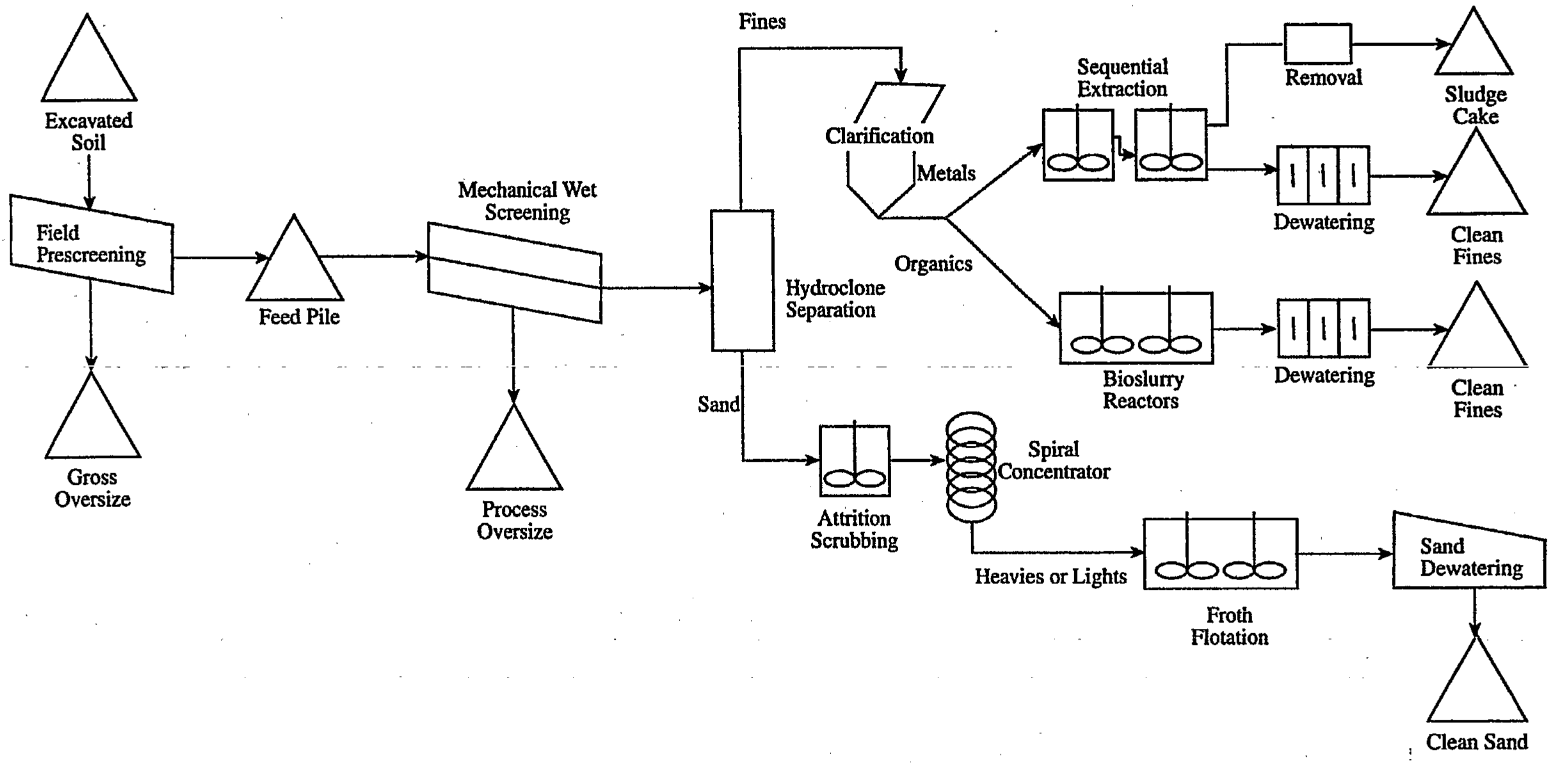


Figure 3.4
Simple Separation plus Sand Treatment plus Fines Treatment



conditions beneath the plant operating pad, the location and specifications of commercial electrical power, the location and quality of process water, and the weather conditions that may be expected during the period of remediation. Evaluation of the site conditions is also important in determining the sequence for excavation, the location of equipment for prescreening activities, and the staging areas for feed soil and products.

3.2.1.5 Treatment Standards

The treatment standards for the contaminants of concern will determine the level of treatment and contaminant removal efficiencies that must be attained. In many cases, the treatment standards will have been established by the performance of a site-specific risk assessment. If so, it is easy to use those values. In some cases, however, the risk assessment may not have been completed or treatment standards may still be under negotiation with the regulators. In those cases, it may be helpful to use the Dutch B levels as a starting point (see Section 3.1.1), for in many cases it has been found that these levels correlate very closely to the end result of a site-specific risk assessment.

3.2.1.6 Schedule

The work performance schedule will establish a reasonable range for the system's throughput rate, which affects the size of equipment that is needed. Project completion dates will be most important and will affect the labor shifts necessary to operate the plant. Soil washing systems are very flexible in the sense that they are easy to shutdown and startup and, as such, allow flexibility in working shift schedules.

3.2.2 Data Collection

The data required to design a soil washing system can come from many sources.

3.2.2.1 Remedial Investigation Information

Remedial investigation (RI) reports will provide a tremendous amount of information, but often not the specific information the designer may requires. Nevertheless, the RI report should be reviewed in detail to learn the nature of the operations that were conducted at the site, as this provides a good indication of the form of contaminants that might be encountered. The report will present the location and analytical results of all the soil samples collected during the investigation. The soil samples may have been obtained through auger boring and split-spoon samples, which are often not very helpful in characterizing feed material to a treatment unit, but they do give an indication of the nature and extent of the soil contamination at the site. Frequently, particle-size distribution analyses are not conducted during the RI and must be supplemented with additional sampling.

3.2.2.2 Site-Soil Sampling Program

To supplement the soil information from the RI and develop site-specific information, an additional site-soil sampling program is required. After spending (on average) more than $1 million on the RI, most clients or regulators are often reluctant to conduct further characterization. Fortunately, the needed sampling is relatively inexpensive (often costing <$10,000), and the work can clearly be defined as part of the design effort.

The site-soil sampling program is intended to observe the physical condition of the soil to be treated, identify other material that might be encountered (e.g., debris) and collect a representative sample of the soil to be treated.

For this activity, it is recommended that "test pits" be installed. A test pit is simply an excavation installed by a backhoe, one bucket wide and as long as may be practical for the site. Material is removed during this excavation and placed directly alongside the trench. The field engineer can observe the cross-section of soil exposed by the trench and collect soil samples from selected areas. Similar test pits may be installed at other selected areas on the site. Soil is recovered from these trenches and packaged for shipment. These soil samples are then used for screening and treatability study testing.

3.2.2.3 Treatability Studies

The treatability study is required for every soil washing project. However, the study, like soil washing itself, can be modified to meet the specific needs of the project being contemplated.

The first phase of a treatability study is often referred to as a "screening" study and can be used as a "go/no go" test to determine whether it is useful to pursue more detailed studies. This screening process consists of conducting a particle-size distribution analysis, analyzing the retained material for the target contaminants, observing the mode of the contaminants, and reporting the findings. The report may also contain a preliminary cost estimate comparison to the other most likely remedial options that could be used at the site and a determination on an order-of-magnitude level, whether soil washing is technically feasible and economically competitive. This screening study can often be performed for $5,000 to $20,000.

A "full" treatability study is also required on every soil washing project. This study is a laboratory bench-scale evaluation of the process on a batch basis. The study is essential to determine the process-flow arrangement to be used; select physical separation parameters; define process unit residence times; test chemistry, additives, and dosages; and to confirm dewatering operations. The treatment units to be used are run together in a simulated manner that will produce the clean products and residuals. The study is essential for the contractor to develop fixed pricing and guarantee the results of treatment. Unfortunately, all treatability studies are not identical. Because soil washing systems vary significantly, each contractor will want somewhat different information and may generate that information in different ways. This fact is often not recognized, and contractors are given "standard" treatability study information upon which they are expected to develop a bid. This weakens the bid response because the contractors do not have the information they really want, and a significant contingency gets built into the bid.

The treatability study will present the findings of the bench-scale work, describe a process-flow arrangement, define operating parameters and develop an implementation cost estimate. A full-scale treatability study can be expected to cost from $10,000 to $50,000.

3.2.2.4 Pilot Studies

Treatability studies vary widely depending upon the particular level of treatment, the complexity of the technology, and the experience of the contractor. As a result, it may be necessary to conduct a pilot study before full-scale implementation of a soil washing project is approved. A pilot study, for the purposes of this document, is a continuous-process test conducted in the field or at fixed facilities, using all of the unit operations that are intended for use in the full-scale installation. Pilot studies are conducted to confirm the treatment concept and to identify any problems related to "scaling up" the unit operations previously assessed in the laboratory-scale treatability study.

The size of a pilot-scale study is not fixed by any existing protocol, but it should be in some ratio to the size of the full-scale remediation. Pilot studies for soil washing have been performed using soil quantities from 91 to 18,144 tonne (100 to 20,000 ton). For average sites (those with about 27,216 tonne [30,000 ton] of soil), performing a pilot study with approximately 907 tonne (1,000 ton) is reasonable. Thus, if a pilot plant has a throughput capacity of 9 tonne/hr (10 ton/hr), the pilot study can be conducted in one month of actual processing time. This time estimate assumes only one shift per day, five days per week. It also factors in the time required to collect samples at a greater frequency than might be used during the full-scale operations. Pilot studies have a much higher unit price per ton than full-scale projects and may cost from $250,000 to $750,000 total.

3.3 Design and Equipment Selection

3.3.1 Introduction

The actual design of a process incorporating soil washing technology will be determined by the treatability study, the pilot study, and the philosophy and experience of the design team. No soil washing system is available "off the shelf." The equipment selected to support the design requirements may be specified by the designer, or it may come as a package provided by a manufacturer or from a contractor who already has a soil washing plant ready for use. If the system designers attempt to select each piece of equipment for the plant, the design team will most likely confer with mining equipment companies, for almost all of the required units are in common use in the mining industry. Equipment that is commonly used in soil washing systems is shown in Table 3.2.

3.3.2 Unit Sizing

Equipment for a soil washing system will be sized based upon the nominal system throughput rate. The system throughput rate will be determined by the mass of soil to be treated and the time allowed for remediation. Common soil washing system throughput rates are 4.5, 9, 14, 18, and 23 tonne/hr (5, 10, 15, 20, and 25 ton/hr). In the United

States and Europe, the most common rate seems to be 23 tonne/hr (25 ton/hr) for a full-scale production unit.

Table 3.2
Common Soil Washing Equipment
(Major Soil Washing Components)

Prescreening Grizzlies and Trommels
Feed Hoppers
Conveyor Systems
Vibrating Wet Screens
Pumping Systems
Hydrocyclones/Separators
Spiral Concentrators
Dense Media Separators
Attritioning Cells
Flotation Cells
Sand Dewatering Screens
Clarifiers
Filter Presses
Bioslurry Reactors
Acid Extraction Equipment

Soil washing systems may be operated on very flexible schedules. They may be shut down, left over the weekend, and started up again. It has been found that one 10-hour shift per day, with maintenance performed on Saturday, is the most convenient operational plan if the schedule permits. Soil washing plants have been found to operate with an 80% or greater availability rate or "up time." Of course, if necessary, the operational schedule can be established on any required basis up to and including 24 hour a day operations, 7 days a week.

Table 3.3 shows the quantities of soil that can be treated using a 23 tonne/hr (25 ton/hr) plant.

Table 3.3
Treatment Capacity of a 25 ton/hr Plant
Under Various Operating Schedules*

Operating Schedule	Soil Mass Treated per Week (ton)	Soil Mass Treated per Year (ton)
1 shift, 5 days per week	1,000	50,000
1 shift, 6 days per week	1,200	60,000
2 shifts, 5 days per week	2,000	100,000
2 shifts, 6 days per week	2,400	120,000
3 shifts, 5 days per week	2,400	120,000
3 shifts, 7 days per week	3,360	168,000

*10 hours per shift for 1 and 2 shift arrangements; 80% unit "up" time; 50 weeks per year.

3.4 Process Modification

A soil washing process is typically assembled from modular units designed principally to maximize the segregation of contaminants from the host soil matrix and secondarily to accommodate the local physical conditions. Soil matrix attributes that affect design and/or operation may include particle-size distribution, moisture content, and the degree and type of contamination. Physical site conditions that may have an effect include ambient temperature, proximity to buildings or sensitive populations, and local infrastructure. Most of the potential problems posed by these variables can be mitigated or eliminated entirely if considered in the planning stages and resolved through treatability studies or accounted for in the system design. This section discusses parameters that should be considered and offers possible solutions to potential problems. Many problems encountered in the field are not readily resolved by any single approach. Site-specific treatability testing, coupled with experienced field operations personnel, is essential for the successful soil washing contractor.

3.4.1 Soil Matrix Characteristics

3.4.1.1 Particle-Size Distribution

Soil washing relies on efficient separation of size fractions. Typically, the smaller particles contain more contamination on a weight basis, both because of their higher surface area and because clay particles have a greater affinity for ionic species due to their chemistry and structure. If the soil matrix includes a large fraction of fine material (i.e., if 20 to 30% of the mass is <200 mesh), it may not be cost-effective to treat the site using soil washing. Treatment costs should be carefully compared to potential cost savings under other options.

If the site includes areas of widely variable particle-size distribution, it may be necessary to stage and blend the feed before processing. If feed batches vary substantially, different modules of the system may be overwhelmed or underutilized, leading to continual process upsets such as plugged lines, inadequate residence time in settling equipment, and poor control of chemical injection. Good site characterization and ample staging area for feed material can allow blending of batches prior to loading in a feed hopper. Balancing the loads on process modules will maximize operating efficiency and system availability.

If the particle-size distribution substantially differs from what was anticipated, or if it varies unavoidably when processing various site areas, processing equipment can be physically modified or operated to compensate for this condition within limits. Upflow classifiers and mineral jigs can be operated over a range of flow rates to vary the size of the carryover fraction. Some hydrocyclone designs allow field modification to change the particle-size cutoff point. Screens can be changed to substitute different mesh sizes.

Most of the changes available will allow partitioning at different size cutoff points, but do not help much in modifying the capacity to handle a particular size fraction. Rather than pushing the turndown ratio limits of the modules, it may be necessary to use larger equipment, parallel units, or longer operating times to increase the system capacity without sacrificing performance. This is why good feed preparation is essential to maintain reliable steady-state operation.

3.4.1.2 Contaminant Distribution

Most of the previous discussion regarding particle-size distribution applies to contaminant distribution as well. Certainly, for a process relying on physical segregation alone, residual contamination levels in the clean-product fractions will vary consistently with the degree of feed contamination if the underlying soil matrix is consistent. A process that solubilizes the contaminant may work most effectively on feeds within a prescribed concentration range, and more contaminated feeds may require additional stages of treatment or longer residence time in some stages. In this type of operation, feed blending may be driven primarily by contamination levels and secondarily by leveling the particle-size loading.

If the contamination levels are extremely variable and "hot-spot" soils make blending impractical, another option is phased operation, which entails segregating the less-contaminated soils for initial processing, followed by treatment of more-contaminated materials. This type of processing requires more planning, but reduces cross-contamination. The less-contaminated soils can be processed at a relatively high throughput, and then the system can be adjusted to process the more heavily contaminated soils more efficiently. In any case, the same basic principles apply. Good site characterization, staging the feed and blending or segregating, if necessary, will permit the most reliable continuous operation.

3.4.1.3 Moisture Content

The moisture content of the feed may vary dramatically in humid environments, in areas with shallow groundwater, or after precipitation. These may alter the water balance in the soil washing process and may require compensation. A natural increase in water content will reduce the need to add water to reduce dust or disperse particles during processing. For a system operating with a net use of water, the natural water source may simply reduce the demand on the utility water source. At some point, however, unrestricted water incursion may make feed materials agglomerate or sticky, or create a slurry too difficult to feed. Grading or contouring the site to control run-on may be just as important as controlling runoff to uncontaminated areas.

Dewatering the residuals may also be complicated unless the filtering, drying, and staging areas are protected from precipitation. Because disposal costs are a function of weight, additional moisture content directly affects project costs directly. Also, the waste-acceptance criteria for landfill disposal restricts free liquids, thus necessitating reasonable control of moisture content. If significant precipitation is expected at the site, the extra capital costs of operating under cover may be readily compensated by increased operating availability regardless of the elements.

3.4.1.4 Clay and Natural Organics

Soils with high clay content load the modules that separate fines. They can also cause agglomeration and may be difficult to dewater. The first problem is addressed above in the discussion of particle-size content. Here, too, larger equipment or parallel units may be necessary to handle the additional fines load. Agglomeration can be minimized by using enough water to disperse the clay particles or by chemically modifying the water. In the rough separation steps, including the bar-screen and trommel, large agglomerates may contain significant contamination, requiring hand sorting or wet operation. Physically breaking up the large pieces of compacted clay is time consuming and energy intensive. Finally, dewatering may require injection of a flocculant to assist settling, followed by a filter press to squeeze the water out of void spaces and compact the settled solids.

3.4.1.5 Oil and Grease

Small amounts of oil and grease can be released with surfactants that isolate the organic molecules in micelles. Good mixing and adequate residence time are essential to facilitating surfactant effectiveness. Agitation may cause foaming, which can be controlled with a defoaming agent. Selection of additives can only be made through treatability studies. Blowdown of a fraction of the circulating water for treatment will be required to maintain the wash water quality.

Greater amounts of hydrophobic contaminants may require pretreatment, such as a solvent extraction or thermal desorption step, prior to soil washing, to remove enough of the organic matter to allow processing in an aqueous system. Weathered hydrocarbons may agglomerate soils requiring sizing prior to pretreatment. A free organic phase may require an oil-water separator to allow the organic to be skimmed off for disposal.

3.4.1.6 Volatile Organic Compounds

The fate of volatile organic compounds (VOCs) must be decided in discussions with regulators prior to commencing work. Most of the VOCs will be lost to the environment during soil handling if no steps are taken to capture them. Potential exposure hazards to workers and the local population must be considered in addition to the consequences of free release to the atmosphere. Both Occupational Safety and Health Administration (OSHA) and US EPA standards apply.

If the releases are to be controlled, open vessels may have to be covered with ventilation hoods. Otherwise, the system can be operated in closed vessels under a slight vacuum, or the entire process can be enclosed in a controlled environment vented to a treatment system. The offgases and water blowdown may require carbon adsorption. The carbon will require offsite disposal or stripping followed by some type of organic destruction. Removal of semivolatile contaminants can be enhanced by vacuum operation and heating of the process. Air monitoring equipment will probably be required to check the ambient conditions at the site to protect workers and to ensure emissions are within prescribed limits.

3.4.1.7 Radioactive Contaminants

Radioactive contaminants may require the same type of controls on free-release as described for VOCs. Radionuclides will either be gaseous (radon) or nonvolatiles carried on dust or mist. Radon can only be vented, but radioactively contaminated particles can be controlled with high-efficiency particulate air (HEPA) filters. Primary and possibly even secondary filtration may be required prior to venting gaseous emissions. Filtration and ion-exchange may be used for water treatment. In addition, process residuals must be disposed at Nuclear Regulatory Commission (NRC)-licensed sites. If the residuals are both radioactive and hazardous under RCRA regulations, they are considered mixed wastes and disposal options are very limited. Wastes must meet land disposal restrictions and the NRC-licensed-waste acceptance criteria for the disposal site.

Treatment of radioactive contaminants will also require oversight by licensed health-physics technicians, and real-time monitoring of the effectiveness of personnel decontamination. This is monitored at points of egress from the soil washing process area using hand-held monitors to detect radioactive contamination on personal protective equipment (PPE).

3.4.2 Physical Conditions

3.4.2.1 Temperature

Although both heat and cold can affect operation, compensating for low-temperature extremes is more difficult. Heat will cause worker fatigue and increased evaporative losses from the system. Heat stress is exacerbated by PPE, but careful planning and limiting work shifts can ensure safe operation. Evaporative losses from the process can be readily offset by adding makeup water. Heat will actually improve dewatering of the process residuals.

Cool conditions will assist workers wearing PPE, but near-freezing temperatures will induce workers to dress warmly, which may again lead to heat stress over prolonged work shifts in PPE. Freezing conditions can be accommodated, within limits, by heating process solutions and heat-tracing low-flow and small-diameter piping. Extended freezing conditions will probably require a hiatus in operation, and cold-weather layup of equipment including a comprehensive checkout to ensure thorough draining of the system. Variations in temperature throughout the day must be considered in planning two- or three-shift operations. Seasonal temperature changes are largely taken for granted, but late or early freezes can fracture small vessels and tubing and thicken reagents beyond use. These variations cannot be prevented, but damage can be controlled by planning ahead and protecting sensitive process areas.

3.4.2.2 Humidity

High- and low-humidity environments create conditions similar to those described for temperature extremes and soil moisture content. High humidity will worsen heat stress, and add to the challenges of dewatering the process residuals. Shortened operating shifts and more rest periods will address the former, and longer drying times and soil turning can help with the latter. In addition, corrosion of instrumentation is an important consideration. It may be necessary to move some field units to a controlled environment, such as an air-conditioned control room.

Low humidity will decrease the impact of the above concerns, but can make it more difficult to control the generation of hazardous dust. It may be necessary to sprinkle excavation and staging areas with water, and operate all equipment accordingly in order to control exposure by inhalation and the potential contamination of adjacent property. Inexpensive, biodegradable water polymer emulsions have also been used to control dust by forming a thin crust on the surface of piles set aside for longer-term storage (e.g., treated piles awaiting confirmation of analytical results). In radioactive environments, dry air will also increase the static charge on polyester clothing and make it more difficult to prevent personnel contamination. Natural-fiber clothing will essentially eliminate the problem.

3.4.2.3 Grade

Most environmental restoration operations will be conducted on developed property. The operating area may only require compaction and installation of a liner to catch spills, or pouring a concrete pad prior to installing process modules. Space must be available for feed and product soil staging, surge water capacity, and analytical support. If the area has not been graded, however, additional planning is required to ensure safe and practical operation. Orientation of support functions, ingress and egress paths, and the utility interface should be functionally designed for efficient operation and movement of materials.

Soil contouring may be required to create surge capacity for process water. A gentle slope can be exploited by discharging the process water blowdown to a small-lined settling basin that cascades to lined secondary or tertiary basins from which the clarified water can be pumped for additional water treatment and process makeup. Similarly, some grade can be exploited for a gravity-flow process in which pumping and level control are minimized by designing sequential process steps in a cascade fashion. Flow between steps is by overflow or syphon. Approximately 929.4 m^2 (10,000 ft^2) of space is required for a full-scale soil washing plant working area.

3.4.2.4 Debris

As of this writing, federal environmental regulations consider materials greater than 60 mm (about 2 3/8 in.) to be debris and subject to different treatment standards for hazardous constituents than smaller materials. The debris classification includes natural materials such as rocks and branches as well as man-made construction materials and trash. A pile of material may fall under this classification if it is judged to be primarily debris by visual observation, even if it is not composed entirely of debris. Legal guidance should be obtained and local or state regulations on pertinent federal regulations checked [see the Code of Federal Regulations (CFR) at 40 CFR 268.2(g) and 268.45] to ensure proper compliance.

The regulations prescribe how debris can be treated and disposed. Further guidance has been published commercially (e.g., Elsevier Science, Inc. 1996, updated annually). Whether debris should be treated, recycled, or disposed as nonhazardous solid wastes, or sent to a hazardous waste landfill can only be determined by a cost analysis and discussion with the responsible regulators.

Debris should be removed from feed materials not only because of these different standards, but because large, irregularly-shaped objects are problematic in operation and may damage processing equipment. Separation from the soil matrix is typically done using a bar-screen or grizzly-type separator and a rotating screen (trommel). However, because of the extreme variety in debris and the history of each site, a tailored approach may be required, including flotation, mineral jigs, and possibly labor-intensive manual sorting.

Special cases also extend to munitions, batteries, and metal fragments. While these materials may be too small to be considered debris, they represent a pure contaminant source that may increase the residual contamination to unacceptable levels for any sample in which they are included. Separation may be affected by exploiting density or magnetic differences between the metals and the soil matrix. Success of the operation may rest on efficient physical separation. Costs may potentially be offset by recycling the metal fraction at a commercial smelter, thus, avoiding the costs of disposal.

3.4.2.5 Vegetation

Vegetation should be removed as debris to the extent possible. Small plants, grasses, and roots will blind screens and filters and float in clarifying equipment. Large amounts of small vegetable matter may require a separate flotation step to allow removal by skimming prior to screening sands and small gravel. Some plants have a substantial affinity for metals and may concentrate contaminants in their tissues. Disposition of this material should be determined in discussions with regulators. Staging of the vegetable matter for separate off-site treatment and disposal may be advantageous.

3.4.2.6 Animals

Indigenous species will probably not affect operations significantly, however, protected species may require fencing or other barriers to limit access to contaminated process water and electrical equipment. Again, this is a matter to be resolved with cognizant regulators and through use of best management practices.

3.4.2.7 Sensitive Populations

Proximity to sensitive populations such as schools, day-care facilities, and hospitals does not present additional constraints, but may exacerbate some of those already described. Certainly, air and water emissions and site access will be more carefully controlled to reduce any potential health and safety risks. Adherence to OSHA, US EPA, and local regulations is, of course, mandatory, but good communication and community relations are essential to maintaining local cooperation and meeting the project schedule. Similar consideration should be given to any population, structure, or protected area, such as watersheds or wetlands that may be perceived to be at risk.

3.4.2.8 Infrastructure

Any supporting resources required for operation must be secured prior to commencing operations. Utility power can be supplemented by generators, but water may have to be trucked in if there are no continuous local sources. Relying on irrigation sources or stream flow will be subject to water rights and may lead to intermittent availability in some areas. Recycling water to the extent possible will reduce supply and disposal costs and minimize the impact of aqueous discharges. Discharge to a local publicly owned treatment works (POTW) may reduce treatment costs and enhance local community relations. Access to roads may be restricted by size and weight limitations. A route for ingress and egress of heavy equipment and waste shipments should be negotiated with local authorities.

3.5 Pretreatment Processes

A soil washing process is intrinsically a modular system tailored to site-specific conditions. As such, the configuration may vary widely from one application to another. In addition, some systems rely solely on physical segregation of highly contaminated fine material from less contaminated sand and gravel fractions, in contrast to extractive systems that use chemical additives to solubilize contaminants. The entire physical separation process could be considered pretreatment for an extractive system that actually dissolves contamination out of the soil matrix. For discussion here, pretreatment steps will be considered to include the materials handling and conditioning operations necessary to segregate the four principal fractions: debris, gravel, sand, and fines.

Site preparation, including characterization, grading, control of run-on and runoff, securing utilities, community relations, and system installation and shake-down, are all essential activities, but are not discussed here. Treatment operations are discussed sequentially in the order they would be expected to appear in a typical process, starting with removal of debris and vegetation, continuing with feed staging and blending, rough separation of gravel, and efficient segregation of fines from sands. Each section concludes with a short discussion of follow-on treatment for the subject fraction.

3.5.1 Debris and Vegetation Removal

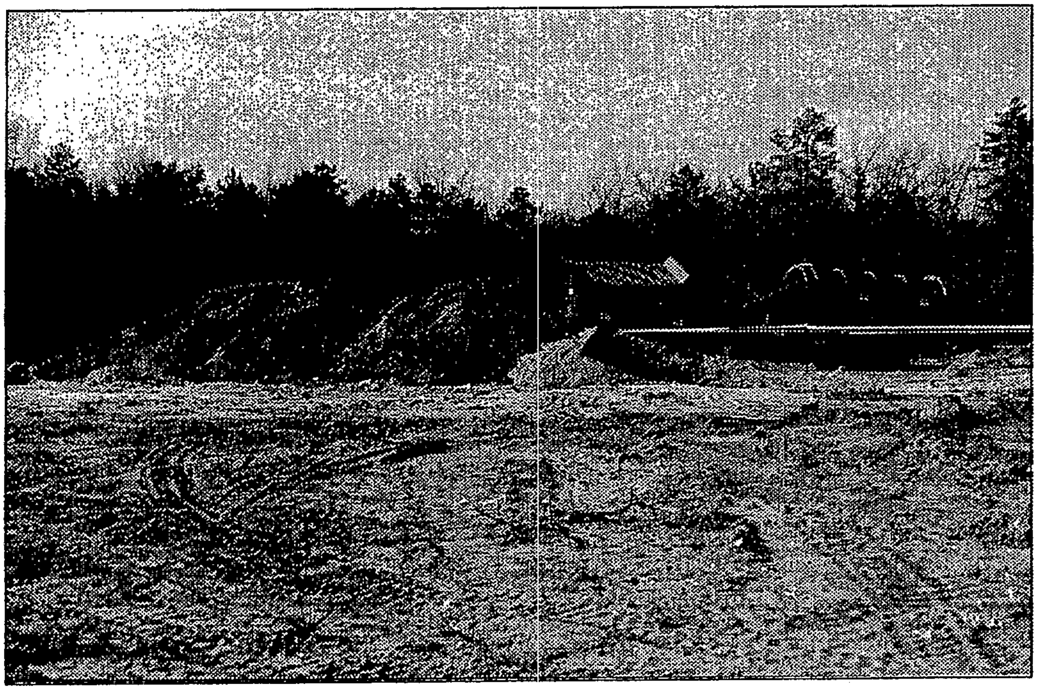
3.5.1.1 Bar Screen Separation

Debris and vegetation are described in Sections 3.4.2.4 and 3.4.2.5, respectively. In general, debris is any material greater than 60 mm (2 3/8 in.) in at least one dimension [see 40 CFR 248.2(g) for a more exact definition]. Debris should be removed because it must meet different treatment standards than other hazardous wastes and because it will interfere with downstream processing equipment. Vegetation should also be treated separately because it will blind filters and screens, interfere with settling and flotation steps, and may contain substantial contamination concentrated by plant metabolic processes.

Most debris can be separated simply by dumping the gross excavated material on a bar screen with the bars appropriately spaced (see Figure 3.5).

Regulations allow reasonably imperfect segregation, as long as the debris is primarily greater than 60 mm by visual inspection. If the material contains a substantial amount of woody vegetation and medium-to-large plants, they should also be separated in this operation. The oversized product will probably pass cleanup criteria without additional treatment because of the low surface-area-to-weight ratio. This may not be true if containers are present with residual contamination inside, if large clay or precipitated metal conglomerates are carried over, or if fragments of regulated metals are in the matrix. Additional characterization may be required to demonstrate this fraction is clean enough for disposal. Depending on the site-specific conditions, manual sorting and/or debris treatment meeting regulatory requirements (40 CFR 268.45) may be necessary.

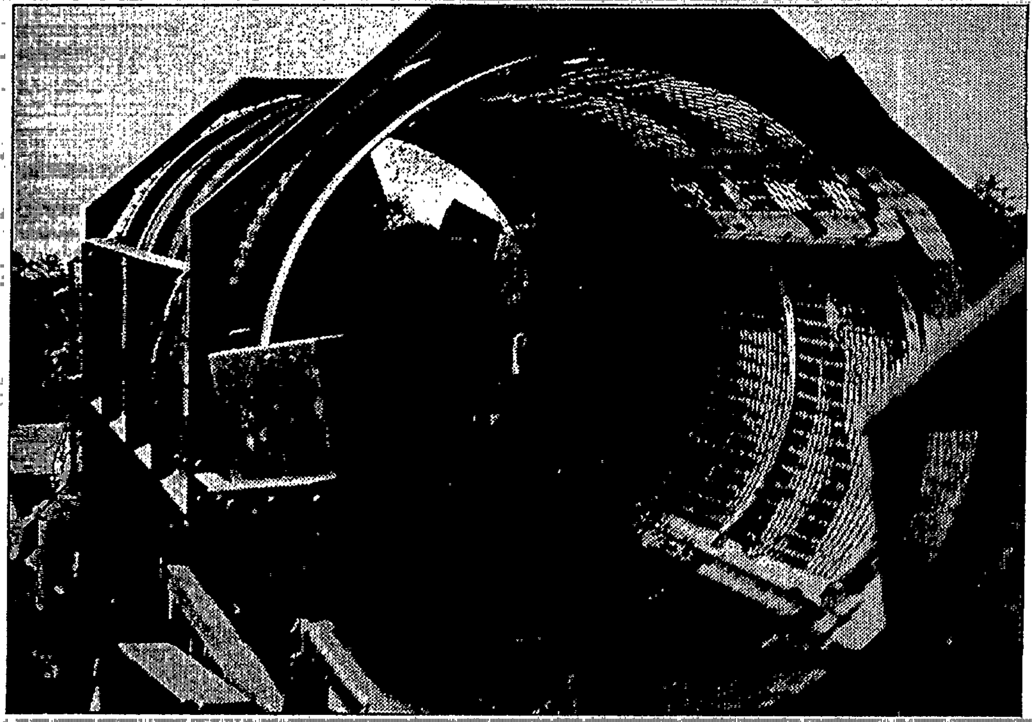
Figure 3.5
Debris Being Separated by Dumping Gross Excavated Material on a Bar Screen with the Bars Appropriately Spaced



3.5.1.2 Rotating Screen Separation

An inclined rotating screen (trommel) may be used to provide additional rough separation (Figure 3.6). The tumbling action of the trommel will also assist in breaking up agglomerates and stripping compacted soil from cobbles and gravel. The trommel may be operated with or without internal water sprays. Dry operation reduces caking in the trommel, but water sprays reduce dust and enhance the comminution effects of the tumbling.

Figure 3.6
Trommel



Small plants, grasses, and some slender debris will carry through the bar screen and, if not separated, will interfere with downstream processes and may damage equipment. A trommel can perform more than one size separation, and if site conditions warrant, the bar screen could be set to remove only very large material (3 to 4 in.) and the trommel used to remove the rest of the debris as well as a smaller size fraction. Upflow water separation columns can be effective in removing small pieces of vegetation and fine humus or humatic organic matter. If gross amounts of plant matter carry through from the debris separation, a second cut with the trommel to yield a +3/8 in. (+4 mesh) gravel fraction would catch most of the vegetation. If necessary, the grassy matter could be floated out of the gravel fraction for separate disposal. The +3/8 in. (+4 mesh) fraction will likely pass cleanup criteria with only limited treatment (water rinsing) or no further processing at all. After sampling to verify allowable residual contamination levels, the gravel could be returned to the excavation.

Cutting out the large gravel fraction at about 3/8 in. enhances downstream cleaning operations, which are only effective on particles up to approximately that size. For example, an attrition scrubber uses opposed impellers to intensively mix a soil slurry, causing the particles to collide and abrade surface contamination. Particles greater than about 3/8 in. are simply too heavy for an aqueous solution to keep suspended, and they settle out, reducing the overall effectiveness of treatment.

3.5.2 Feed Preparation

Steady-state operation allows the process to run most efficiently for the longest period of time. This translates directly to cost-effectiveness and building confidence in the eyes of regulatory authorities. A soil washing system is only as good as its designers can make it based on their experience and the site-specific information they are provided. Good treatability studies and field/fixed-facility pilot studies can provide the needed information and often pay for themselves in better designs and reliable full-scale operations. Good operators can make up for some operating excursions, but operating a system under conditions outside the scope of design will still probably be reflected in the final results. Good feed preparation and feed soil blending are often essential to keep the process within its reliable operations boundaries or "operating envelope."

Discussions on the ramifications of particle-size and contamination distribution are presented in Sections 3.4.1.1 and 3.4.1.2. Comprehensive site characterization includes a good understanding of both typical site conditions and extremes to be handled by the process. Designing a system to readily compensate for any extreme would be cost prohibitive, so a good design is always a compromise between reliable and flexible operation. A project that involves variable feed, and restrictive controls on the product places greater responsibility on the operator to keep the system on line and running satisfactorily. By staging feed batches and blending extremes in particle size or contamination, process parameters can be leveled and more reliable operation made possible.

Continuous characterization of feed soils to support smooth operations and good treatment performance is absolutely necessary. The number and type of analyses is site-specific, and initial estimates based on characterization data may require adjustment based on field operation experiences. Developments in field instruments, including x-ray fluorescence (metals), gas chromatography/mass spectroscopy (organics), and germanium iodide (alpha radiation), allow real-time measurements that can be supported by periodic laboratory analyses using US EPA-approved SW-846 methods (US EPA 1986). Normally, confirmation is performed using a five-point grab sample composite for every 100 tons processed.

Ample space should be allowed to hold feed batches for characterization and blending prior to processing. With debris and large gravel removed, representative sampling and homogenization are simplified. As the job proceeds, the time and care invested in feed preparation can be adjusted to fit operational needs for cost-effective processing.

3.5.3 Gravel Separation

Site-specific conditions dictate whether additional gravel separation and/or cleaning is warranted. Vibrating screens may be used to segregate gravels from the sand and silt/clay fractions and remove most of the remaining organic debris, such as leaves and grasses. Again, pressurized water sprays can be directed at the screen deck to enhance cleaning of the gravel and wash sand and fines through the screen. Inclined screws can also be used to perform this separation.

At munitions sites, a significant amount of metal may be contained in the gravel as both metal fragments and partially oxidized deposits smeared on particle surfaces during impact. A mineral jig, which is a type of upflow classifier, may be used to separate metal fragments as the more dense underflow. A jig also abrades soil particles in an agitated bed of metal or ceramic balls. Additional cleaning may be accomplished by adding an extractant and taking advantage of the good mixing in the jig to solubilize metal deposits. However, treatability studies are necessary to determine whether the extraction is cost-effective in the presence of a free metal fraction. It may be more effective to separate the metal fragments with water to minimize dissolution. If the gravel fraction requires additional cleaning to meet disposal criteria, treatability studies should be used to design a cost-effective extraction scheme to reduce the residual contamination.

3.5.4 Separation of Fines from Sands

In many cases, the sand fraction will require only modest treatment, if any. The fine silt and clay fractions may be the only material contaminated beyond release limits, and, if the sands are rinsed free of fines, it may be possible to release them after verification sampling. If cleaning of sand is necessary, attrition scrubbing can be used for particles as small as 200 mesh (75 μm). Below this size, the momentum of the particles is not sufficient to cause significant surface abrasion in an aqueous solution. Whether or not the sand fraction must be scrubbed, thorough separation of sand from finer material is key to the success of the process. Carryover of a small fraction of highly contaminated fines can cause the relatively clean sand fraction to fail verification testing.

Rough separation can be achieved with an inclined screw to provide initial sizing between gravels, sands, and fines. The classification obtained will reduce the load, but secondary separation will probably still be required to provide a clean sand fraction.

Hydrocyclones can efficiently perform this separation. Some cyclone designs allow reconfiguration in the field if the initial design requires modification to adapt to field conditions. A hydrocyclone operates in a fashion identically to the cyclones used for separating dust and grains from gaseous streams, except the motive fluid is water. Particles are separated by their relative drag as the rotational flow of a slurry imparts centrifugal force. The slurry enters the cyclone tangentially, and larger particles are forced to the vessel walls to exit the bottom while finer particles exit the top of the cyclone. Separations of over 90% efficiency are attainable in a single pass, and banks of hydrocyclones can be operated in series to attain a desired efficiency.

Nearly absolute separation can also be achieved using an upflow water column classifier. Particles are once again separated by their differences in density and relative drag, this time manifested in settling rates. The slurry is pumped into a column of rising water. Those particles settling more rapidly than the bulk flow exit the bottom, and finer particles are eluted with the water to exit the top. The particle-size cut is adjusted by simply varying the water flow rate.

3.6 Posttreatment Processes

Posttreatment processes will vary depending on the configuration required for the specific application. For the purposes of this discussion, it is assumed that all planned soil decontamination has been accomplished, and proprietary solvents are not considered. All that remains are the treatment of gaseous and aqueous effluents and the preparation of process residuals for disposal. All requirements should be negotiated with authorities and communicated to the public prior to commencing operations.

3.6.1 Gaseous Emissions

Most soil washing applications are intended for treatment of surficial soils exposed to the atmosphere. Most, if not all, volatile contaminants have been lost. If the process solutions are primarily water, possibly with some pH adjustment and some flocculant added, the capture and treatment of gases will probably not be required. Atmospheric controls may be limited to mitigating fugitive dust during excavation and materials handling during feed preparation.

If significant amounts of VOCs or radionuclides are present, however, offgas control and treatment will probably be required. Controlled ventilation, activated carbon adsorption, and high-efficiency particulate air (HEPA) filtration are discussed in Sections 3.4.1.6 and 3.4.1.7.

3.6.2 Water Treatment

Ideally, the soil washing process is run as a net user of water because the product soil fractions contain more water after processing than they contained as feed. If this is possible, only the water contained in the process at job completion may require treatment. If this is not possible, or if a blowdown stream is required to maintain water quality or chemical effectiveness, then a water treatment system will be required. The simplest form of treatment can be accomplished using a quiescent settling pond to clarify water for reuse or discharge. The site can be contoured and a liner used to create such a pond. Clarified water can overflow or be syphoned to another pond for reuse or sampled prior to discharge. Ideally, the clarified effluent can be discharged to a local POTW and must only meet local sanitary standards.

If contamination is significantly solubilized and the local POTW cannot accept effluent after clarification, or if the discharge must be to an open body of water where more stringent requirements apply, more sophisticated treatment may be required. Suspended solids can be reduced further using sand or multimedia filters. A free organic phase should be skimmed using an oil-water separator, and dissolved organics free of fines can be adsorbed using activated carbon. The spent carbon will require off-site disposal or stripping followed by some type of organic destruction. Metals and radionuclides can be removed using some combination of precipitation and filtration or ion exchange. Careful pH control can minimize the amount of sludge generated and facilitate settling and filtration. Many selective ion-exchange resins are available to focus on specific ions rather than depleting exchange capacity on the salts typically found in natural waters or leached out of the soils during processing.

Treatability studies may be required to ensure that fairly standard water treatment practices will be effective under site-specific water chemical characteristics, particularly if the process used chemical additives that may interfere with coagulation or ion exchange. Simple jar tests can be used to determine initial feed rates. Pilot testing is used to refine feed rates to ensure reliable, effective treatment.

3.6.3 Dewatering Fines

In many cases, soil washing is limited to separation of contaminated fines from the rest of the relatively clean soil matrix. In some cases, the contaminant(s) can be extracted from the fines, but there are always some residual fine materials left from processing. Dewatering the residuals can be the "Achilles heel" of the process.

Clay particles are very small, and the negative surface charge on the particles repels like particles, so they do not settle even after extended periods. Flocculants are long organic molecules with many charged sites along the chain that can stabilize surface charges and allow the molecules to bridge between particles. Small amounts of flocculant can sometimes greatly assist settling and clarification. The settled slurry can then be pumped to a filter press, which forces water out of the slurry to create a sludge for disposal. Plate and frame presses may be used, but are limited to batch operation. A continuous-belt press is better to support continuous operation. Centrifuges are another possible dewatering device, but care is required in design/testing to ensure that the required performance can be obtained.

For processes that solubilize metallic contaminants, similar dewatering is necessary following precipitation of the metal by pH adjustment. Dewatering can also take place in stages, depending on site-specific project needs, with a press or centrifuge doing the bulk of the job followed by "polishing" dewatering conducted with solar, surcharging, or electroosmosis techniques. The added dewatering cost can often offset high disposal cost.

3.6.4 Disposal

The waste-acceptance criteria for the ultimate disposal of residuals will dictate additional requirements for stabilization, analyses, and packaging. Landfills cannot accept shipments containing free liquids, so it would be wise to place dewatered residuals under cover to preclude exposure to rain or snow. Ample space should be available to continue processing even if shipment is delayed because of analytical or transportation difficulties. In arid environments, it may be advantageous to enhance contact between the sludges and the ambient air to further reduce the water content and, therefore, the weight of material to be shipped. This can be accomplished by turning the pile or spreading it if space permits.

Leachable metals in water treatment sludges or soil fines may require stabilization prior to disposal. A variety of methods based on pH adjustment, sulfides, and pozzolanic additives are available. Treatment may also be available from the disposal unit operator, or on-site services can be purchased from commercial vendors.

Organic material, such as contaminated humic matter or loaded activated carbon, may be incinerated, stabilized, or directly disposed at a landfill, depending on its characteristics after treatment and the relevant waste-acceptance criteria.

Disposal of radioactive residuals is discussed in Section 3.4.1.7.

3.6.5 Equipment Decontamination

Decontamination of process equipment is necessary before removing it from the remediated site. For typical organic and RCRA-regulated metal contaminants, this may only require flushing the process lines and rinsing the equipment with fresh water. Rinse water can be treated with residual process water, which will also serve to flush out the water treatment process.

This requirement becomes much more restrictive when processing radioactive materials. State-of-the-art field measurement of radionuclides is at the picocurie level, which, for short half-life nuclides, translates to several orders of magnitude below detection limits for chemical species. Process lines nominally smaller than 2 in., small pumps, filters, and ion-exchange media will probably be disposed as wastes. Decontamination of process equipment may require aggressive solutions that will quickly corrode carbon steel. In addition, it is common practice for health-physics technicians who are responsible for preventing the spread of contamination to automatically consider contaminated any surfaces that they cannot access to monitor.

Decontamination requirements for transporting equipment from a contaminated site must be negotiated prior to deployment. Finally, it is also advisable to negotiate valuation and disposition of equipment that cannot be decontaminated prior to accepting a restoration contract in a radioactively contaminated zone.

3.7 Telemetry, Process Control, and Data Acquisition

Equipment used for data acquisition, process control, and telemetry have been greatly improved and diversified, making it possible to constantly monitor and control most types of feed streams and many variables (e.g., pH, flow rate, percent solids, etc.). Such equipment can improve the operation of soil washing units and reduce costs. This section discusses the benefits of this technology, its potential applications, specific types of meters and telemetry equipment, and overall costs. This is not intended to be an exhaustive discussion of meters and applications relevant to soil washing. The purpose is only to provide examples of instruments and stream types that have been monitored in past projects.

3.7.1 Benefits

Automatic data acquisition, process control, and telemetry techniques have many benefits for soil washing operations. Automation can cut labor costs by reducing manual monitoring and sampling. Soil washing results may improve because constant, real-time control is possible, allowing operators to know immediately when a stream's characteristics fall outside the required operating parameters. Constant feeds can be achieved and monitored, which is a necessity for optimal operation of most soil washing equipment. Finally, data are more accurate when recorded automatically. These techniques reduce the amount of manual dictation required and improve the frequency of data collection.

Telemetry options provide greater flexibility for soil washing operations. These systems allow data to be monitored and controlled from the project site or from remote locations. In addition, these systems can be configured to give personnel at remote locations greater access to the data.

3.7.2 Potential Applications

Data acquisition, process control, and telemetry equipment can be applied to most unit operations in a soil washing process. Some of the operating parameters that can be measured are pH, flow rates (for liquids, solids, and some sludges), totalized flows, temperature, pressure, density, and sump levels. In addition to performing data acquisition functions, the equipment can be configured within process loops for automatic control, automatic sampling, and alarms. Telemetry systems can be used in any application provided there is a means for sending the information (e.g., radio, telephone, or broad-band cable television).

Certain conditions may affect the accuracy of telemetry equipment and hamper its use in a soil washing operation. Examples include high-range or high-plasticity solids, low flow rates with high solids content, pulsating feeds, or pipes that do not run full at all times. Telemetry accuracy may also be affected if meters are placed on equipment that vibrates severely or is very sensitive to head or volumetric displacement.

3.7.3 Meter Type

3.7.3.1 Conveyer Load Cells

Conveyer load cells can be effective for measuring high-solid streams. They are installed into existing equipment and can replace additional materials-handling steps, such as weighing solids before they are fed to the soil wash unit. These cells vary by design and capability, but generally consist of electronically balanced load cells, which provide a weight signal by measuring vertical forces of mass transmitted. The cells are supported by a conveyor, which has a speed sensor. When the speed and weight reading are combined, the flow rate and amount of totalized materials can be integrated.

The size of the load cells varies with the size of the conveyer. Several options and measurement designs are available, depending on the application. Process-control loops can also be installed to make feed rates more constant.

3.7.3.2 Digital Doppler Meters

Digital doppler flow meters are recommended for liquid streams that contain fine mineral matter or have low solids content. These meters work with sound waves or magnetic flux to measure flow rates through pipes and are designed to measure aerated and/or solids-bearing fluids. Since the doppler meters clamp to the outside of the pipe, they are nonintrusive, preventing contamination and leaks. For this reason, these instruments are effective for use with corrosives and petroleum products. The operating parameters to be measured and the processes to be controlled by these meters vary and are determined by the user. Some units have the capability to discriminate and reject noise frequencies and power-line harmonics.

3.7.3.3 "Venturi" or Differential-Pressure Transmitters

Differential-pressure transmitters read the change in pressure across an orifice or a narrow throat that, in turn, is related to the flow rate of the stream. This can be used to measure flow rate, level, low gage pressure, vacuum, and specific gravity. The amount of volumetric displacement monitored by these instruments depends on a particular unit's design. The range of pressure change, output signal, material of construction, and other options depend on user needs.

3.7.3.4 pH Meters

For process-control applications, automatic pH meters require a sensor and analyzer controller. The analyzer portion can be used for on/off relay control and proportional control capability. Analyzers are available to provide a pH signal as a voltage or an amperage, as required. The pH sensors either read pH directly or measure it differentially with respect to a solution-ground electrode. Materials of construction, measurement signals, mounting requirements, and temperature sensors can be adjusted based on needs.

3.7.3.5 Temperature and Pressure Meters

Temperature and pressure meters are quite common and readily available. Like pH meters, they can be included in process-control loops by using a sensor and analyzer controller unit. Many different styles are available to accommodate most user needs.

3.7.4 Costs

The cost of instrumentation for a soil washing system depends largely on the complexity of the telemetry system and instrumentation desired. The greater the number of streams and variables monitored, the higher the cost will be. The function of the instrumentation also affects cost dramatically. For example, process control loops are much more costly than systems designed solely for data acquisition. The complexity of the telemetry equipment (e.g., the communication mode and number of listening master units) also plays a significant role in system costs.

The estimated design and equipment cost for a telemetry system to perform automatic data acquisition for a soil washing plant that processes 1 to 5 feed streams at process rates of 1 to 10 tonne/hr (1 to 11 ton/hr) ranges between $40,000 and $80,000. The addition of complex devices, such as density meters or process-control loops that completely control the soil washing system, can increase the cost by amounts ranging from $250,000 to over $500,000. Special materials of construction, elaborate telemetry systems, or unusual instrument functions will significantly affect these cost ranges.

3.8 Safety Requirements

3.8.1 General Considerations

Safety during the soil washing operations is essential to protect on-site and off-site workers and the public from the associated hazards and pollutants. This is accomplished by site safety and environmental control plans. The environmental control plan is a separate document which is linked to the operating permits and is addressed elsewhere. The site Safety Plan is a detailed operational document defining how workers and site visitors will be protected. It should contain all the information and response data required for the worker, including such items as the location of hospitals, types of wastes to be handled, recommended levels of safety equipment, and emergency procedures and contacts for the site. The Safety Plan must be made available to all workers at the site, and the workers must be given an opportunity to review the Plan and indicate their concurrence and acceptance by signing Safety Plan Review Checklist. The Safety Plan should be a dynamic document which is revised whenever there is an safety incident.

The Safety Plan is implemented through a Manual of Safety Procedures. These procedures govern the operations at the site and typically include such items as lock-out tag maintenance, confined space entry, respiratory protection areas, respiratory protection documentation, visual inspection, safety reviews, protective clothing, hardhat color coding, sampling, and hydraulic equipment, electrical equipment, and power machinery operations. Sometimes safety procedures are coordinated with union contracts, and in that instance are also delineated by trade. All employees working on the site must be trained in the general safety procedures and those which pertain to their work.

3.8.2 Identification of Safety Hazards in Design

Many potential safety hazards can be eliminated in the design of soil washing facilities. Some hazards are eliminated by the component equipment manufacturers by following the Underwriter's Laboratory and National Fire Protection Association (NFPA) codes. In such instances, the safety controls must be reviewed to ensure that they meet the operational and safety standards for the site. Other hazards are minimized or eliminated in the design of items, such as protective railings, ladders and climbing equipment, ramps over potential tripping hazards, protective shrouds or insulation over pipes carrying hot liquids, electrical grounding protection, etc.

Site hazards which must be planned for include underground utilities, buried cables, underground storage tanks, buried drums, and buried foundations. Generally, these hazards have been located and identified prior to the design by the site characterization, but it is recommended that the local utilities mark the location of buried cables and underground utilities on the site.

Special precautions may be warranted during facilities construction installation. At that time, the site is full of heavy equipment and there are many dangers such as crushing, dropping, or other hazards related to moving heavy equipment on and off trucks, cranes contacting overhead power lines, insufficient soil bearing capacity for machinery loads, front end loaders working too close to the edge of an excavation, etc.

Decontamination of equipment is an extremely important consideration during design. Every piece of equipment being brought on the site must be decontaminated before it leaves the site. This is especially important at sites where nuclear wastes are being treated. At the Hanford Nuclear reservation and other DOE sites, it is not uncommon to find complex equipment which was abandoned by contractors because it could not be successfully decontaminated.

Typically, the Safety and Process reviews are conducted after the development of the Process and Instrumentation Diagram (which is equivalent to about 10-15% of the completed design), at the 30% completion level, at the 60%

completion level and again at the 90-95% completion level. These design reviews grow increasingly thorough and complex as the design is finalized.

The Process Safety Manual (PSM) development should be started when the P&ID is finalized. The Process Safety Manual is developed from equipment specifications and design considerations. The PSM is completed as the final equipment specifications are developed. Depending upon the needs of the PSM review process and the degree of hazard associated with equipment failure, the PSM may be a very thin or a very extensive document. When completed the PSM will become a part of the operating manual and will be cross referenced to the Safety Plan.

3.8.3 Personal Protective Equipment and Worker Safety

The specific personal protective equipment (PPE) required can be minimal or significant. Many of the hazards at a soil washing site are dust hazards, but chemical hazards can also be present. It is important to consider all the chemicals on site and the conditions which the worker may encounter. The degree of protective equipment appropriate to the hazards present at the site should be specified. Also, entry and decontamination zones should be established according to the degree of probable worker exposure. The following suggestions are offered.

- If respirators are to be used at the site, all workers requiring respirators must be fit tested, and that testing documented and maintained. This also means that there must be a policy prohibiting facial hair.
- Safety equipment is often cumbersome. Work schedules and activities must be able to accommodate this reduced productivity. For example, in some instances, additional layers of protective gloves may be required making it difficult to pick up and use equipment.
- Hard hats, eye protection, hearing protection, and safety shoes are almost always mandatory. If hearing protection is required, the workers must be made aware that specialized hazards are created when workers cannot hear heavy equipment and alarms.
- Communication by walkie-talkie and/or voice-actuated intercom may aid coordination between workers and heavy equipment operators and control house operators.

- Many workers will be allowed to wear only coveralls for protection. However, there may be other potential chemical exposures which need special protection or even Self Contained Breathing Apparatus protection for their work.
- For most hazardous waste operations, especially those where protective suits are required (which can add up to 20 kgs of weight and bulk), the three-person buddy system must be used. This system enables two to rescue one who suffers a physical problem or injury. Standby personnel should also be available for rescue during hazardous operations.
- Worker training is an effective tool in creating safe work conditions. This training can be a combination of classroom and on-the-job training, but the training must be documented and the records kept in a separate personnel file.
- Medical examinations, which include enzyme blood work and stress testing, may be necessary depending upon the type and level of exposure. These decisions should be made in conjunction with a qualified physician or health professional.
- All emergency response personnel, including fire and rescue, hospital emergency room, and transport ambulance personnel must be made aware of the type of contaminants on the site so that they can take appropriate precautions to decontaminate an injured person and protect the emergency equipment, facilities, and themselves. This is best accomplished in advance of any site emergency.
- Safety and fire drills should be mandatory. It is always a good to plan for emergencies and then during the startup operations conduct an unannounced safety drill to test the Safety Plan and procedures.
- An emergency response action plan — a plan of whom to notify and which actions to take in the event of an emergency should be provided to all potential emergency response agencies. The plan can be relatively brief but should cover many of the likely scenarios which can be reasonably anticipated, such as electrical fires, electric shocks, equipment fires, personnel injury, spills, other releases, and night and unattended operations where appropriate. The plan should be sent (via

registered mail) to the local hospitals, fire stations, and the Local Emergency Planning Committee.

In 1997, NIOSH published new standards for respiratory protection (see 42 CFR Part 84) which changed the definition of particulate and vapor protection. This new rule effectively voids the older classification of protection against dust, mist, fumes, and radionuclides. The newer standard has nine classes of filtration protection — three classifications of filtration efficiency and three more groupings relating to the filter's efficiency in removing oil aerosols. The new standards are a substantial improvement over the older classifications; references in the Safety Plan must be based on the newer guidance.

In some states, the Incident Command System is used, which designates a specific official as the Incident Commander during a specific emergency. Where the Incident Command System is being used, the Incident Commander has control of all the assets of the site and the companies who have financial responsibility for the ownership and operation of the equipment and the land on the site for the duration of the emergency. The Incident Commander may, if he or she so chooses, order the destruction and removal of all the equipment on the site to mitigate the emergency. It is wise to keep this contingency in mind when developing the site Safety Plan.

3.8.4 Site Operations

Sometimes, the site remediation facilities will be operated by a third party who may or may not have been associated with the construction of the equipment. In these instances, the operations contractor will probably have his or her own safety professionals and engineers review the equipment layout and operating plans and will want to incorporate their own safety plans and equipment into the site operations; however, such plans must be subordinate to the site Safety Plan.

Regardless of the operator, all OSHA guidelines regarding worker training and jobsite conditions must be followed. These are specified in Part 29 of the Code of Federal Regulations, and worker training and safety communication is specified in 29CFR1910.120, and other paragraphs.

OSHA has developed a Process Safety Review program for site operations. This program requires a detailed set of process control procedures be developed for the site equipment which defines normal operational control parameters and alarm conditions and tells the control room operator what must be done to bring the process back under control. While these procedures may not be required for soil washing operations, the manufacturer's literature on the equipment should be reviewed and the normal control parameters for the equipment should be established prior to commencement of field operations.

3.8.5 Laboratory Operations

Laboratory safety is also a part of overall site safety. Where the laboratory is onsite, special precautions may be required to protect the laboratory personnel from site dusts and chemicals. Often, these contaminants can be carried into the laboratory space through the air handling system.

Samples of hazardous wastes and soils can also present their own degree of hazard, not only during the analyses, but for the disposal of the samples. The laboratory must be located and operated to prevent onsite pollutants from entering the laboratory and from the laboratory into the community.

Quality Assurance/Quality Control (QA/QC) plans should be considered part of the laboratory operations. Safety in sampling, protective equipment, and sample disposal must be addressed as well. The QA/QC plan should consider external sources of control and contamination. While the laboratory QA/QC plan may not be a direct part of the site Safety Plan, certain elements of it, including testing and calibration of safety equipment and the priorities for analyses must be considered.

3.9 Specifications Development

The key to developing and successfully implementing a soil washing process is careful development and design that addresses the following main areas:

- soil and site characterization,
- treatability and pilot testing,

- designed excavation,
- health and safety, and
- full-scale process design.

Throughout the development and design program, the ultimate goal is to develop a site-specific soil washing process "flowsheet" or design (and project implementation workplan) that will accomplish all remediation project objectives cost-effectively. Specification development, or determining the project goals and specific project requirements that must be met to ensure success, must be a major focus early in the overall program. The detailed process flowsheet or design specifications will then follow logically.

There are several ways to successfully accomplish specification development. In traditional serial (sequential) methods, the customer typically provides project requirements to a research and development (R&D) group, which develops flowsheet specifications from these requirements and optimizes the process or product. Usually the R&D group is left on its own to perfect the design for full-scale operation. What typically happens is that project goals and requirements change and the R&D group's original design must be recycled for re-design and re-evaluation of requirements. This naturally results in delays, inefficiency, and increased cost. An innovative alternative, which is gaining popularity throughout U.S. industry, is "Simultaneous Engineering" (SE).

SE provides an organized method for individuals with different functions, responsibilities, and technical specialties to work together as a team to develop, design, and validate a process or product. SE team members use their combined expertise and knowledge to accomplish the task *simultaneously* instead of serially. The team leader is responsible for resolving the inevitable conflicts and keeping the overall development/design program on track. Several of the characteristics of a successful team are shown in Table 3.4.

SE stresses that most of the effort be accomplished early on in the project, when there is maximum flexibility. In this way, SE avoids many of the problems associated with the traditional serial methods and typically shortens the timeframe for product or project development, reduces cost, and improves overall quality. It is used by many leading companies, such as Ford Motor Company, Martin-Marietta, Monsanto, and DuPont.

Table 3.4
Characteristics of a Successful "SE" Team

Team members are able to meet and communicate regularly and keep each other informed.
Appropriate skills are represented on the team.
Appropriate levels of organizational authority are present within the team for effective decision making and commitment of funds.
All team members are involved in setting project definition, project requirements, and time deadlines.
Progress is set with realistic time frames and tracked regularly.
Individual roles are clearly defined, don't overlap, and are supported by all team members.
Team members and the team leader understand their assignments, tasks, and time deadlines.
Team members and the team leader support and help each other.
Decisions are mainly made by consensus and only rarely arbitrated by the team leader.
Team emphasis on solving problems vs. placing blame.
All members actively participate in meetings and communications.
The team has an identity and mutual respect/admiration among team members.
Conflict is openly discussed, often resulting in critical growth and learning by all team members.

The primary tasks of the SE team are to:

- define the project goals and requirements,
- generate ideas and develop the best process, and
- complete the full-scale design.

Defining the project goals and project requirements includes identifying, collecting, documenting, and prioritizing all goals and requirements that must be met for project success. For a soil washing remediation project, requirements can often be grouped into categories, which might include technical parameters (a high processing rate), regulatory considerations (an easily permitted process), customer needs (a cost-effective process), and public acceptance (minimal emissions and noise). The requirements that are identified represent what the SE team members believe are critical needs to make the project successful. Arranging and documenting the requirements in categories helps keep them organized and facilitates comparison. The team continuously updates project goals and requirements.

The SE team should also rank the importance of meeting each requirement; that is, whether meeting a requirement is absolutely critical to project success or only a desirable option depending on cost constraints. Ranking or rating each requirement provides a quantitative means to establish tradeoffs among all requirements, although qualitative considerations can also be used. This helps to avoid making critical decisions based on emotion or "soft" reasoning. Although ranking can take several forms, a simple, commonly used system is to assign a numerical rating from 1 to 10, as follows:

- 10 — A critical need; the project cannot be successful unless this requirement is met.
- 8 — An important need; the project can only achieve partial success if this requirement is not met.
- 5 — A strong desire that will enhance success, performance, and cost; the project can still be mostly successful if this requirement is not met.
- 3 — A desire that would be good to have if cost-effective; it will have little impact on success if not met.
- 1 — Of low importance, good to have if at no expense; will not affect success if not met.

To the extent practicable, a tangible measure of success (a "metric") should be assigned to each requirement to evaluate whether it has been met by the development and design program. This metric essentially becomes the detailed design specification that must be met during laboratory treatability testing, field pilot testing, and detailed design. Several common soil washing project requirements, possible rankings and metrics (design specifications) are shown in Table 3.5 This is not intended to be a comprehensive or exhaustive list. The final list of documented, prioritized requirements, and related detailed design specifications can serve as a guidepost for the team to routinely revisit and update.

3.10 Cost Data

All remedial decisions are based upon cost, risk mitigation, and site-specific factors. But, cost is by far the overriding decision variable.

Table 3.5
Typical Soil Washing Project Requirements and Detailed Design Specifications

Number	Requirements	Category	Rank	Design Requirements (Measurable Metrics)
1	Excavation of Soil	C	10	Compliance with OSHA Excavation Standard
2	Implementation of Excavation Safety	C	10	Favorable Field Audits, No Incidents
3	Safe Process Syst. (SW) Before and During Operation	C	10	PSA (Pre), Favorable Field Audits During Operations
4	Collect Process Samples for Technology Evaluation	C	10	Develop Method, Schedule and Plan
5	Develop Community Relations Plan	C	10	Yes/No (Verify Level of Importance)
6	Low Unit Cost	C	8	Less Than $300/ton
7	Work Plan for All Site Operations Completed	C	10	Yes/No
8	Obtain Permit — RCRA Part A	R	10	Yes/No
9	Obtain Permit — Local Construction	R	10	Yes/No
10	Obtain Permit — Local Electrical	R	10	Yes/No
11	Obtain Permit — CAMU	R	10	Yes/No
12	DOT Regulations Met	R	10	Yes/No
13	Develop Waste Management Plan	R	8	Yes/No
14	Low Level of Lead in Treated Soil	T	10	< 500 ppm
15	Power Required	T	10	Yes, Define Quality
16	XRF Screening of Excavations	T	8	Yes/No
17	High Percentage Yield of Clean Soil	T	8	≥ 70%
18	Separate Soil from Debris	T	8	< 10% Soil (by weight)
19	Low Level of Water Contamination (by-product)	T	7	Meet WWT Discharge Requirements
20	Treated Contaminated Soil Lead Concentration	T	4	> 1% Lead (by weight)

C	Customer Requirement
R	Regulatory Requirement
T	Technical Requirement
PSA (Pre)	Pre-startup Process Safety Audit
WWT	Wastewater Treatment Plant

One of the most common sources of confusion arises from a failure to clearly define what is included and what is not included in the price. The purpose of this section is to highlight the basic variables that affect a soil washing treatment system and to list the cost elements that must be considered in preparing a cost estimate that can be used to compare soil washing and other remedial alternatives.

3.10.1 Cost Variables

The key variables required to estimate the cost of a soil washing process are:

- the volume of soil to be treated in cubic meters (m^3) or cubic yards (yd^3);
- the approximate density of the soil in ton/yd^3 or tonne/m^3;
- the particle-size distribution that quantifies the percentage of the target soil that exists in the oversize, the sand, and the fines fractions;
- the end use of the soils;
- the schedule under which the project must be completed;
- the key contaminants, the feed concentrations for such contaminants, and their respective treatment standards;
- residuals management costs and standards;
- the sampling and analysis plan to be followed; and
- the treatment goals for determining success of treatment.

3.10.2 Capital Costs

The capital costs for soil washing are usually limited to the treatment plant and supporting equipment. Since the average quantity in all currently identified projects is approximately 27,216 tonne (30,000 ton) of soil, no single project can bear the entire cost of a treatment plant. Thus, only the applicable depreciation is charged to the project. In some cases DOE is an example), the project feed is so large that treatment may go on for 10 years or more. In these cases, the entire cost of the treatment plant may be recovered by that single project. There is no fixed depreciation life for this equipment, although mining companies depreciate similar equipment in 5 to 10 years, with 7 years being common. Generally accepted accounting practices allow straight-line depreciation or a "use basis" depreciation method based upon the actual tons processed. Remediation contractors will decide upon the approach that best fits their business practices.

For a frame of reference, a 23 tonne/hr (25 ton/hr) soil washing plant with built-in flexibility of treatment unit operations costs in the range of $3 to $5 million.

3.10.3 Operating Costs

The operating costs of a soil washing plant consist of the following items:

- *Plant Labor*. The plant workforce is the personnel directly involved in the operations of the system and will include, in some combination, a plant manager, a process engineer, a health and safety officer, a shift supervisor/lead operator, health-physics technicians (if radioactive materials involved), plant operators, a plant electrician, and laborers.
- *Plant Consumables*. Soil washing systems vary widely, as does the use of chemicals, acids, caustics, surfactants, and polymers. Plant consumables include chemicals, protective clothing for workers, and other non-capital replacement items.
- *Utilities*. This cost element includes the cost of commercial electrical power, process water, and, in some cases, surcharges levied by the POTW for the discharge of wastewater.
- *Process Analytical Controls*. Process and system controls focus on the control of physical separation, the chemistry of treatment units, intermediate process quality, and sampling and analysis of the oversize, sand, and sludge cake.

3.10.4 Support Costs

There are a significant number of support costs that must be considered and included in a complete remedy cost estimate. Support costs are:

- *Mobilization and Demobilization*. Mobilization and demobilization include transporting of the treatment plant to the site, erecting and connecting the units, and dismantling the plant upon the conclusion of the remediation.

- *Site Preparation.* Site preparation activities will vary widely based on the specific site to be used. Site preparation activities may include constructing access roads, clearing and grading the plant location, constructing a plant operations pad, constructing staging pads for feed and product soils, erecting a building to enclose the plant, installing a site office and personnel decontamination facility, and installing fencing and hiring a site security force.
- *Site Administration.* Support costs for site administration may include hiring a site secretary, installing phone lines, setting up a fax machine and a computer/printer, and paying for mail and overnight delivery services.

3.10.5 Materials Handling Costs

The costs of materials handling to support the soil washing treatment must also be considered. These costs include:

- *Site Clearing and Grubbing.* This includes removing, staging, and disposing of existing vegetation in the area(s) of excavation.
- *Excavation.* This includes the excavation and transport of soils to be treated to a staging area for initial processing.
- *Prescreening.* This includes separation of oversize material (usually >2 in.) and undersize material (<2 in.) from the excavated soil will be prescreened using standard equipment such as vibrating bar screens ("Grizzlies") and rotating trommel screens and staging of these separated materials.
- *Feeding the Plant.* This includes moving the feed soils from the staging pile to the plant feed hopper.
- *Managing Clean Products.* The clean products include the process oversize (gravel) and sand, which are staged in separate piles outside the treatment plant. Normally, the sand and gravel are mixed with a loader to prepare the material for movement into a designated portion of the excavation area as clean backfill.
- *Regrading and Revegetation.* After completion of treatment and when all the materials have been backfilled, the working site is regraded to designated elevations and then revegetated or restored to a condition consistent with the final design.

3.10.6 Residual Disposal Costs

All soil washing operations generate some residuals that must be disposed off-site at the conclusion of the project. The material requiring disposal will normally include a volume of sludge cake and residual process wastewaters that are retained in the process tanks and reactors.

Sludge cake disposal will normally be performed at a RCRA Subtitle C hazardous waste landfill. Landfill disposal restrictions (the so-called "land bans") must be considered. In some cases, additional treatment of the sludge cake may be required prior to disposal. There may be unique situations where the sludge cake is not a listed hazardous waste and does not exhibit the characteristics of hazardous wastes. Under these circumstances, it can be disposed in an industrial waste landfill.

Process wastewaters may be disposed off-site. If groundwater remediation is planned at the site, there may be a wastewater treatment plant that can be used for process wastewaters. Otherwise, they must be disposed at an off-site, permitted wastewater disposal facility.

3.10.7 General and Administrative Costs, Overhead, and Contingencies

Overhead and contingency costs must be included in the overall cost estimate. Individual contingencies may be allocated as they occur, but an overall contingency factor of 10 to 20% is common.

3.10.8 Contractor Profit

Contractor profit should also be included in the cost estimate.

3.10.9 Cost Estimating (Workshop)

The total cost of a soil washing project has many components. When estimating costs, it is helpful to use a worksheet to identify all associated with the project. A sample cost-estimating worksheet is presented in Figure 3.7.

3.11 Design Validation

The key to developing and successfully implementing a soil washing process is a careful development and design program that addresses the following main areas:

- soil/site characterization,
- treatability and pilot testing,
- designed excavation,
- health and safety, and
- full-scale process design.

Design validation is a means of ensuring that the process "flowsheet" and project work plan are correct, appropriate, and complete. This must be an ongoing component of the overall soil washing project.

Generating ideas and developing the best soil washing process flowsheet should begin with good site and soil characterization, treatability testing, and pilot testing. The extent and degree of soil and site characterization or testing that is needed is site-specific and should reflect the size and complexity of the project. Generally, before the best soil washing process can be chosen and a system designed, the physical nature of the soil and contaminants must be thoroughly understood. Key factors that often influence system design include contaminant speciation and distribution, contaminant and soil bonding or binding, contaminant mobility, and soil composition. Site conditions such as access to soil, climate, and the availability of utilities can also affect project requirements and costs. Based on site and soil characterization, carefully designed treatability or field pilot testing studies (or both for larger, more complex projects) should be used to evaluate soil washing process options and generate preliminary cost information. The SE team should routinely validate that the process selected will meet all project goals and requirements cost-effectively and safely.

In completing the full-scale design, the team should consider all project requirements and all the information generated in developing the process. The detailed full-scale process design should also address good engineering design practices and standards, worker health and safety, ease of regulatory permitting, site preparation, system mobilization and demobilization, project timing, required analytical monitoring, process instrumentation and controls,

Figure 3.7
Wastech — Soil Washing Cost Estimate Worksheet

Key Assumptions:	Plant Throughput Capacity:	25 tons per hour			
	Tons to be Treated:	30,000			
	% of Feed < 0.063 µm:	0.2			
	Schedule, months:	9			
	Level of Treatment:	Simple + Sand Treatment			
Category	Activity	Basis	Guideline	Mass (tons)*	Cost ($)
Capital Cost					
	Plant Cost	Purchase Price	$2-5 MM	NA	NA
	Depreciation Amount	Straightline or Use Method	$10-20/ton	30,000	450,000
Treatment Cost					
	Plant Labor	Plant Direct	$40-50/ton	30,000	1,350,000
	Plant Consumables	Chemicals	$1-10/ton	30,000	165,000
	Utilities	Power/Water	$1-3/ton	30,000	60,000
	Special Treatment Steps	Bioslurry/Extraction	$50-100/ton	30,000	0
	Process Analytical	Controls	$5-10/ton	30,000	225,000
Subtotal, Soil Washing Cost					2,250,000
Support Costs					
	Mob/Demob	Includes Erection	$2-5/ton	30,000	105,000
	Site Preparation	Infrastructure Reqts	$15-30/ton	30,000	675,000
	Operations Support	Office Support	$1-2/ton	30,000	45,000
Subtotal, Project Support Cost					825,000

Material Handling Costs					
	Clearing/Grubbing	NA	$1-3/ton	30,000	60,000
	Excavation	Includes Equip & Ops	$5-10/ton	30,000	225,000
	Prescreening	NA	$2-4/ton	30,000	90,000
	Plant Feeding	NA	$1-3/ton	30,000	60,000
	Clean Product Handling	NA	$2-5/ton	30,000	105,000
	Regrading/Revegetation	NA	$5-10/ton	30,000	225,000
Subtotal, Material Handling Costs					765,000
Residual Disposal Costs**				>Tons, Wet Cake<	
	Loading	Sludge Cake Handling	$1-2/ton	10,800	16,200
	Transportation	Dump Trailers to TSDF	$50-75/ton	10,800	675,000
	Disposal	Landfill "Gate Rate"	$100-200/ton	10,800	1,620,000
	Taxes	All Applicable Taxes	$10-35/ton	10,800	243,000
Subtotal, Residual Disposal Costs					2,554,200
Subtotal, Project Costs					6,394,200
General, Administrative, Overhead Costs		NA	10-30% of Project Costs		1,278,840
Subtotal, Burdened Project Costs					7,673,040
Contractor Profit			5-20% of the Burdened Cost		959,130
Project Total Price					8,632,170
Project Unit Price per Ton					288

*Enter the Feed Tons, except in the case of residual disposal
**Assumes Disposal at a RCRA Subtitle C Landfill

residue disposal, materials handling and management, and clean soil recycling. After the full-scale design is complete, the SE team should provide a final overall validation that the project will successfully meet and address all these issues in a cost-effective manner.

A validation issues checklist is provided in Table 3.6. This is only a guideline intended to identify the types of issues that should be addressed during SE team validation. It is not meant to be an exhaustive design review checklist.

Table 3.6
Validation Issues

Review work accomplished to date.

Establish that decisions on a best process or selected design will be consensus driven, with active participation by all team members.

Identify the most promising best process and selected designs.

Evaluate (quantitatively to the extent practical) a best process or selected design against project goals and requirements.

Synthesize, modify, and strengthen the most promising best process or selected design.

Make a tentative team consensus decision on a best process or selected design.

Assess implementation risks and assumptions used to make any tentative decision.

Develop plans to support a final decision on a best process or selected design.

Summarize and document assumptions, implementation risks and any key factors leading to a final decision on a best process or selected design.

3.12 Soil Washing Permitting

3.12.1 Pertinent Environmental Regulations

There are two primary federal statutes which govern site remediation. A summary of the purpose of each follows. The Resource Conservation and Recovery Act (RCRA) was originally enacted in 1976. It has been amended over the years by additional laws, such as the Used Oil Recycling Act of 1980 and the Hazardous and Solid Waste Amendments of 1984. RCRA's primary focus is protection of human health and the environment. It also addresses conservation of valuable recyclable and energy materials. Its goals are achieved through extensively regulating the management (generation, treatment, recycling, transportation, and disposal) of solid and hazardous wastes. Extensive permitting, record keeping, and paperwork documentation are required to meet the regulatory requirements. Remediation is regulated through RCRA's Corrective Action Program, which addresses releases from active sites.

The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), also known as the Superfund statute, is designed to address three major environmental issues: oil spills, spills of hazardous substances, and remediation of uncontrolled hazardous-substance disposal sites. The regulations promulgated under CERCLA are designed to provide guidance for the discovery and remediation of hazardous substances and to establish liability for cleanup of inactive or abandoned sites.

3.12.2 Permitting Issues

Careful attention and planning should be given to permitting for each site-specific soil washing application. For simple systems treating nonhazardous soils, permitting can be straightforward. However, for applications where RCRA- and CERCLA-regulated hazardous contaminants are involved, permitting can be quite complex, involving federal, state, and local regulations. The soil washing project team must ensure that all necessary permits are obtained to avoid the delays and added cost caused by fines or equipment demurrage. Depending on project complexity, federal, state, and local permits may all be needed for soil treatment, soil and waste storage, air emissions, excavation, impact on sensitive land areas (e.g., coastal areas, wetlands, etc.), site construction and mobilization, and vegetation grubbing and clearing.

The bulk of permitting needs for soil washing remediation projects are usually driven by RCRA or CERCLA remedial regulations, although other permits may be required for soil and waste storage, excavation, and air emissions. It should also be recognized that a Toxic Substances Control Act (TSCA) regulated concentrate can be created from non-TSCA regulated feeds. Obtaining permits is a difficult, expensive, and time-consuming task. The permitting process is a impediment to the use of innovative technologies, like soil washing.

Most recently, US EPA has worked with the regulated community to revise and streamline the RCRA permitting process. A good example of this permitting reform is found in the 1993 RCRA Corrective Action Management Unit (CAMU) regulations (40 CFR 264, Subpart S). The CAMU concept and the associated Temporary Unit designation offer significant flexibility and permitting relief. CAMUs will help speed up remediation by easing the permit burden. The concept will also encourage the use of innovative technologies like soil washing. Obtaining a CAMU permit is still a significant task, but well worth the effort. Many states, Washington for example have also incorporated the CAMU and Temporary Unit concepts into their own remediation regulations and policies.

Essentially, the CAMU rule allows the management, treatment, and replacement of remediation wastes on-site in temporary storage and/or treatment units subject to various US EPA and state constraints and approvals without requiring the activity to meet the existing restrictions of:

- land disposal restriction (LDR) technology-based treatment standards;
- minimum technical requirements (MTRs) for waste piles, landfills, and impoundments;
- some of the RCRA design, operating, closure, and permitting requirements for land disposal units and remediation treatment units; and
- typical RCRA Part B permitting requirements.

LDRs and MTRs are waived for remediation wastes managed within the CAMU, and design, monitoring, operating, and closure requirements are tailored to the activities performed within the CAMU. Site-specific requirements will typically be specified in RCRA Corrective Action permits or orders. Further, standards and requirements for some kinds of remediation storage and treatment activities (for example, tank- and container-based systems) will be based on the nature of the treatment unit and the waste being treated, instead of the full RCRA standards.

CAMUs must still be approved by US EPA (or an authorized state regulatory agency) and also require extensive public meeting and comment procedures. The time limit on a CAMU is one year, with the possibility of a one-year extension.

The CAMU rule itself lays out a series of criteria or guidelines that US EPA must employ when considering a CAMU for acceptance. These criteria, which must be addressed in any CAMU permit application, are summarized as follows:

- The CAMU shall facilitate the implementation of reliable, effective, protective, and cost-effective remedies (soil washing is recognized by US EPA and many state regulatory agencies recognize soil washing as a good, effective remedial technology/remedy);
- Waste management activities associated with a CAMU shall not create unacceptable risks to humans or the environment resulting from exposure to hazardous wastes or hazardous constituents;
- The CAMU shall include uncontaminated areas of the facility only if including such areas for the purpose of managing remediation wastes is more protective than management of such wastes at contaminated areas of the facility;
- Areas within the CAMU, where wastes remain in place after closure of the CAMU, shall be managed and contained so as to minimize future releases, to the extent practical;
- The CAMU shall expedite the timing of remedial activity implementation when appropriate and practicable;
- The CAMU shall enable the use, when appropriate, of treatment technologies (including innovative technologies) to enhance the long-term effectiveness of remedial actions by reducing the toxicity, mobility, or volume of wastes that will remain in place after closure of the CAMU; and
- The CAMU shall, to the extent practicable, minimize the land area of the facility upon which wastes will remain in place after closure of the CAMU.

All these issues must be carefully considered and thoroughly addressed to ensure acceptance by US EPA (and the public) and to ensure successful implementation of the CAMU.

Other federal, state, and local permits may also be needed and should not be overlooked. Since this section is not intended as a comprehensive review of all possible permits, only the more commonly encountered permit requirements are highlighted below.

- *RCRA Part A/B Permit Modification.* Remediation sites that are currently covered by a RCRA Part A or Part B permit may have to modify the existing permit (40 CFR 270, Subpart B) to incorporate a soil washing pilot study or full-scale remediation project (soil washing treatment system).
- *National (or State) Pollution Discharge Elimination System (NPDES) Permit.* The discharge of wastewater from a soil washing system or other aqueous wastes (e.g., spent leaching solution) may require that the site's existing NPDES permit (under the Clean Water Act, Section 402) be modified, or it may require a new, separate permit for the soil washing system discharges.
- *Air Emissions Permit.* A federal or state permit may also be needed to address potential air emissions (dust, vapors/fumes) and odors from the soil washing process caused by contaminants in the soil matrix or process chemicals and additives used in the soil washing process. In particular, certain toxic organics, such as benzene, will require additional attention and safeguards to prevent process emissions and personnel exposure. First, care should be taken to avoid using additives, leaching solutions, or process steps that generate emissions. Then, to the extent practical, process designs should incorporate engineering controls to minimize emissions. In particular, for soil washing applications that address soil contaminated with volatile organic compounds, special attention should be given to ensure that air permit issues are addressed.
- *Soil Erosion and Sediment Control (Excavation) Permit.* Many states and local authorities require a permit or written plan to ensure that control of soil and sediment erosion is properly addressed during construction and excavation operations.
- *Wetlands Permit.* If soil washing operations have the potential to adversely affect sensitive areas, such as wetlands or coastal soils, the applicable oversight regulatory agency in charge may require a permit or plan to ensure that the potential impact is minimized or at least managed effectively.

Site-specific permit requirements and clean-up goals for both soil recycling and residue management should also be negotiated early in the remediation project process. The reusing or recycling of clean soil on-site and the management and disposal of process residues are key issues that will affect required system performance, cost, and the ultimate benefit of using soil washing technology. If clean soil cannot be recycled or beneficially reused on-site, a major benefit of soil washing is lost. Clean-up goals can be based on total concentration or leachable concentration, or both. Project cost and scope can also be influenced by other regulatory permit conditions or requirements, such as requiring soil amendments for treated soil after treatment and prior to recycling (to restore original permeability or ability to support plant growth) and restoration and revegetation of excavated areas. Since all these issues are driven by clean-up goals and regulatory compliance and permitting issues, they should be addressed in regulatory negotiations.

Permit requirements for technical analysis of compliance measures should also be carefully considered during regulatory negotiations. Compliance analytical issues in permits might address certain size fractions in the soil, establish sampling methods or techniques, and even specify sample preparation. The sample type (grab or composite), sampling frequency, sample preparation methods, and specific analytical methods can also be set as permit conditions with the oversight regulatory agency. For example, the state of Washington sets compliance based on total analysis of <2 mm soil fractions, whereas federal guidance sets compliance at the <60 mm soil fraction size.

3.13 Performance Measures

Site restoration is conducted to reduce health risks to human beings and to reduce the impact on the environment. Clearly, the simplest and most expedient action would be to excavate the site and ship the soil to a well-designed landfill to isolate the contaminants from human contact and the environment in perpetuity. Soil washing is only undertaken to reduce the volume of contaminated materials and, thereby, lower the costs of shipping and disposal. The primary measure of performance is the decontamination efficiency of the system as measured by the maximum cost-effective return of clean material to the excavation site. As long as additional volume reduction can be accomplished at less expense than the avoided costs of disposal, more treatment steps are warranted. Further, it must be realized in planning that "clean" material does not mean only those particles that individually meet release criteria. The matrix returned to the excavation can contain some substantially contaminated media, so long as an assay of a representative sample is within agreed limits. Understanding this concept is essential to monitoring system performance.

The work plan negotiated with regulators and disseminated to the public should clearly state the restoration goals negotiated in the record of decision (ROD) for the site. This should include both a risk-based allowable level of residual contamination in the material to be returned to the site and the planned percentage of material to be returned to the site. The latter value should reflect the estimated recoverable fraction based on treatability studies, less some contingency calculated for process efficiencies expected from full-scale equipment. These values become the benchmarks against which performance is measured throughout the job.

Performance data may also focus on any module internal to the process, such as hydrocyclone separation efficiency or suspended solids removal across the clarifier. These data are also used to monitor operations and in that context are discussed in Section 4.4.

Sampling methodology should be explained in the work plan. This includes how representative samples will be obtained, the frequency of sampling, and the maximum allowable deviation in any product sample or duration of off-specification operation. Sampling of process effluents and residuals should also be delineated. Effluent data will be evaluated against any required permits or negotiated limits in the ROD. Residuals data will be used to satisfy the shipping and disposal waste-acceptance criteria. All analytical work for quality assurance (QA) samples should be performed using US EPA-approved SW-846 methods and/or other standardized techniques approved by regulators prior to commencing operations.

An independent analytical service will probably be used to perform QA checks, but it is essential that operating personnel take similar samples in the same manner to ensure that QA data accurately reflect process and performance monitoring data. This is particularly important where field determinations are not absolute and actual contaminant levels must be inferred from field data. For example, field measurement of metals by x-ray fluorescence must be periodically checked against wet chemical measurements with total sample digestion to ensure that the field determination is representative.

3.14 Design Checklist

The following is a design checklist to assist in conceptual planning for a soil washing project.

1. **Soil Physical Characteristics**
    - Site topology and geology
    - Particle-size distribution curve
    - Percentage of oversize, sand, and fines fractions
    - Organic carbon
    - Mineralogy
    - Plasticity index and moisture
2. **Contaminant Occurrence**
    - Free, particle, coating, bound, and/or soluble
    - Relative contribution by fraction
    - Chemistry of contaminant with respect to washing solution
3. **Level of Treatment**
    - Simple separation
    - Simple separation plus treatment of the sand fraction
    - Simple separation plus treatment of the sand and fines fractions
    - Special case
4. **Site Conditions**
    - Site access
    - Facilities layout
    - Excavation plan and staging plan
    - Pad and containment requirements
    - Utilities access
    - Building requirements
    - Supporting facilities (offices, decontamination areas)

5. Treatment Standards

- Key contaminants
- Required concentrations
- Handling and use of "clean" material

6. Schedule

- Mobilization to site
- Site preparation period
- Obtaining approvals
- Waste processing period
- Required throughput to meet schedule

7. Treatability Study Information

- Soil matrix/contaminant evaluation
- Conceptual process-flow diagram
- Conceptual engineering

4

IMPLEMENTATION AND OPERATION

4.1 *Implementation*

The implementation of a soil washing project must consider the services to be provided, the procurement methods, and the method of contracting.

4.1.1 Procurement Methods

4.1.1.1 Traditional

The traditional procurement method involves bids submitted by contractors and approved by the client for each stage of the remediation process. In the case of soil washing, the approach would be to prepare a bidable work package for each stage of the work, such as the treatability study, the design, the pilot study, site preparation, excavation, treatment operations, and residual disposal. The advantage of this method is that the lowest possible price can be obtained through the multiple competitive steps, but a major disadvantage is for the loss of coordination among the inter-related activities. It requires a very strong client Project Manager to make this approach successful.

4.1.1.2 Design-Build/Operate

In some soil washing projects, the work is divided into two main parts. One contractor will perform the treatability study, prepare the design, and manufacture the plant. After delivering the plant to the site, erecting it, and providing some basic training, that contractor leaves the site. A second contractor will take over the plant, usually on a project lease/rental basis. This contractor will operate the plant, complete the project, and turn the plant back over to the original manufacturer upon completion. The advantage of this approach is that a dependable contractor, not normally in the soil washing business, can access a treatment unit at a reasonably low cost while not incurring the cost of developing that capability internally. Of course, a major disadvantage is that the plant provider is not included in the loop of responsibility to ensure that the project is successful and that any major design or manufacturing flaws are corrected. The operating contractor may have received some basic training on the plant's operations, but is not prepared to perform sophisticated troubleshooting when required. The apparent cost of this method is low, but a high risk is present if processing problems arise because such problems could seriously jeopardize the project.

4.1.1.3 Design-Build-Construct-Operate

Another approach to soil washing projects is to select one contractor who will perform all activities related to the soil remediation, including the treatability study, the design, the pilot study, treatment operations, residuals disposal, and site closure. The advantage of this approach is that all the responsibilities reside in one contractor, and there is single source accountability from the client's perspective. All corrective actions needed to make the project work are in the contractor's control. The disadvantages to this method include the problems that will arise if a contractor cannot perform or does not have the financial resources to correct problems. Unless care is taken by the client up front, there is the possibility that the price of this approach may not appear to be the most competitive, although in the long-run it may be.

4.1.1.4 Contract Operations

The contract operations method might logically be used in a large government remedial project where the duration of the project extends beyond the normal operating life of the capital equipment. In such a case, it might make sense for the government to design, procure, and construct a plant under one contract, and then to solicit a second contract for the long-term operations. There still remains the concern that the operations contractor may not be properly keyed into the development of the plant, but this potential problem is likely to diminish over the long-term operations period. Additionally, the client (the government in this example) may choose to require an extended carryover period during which the plant design contractor is available to assist with operations.

4.1.2 Contract Terms

Contracts for soil washing may be awarded under different terms, each having their own advantages and disadvantages.

4.1.2.1 Lump Sum Contract

A lump sum contract is a fixed price arrangement for a specified piece of work. This contracting vehicle is generally one that clients like because their risk is capped for the specified work. No extras are recoverable by the contractor. If the work costs more than projected, the contractor is responsible, and if the work costs less, the contractor benefits. Under this approach, there is no difficult accounting required to check and discuss each element of cost during performance of the work since there is only one real measure, completing the work. For a soil washing project, the lump sum is usually defined by a quantity of soil to be treated. Appropriate language is normally included in the contract to allow for renegotiation if changed site conditions result in more work.

4.1.2.2 Cost Plus Fixed Fee

The cost plus fixed fee (CPFF) contract allows all costs of the project to be reimbursed to the contractor, but that contractor will receive only a fixed amount of "fee" (i.e., profit) no matter what the ultimate scope of the project. This approach requires the client to check each and every cost element of the project, a process that often turns adversarial as site changes and difficulties arise. The client may, in the end, obtain the lowest apparent price, but at the cost of the heavy involvement of a client project management team. A variation of this contracting arrangement is a cost plus award fee in which the fee is based on performance.

4.1.2.3 Unit Price Contract

A unit price contract may appear similar to a fixed price or lump sum contract in that it contains a total price based on *estimated* quantities. However, the actual cost is based on a unit price per ton for soil processed. With this arrangement it is essential that all terms be defined, including:

- unit basis — tons of soil excavated, screened, fed to the plant, **or** produced;
- weight basis — dry weight or wet weight; and

- method of measurement — a calibrated weigh cell, approximated by a number of bucket loads, or some other.

Generally, the contractor will want to treat the most tons possible while the client will want the least amount treated for a given unit price.

4.1.3 Preferred Combination

For most soil washing projects, the preferred combination of procurement method and contract terms is the design-build-construct-operate procurement method (see Section 4.1.1.3) using a lump sum contract. The responsibility to perform is placed clearly on the shoulders of the contractor. The contractor must plan and manage all activities required within the scope of services. The work can be controlled and measured by the client with a reasonable level of effort. The project can still be bid competitively. A well thought-out request for proposals can define the cost elements so that the resulting lump-sum pricing is fair.

4.2 Start-up Procedures

4.2.1 Startup

Start-up activities generally commence after the soil washing plant is erected and clean process water is introduced into the tanks to prepare for operations. Start-up activities will generally consist of three key steps:

1. *Running the System on Clean Water.* Once all of the process tanks have been filled and mechanical and electrical continuity checks have been made, the system will be started up to check for leaks, mechanical misconnections, and proper flow through the tanks, cells, and treatment units. This run will usually be completed in one day.
2. *Running the System on Clean Soil.* Once the mechanical and plant integrity issues are checked, the next step is to introduce solids into the plant. It is advisable to conduct this phase of the startup with clean soil so that if there are any problems, they can

be handled without the concern of contamination. A clean soil stockpile can easily be prepared at the project site. The volume of clean soil prepared should be enough to load the cells and treatment units to the normal solids operating levels, plus the additional amount required to produce some products (oversize, sand, and sludge cake). This phase of the startup is intended to confirm the ability to move solids though the plant and to test solids handling systems such as the conveyors, screens, and dewatering equipment. Some problems may be encountered at this stage and some troubleshooting should be expected. This phase can generally be completed within 1 to 3 days.

3. *Introducing Contaminated Soil.* Once the plant has been checked using clean soil and any necessary corrective actions have been completed to the satisfaction of the team, the plant is deemed ready to accept contaminated soil. At this stage, the plant should still be considered to be in a start-up condition and should be operated carefully. A stockpile of contaminated test soil will be prepared by the contractor. The plant must be loaded to levels that are sufficient to allow the various treatment units to be operated. In most cases, the clean soil introduced in the earlier stage does not need to be removed from the system prior to this step.

The start-up test run is performed to confirm that the plant is operating and can produce products that meet the designated treatment standards. This is not the period when the plant is optimized or when extensive testing should be demanded. This is merely the first step in preparing the plant to perform.

4.2.2 Performance Optimization

Once the plant has been confirmed to be operating properly, the operators will optimize the plant's performance.

4.2.2.1 Field Pilot Study

A field pilot study can be performed with the full-scale process plant before commencement of the actual remediation. This field pilot study is an excellent opportunity to see the plant in full operation and affirmatively set the stage for normal, steady-state operations. The field pilot test is conducted on the contaminated soil that will be fed to the plant during normal operations. A stockpile of material will be prepared by the contractor for this purpose. For an "average" project, about 5% of the mass to be treated could be considered an appropriate feed amount for this field pilot study. The field pilot study is not intended to determine if the technology works (that should have been confirmed long ago), but rather to provide actual field operating and cost data and to assure the client and the regulators that the plant is up and performing, and can be reasonably expected to meet the requirements of the various work plans and regulatory requirements cost-effectively.

During the field pilot study, the contractor will operate the plant in the manner specified in the operations plans. Known feed material will be loaded into the machine, and the specified products and residuals will be produced. This phase will involve more product sampling than is usually required. With these data, the contractor can confirm the attainment of the treatment standards and calculate the process mass balances, leading to calculation of the volume reduction attained and the ability to track the mass of soil and contaminants through the system.

4.2.2.2 Process Adjustments and Modifications

During the field pilot study, it is natural to expect that adjustments and minor modifications will be required and will be implemented. Some of the variables that may be addressed during this stage include:

- adjusting the feed rate;
- changing the decking on selected mechanical screens;
- modifying the sand/fines separation cut point;
- adjusting the residence times in key treatment units;
- adjusting the dosage rate of chemicals in key treatment units;
- tuning overflow rates in clarifiers; and
- improving the dewatering performance of essential units.

4.2.3 Process Validation

After all objectives of the field pilot study have been accomplished, it is expected that the contractor will be given approval to operate at a specified throughput level and under the requirements of the normal operations plan by the cognizant regulatory authority(ies).

Systems Integrity. A successful pilot study demonstrates the integrity of the systems within the soil washing plant. Any new problems or upsets will be handled as part of a corrective response measure or as part of the normal maintenance program.

Product and Residual Confirmation. Information about the quality of plant products and residuals will be collected under a detailed sampling and analysis plan. The plan will define the location, frequency, and method of collecting the samples required. At a minimum, sampling will include the feed material, products (process oversize and sand), residual materials that may require off-site disposal, any recoverable products, and any required intermediate products.

Process Economic Confirmation. Operations data from the field pilot study will enable the contractor to confirm anticipated full-scale costs.

The real measure of quality will be the concentrations of target contaminants in the products. Soil washing is rather unique in the sense that it is a "fail-safe" system. That is, if something goes wrong, it does not result in a precipitous action that jeopardizes the equipment or personnel. The main failure that can occur is that the soil does not meet the quality standards. This can be easily measured. Soil that does not meet the standards can be staged outside the plant while the plant problems corrected and then reintroduced for further treatment.

4.3 Operations Practices

The soil washing process will be managed and controlled by the contractor responsible for the operations. The most indicative measure of a process under control is one that produces products of steady, compliant quality. The client, engineer, or regulator can quickly obtain a good assessment of the process by looking at the sampling log data on product quality and by reviewing the manifests that record the quality and quantity of residuals shipped off-site for disposal.

No products are allowed to be placed back on the site as clean material until the approved analytical data confirms the attainment of the treatment standards, and, not until the area of excavation has been sampled and cleared.

4.3.1 Process Control

The process will be controlled by a number of intermediate parameters determined by the contract and consistent with the information they will require in order to make products attaining the treatment standards.

4.3.2 Process Upsets

Every process will have unplanned upsets. These upsets may range from minor occurrences that can be easily corrected during the normal course of treatment to catastrophic occurrences that may require long-term plant shutdown and even the replacement of portions of the system. Every good contractor has a contingency plan for these events, but not all of the possible upset situations can be foreseen.

"Normal" upsets are handled by having a good understanding of an engineered plant along with well-trained operators, a reasonable supply of spare parts, and a technology/equipment backup resource that can be called upon during unusual circumstances.

4.3.3 Maintenance Requirements

Plant maintenance activities fall into two primary categories: preventive maintenance and corrective maintenance.

Preventive maintenance is performed on a schedule and includes planned upkeep activities such as lubrication, checking pumps, and cleaning out chemical dosing units. This work will include activities scheduled to be performed weekly, monthly, quarterly, or annually, based upon the manufacturers' recommendations. A preventive maintenance plan is a normal part of a soil washing plant operations plan. Preventive maintenance is often performed on Saturday morning if the plant is operating five days a week with one shift per day.

Corrective maintenance is the activity that must be undertaken immediately to correct some fault with the plant. Problems requiring corrective maintenance may include an overflowing tank, a blocked pump, a blinded screen, or a loss of flow or chemical supply. Most of these problems are common and easy to fix. Good operators and a reasonable supply of spare parts can usually take care of these problems. Naturally, some events may cause serious damage or plant outages that will require skill on the part of the plant operations team and use of the backup resources. Since every possible problem cannot really be anticipated, the client or the regulator must have confidence in the contractor's ability to understand the technology and manage it.

4.3.4 Safety Practices

Good safety practices are essential in the operation and management of a soil washing treatment system. Every soil washing operation should be performed with an assigned, full-time Health and Safety Officer (HASO). The ultimate responsibility for safety belongs to the contractor (although it is common for clients to also take responsibility for safety issues). Authority for safety performance, checking, and corrective actions is delegated to the HASO. Every remediation operation is required to have a detailed health and safety plan (HASP) as discussed in Section 3.8.3. The HASP will outline the responsibilities of all team members, specify personal protective equipment requirements, define respiratory protection requirements, identify routes to the nearest medical facilities, and define the requirements for safety meetings and periodic review of the ongoing operation.

4.3.5 Laboratory Requirements

Laboratory analyses are indispensable to operational control and it can be enhanced if those analyses which can be quickly performed are selected as primary control indicators. Even with on-site facilities, certain laboratory tests take days to perform and this time lag can be detrimental to ongoing operations. If the laboratory is off-site or not under the control of the site operator, additional delays are possible. The time required for properly performed (with applicable QA/QC) analyses must be incorporated in the operating plans. Additionally, provisions must be made for re-treating soils which do not comply with treatment requirements determined by confirmatory laboratory testing.

4.4 Operations Monitoring

System reliability and performance are the results of insightful design, good planning, observant and creative operators, and proper instrumentation. This is not necessarily the order of importance. The key point is that operations monitoring involves more than collecting data. Even in cases where a system is well designed, project management has planned for all foreseeable circumstances and all process indicators are well within normal ranges, a system walk-through by a good operator may identify an off-normal condition before it is manifested as a significant process upset. The following paragraphs identify some of the measurements that can be taken to characterize a process and help operating personnel diagnose problems and improve efficiency.

As described in Section 3.13, the true indicator of performance is cost-effective volume reduction. Thorough characterization by testing and other monitoring can allow calculation of the maximum amount of material that can be returned to the excavation for any allowable residual level. The extent to which the process approaches this ideal state is limited by the effectiveness of physical segregation of the more contaminated particle sizes. For non-extractive processes, the residuals are the contaminated fines. For systems that use chemical extractants to solubilize contaminants, physical segregation is just as important, but process residuals can be further reduced by concentrating the contaminants in process solutions.

4.4.1 Process and Instrument Diagram

Each process module will have some characteristic measure of operating efficiency from which the total process efficiency is calculated. Based on the feed characterization, treatability studies, and experience, a detailed process and instrument drawing (P&ID) can be developed. Initially, the P&ID will act as a guide to evaluate operating data at any point in the system. As the job proceeds and soils from the site are processed, actual data can be used to update the P&ID. Keeping an up-to-date P&ID in the control room for operator reference is good practice and will pay for itself many times over. Ideally, the values taken when the system seems to "run itself" should be noted in detail, so that when an upset must be analyzed, engineers have a basis for comparison in the operating log.

4.4.2 Mass Balances

If the amount or the quality of the clean product soil fraction deviates significantly from the expected values, soil mass balance data from each module will provide a starting point to determine where the losses are occurring. Internal QA samples will also be necessary if the contaminant or particle-size distributions are not consistent. Product quality can deteriorate if the separation of contaminated fines is inadequate. Even with good separation, product quality can deteriorate if the contaminant distribution changes and more contamination is present in the larger size fractions. If the equipment is working well, the mass balance of the contamination could be the problem. Analytical data will be required to separate the two phenomena. Without the proper data, operations personnel could spend a great deal of time analyzing the wrong questions.

4.4.3 Representative Samples

Representative samples of product piles are essential. There will always be a certain amount of contaminant carryover. For example, a few pure metal fragments or contaminant conglomerates can probably be found in the "clean" gravel pile at any given time. This is expected. As long as sample results are within acceptable limits, the system may continue to run without question. However, undetected damage to a screen or poor operation can lead to additional contamination and spot-check QA samples collected through routine procedures may not detect the problem for some time.

Well-intentioned sampling personnel, accustomed to seeing unusual particles may not realize the number has increased. Analytical personnel may not include a metal fragment in the analysis because they, too, may get accustomed to separating out an occasional fragment. The problem may require visual inspection of the piles or counting the number of metal fragments in a randomly taken bucket of product. The sampling protocol must be designed to capture representative features of each type of product at the site.

4.4.4 Parametric Testing

Most parametric testing is done during the treatability tests, but there are always differences in full-scale equipment that will warrant additional testing. If time permits, some of the module operating conditions can be varied to maximize performance and throughput.

4.4.4.1 Screens

Vibrating screens can be varied in frequency and amplitude to minimize the required residence time and maximize size separation. The water flow rate to sprays can be varied to provide adequate dispersion of particles and prevent clay from agglomerating and blinding the screen.

4.4.4.2 Cyclones and Classifiers

Cyclones and classifiers operate under physical principles that are essentially pure cause and effect. Within an allowable range of flow rate and particle loading, they will provide continuous, reliable separation. The operating envelope can be defined and documented for operators, and performance should thereafter be monitored by checking flow meters.

4.4.4.3 Attrition Scrubbing

Attrition scrubber operation can be modified by altering impeller speed and residence time. These parameters can be well tested in the laboratory, but there is the potential to improve the cleaning of sand and small gravel by varying the initial setpoints modestly. Analytical data and possibly a stereomicroscope will be necessary to determine improvements in cleaning.

4.4.4.4 Flotation

Efficiently floating specific fractions (e.g., organic matter, clay fines, or specific mineral types) are the result of selecting the correct residence time, air injection rate, mixing speed, and a variety of possible chemical additives to enhance, suppress, or modify the attraction of gas bubbles to the desired particles. Chemical additives will be selected based on laboratory experiments, but the other variables can be optimized in the field.

4.4.4.5 Settling

Clarifiers operate on the basis of adequate residence time. However, flocculants added in the proper amount and well mixed into the slurry may markedly reduce the residence time required for settling. The mixing step is important and should not be ignored. The flocculant must contact the particles to be settled. The chemical injection rate should be varied to minimize settling time which may be the critical limiting step in the process.

It is noted that changes in the waste stream composition which can occur during processing may require a change in the type or amount of flocculant to ensure effective settling.

4.4.4.6 Water Treatment

Metal removal and/or recovery is typically accomplished by pH adjustment to cause precipitation, settling, and filtration. Each of these steps can be optimized to maximize the cost-effectiveness of the process. The optimum pH for precipitation of one metal may conflict with that of another. Whether they are both optimized and done sequentially, or a compromise condition is used to remove the most metal attainable in one step, will depend on the water quality requirements of the process and the discharge. Settling time, type and duration of filtration, and use of flocculants are also parameters that can be varied to reduce costs while meeting water quality criteria.

Ion exchange may be used to recover valuable components or radionuclides. The type of regenerant chemical, the concentration, and regeneration cycle time will all affect the performance of the system. The manufacturer's recommended practice is always a good place to start, but unique field conditions may require testing to optimize the cost-effectiveness of the system. Regenerant chemical usage and operating time between regeneration cycles are good parameters to monitor to optimize operation.

Treatment for organic contamination and extractant conditioning may have several more variables to control. Examples may include temperature, pH, residence time, and chemical additives, such as defoaming and emulsion-breaking agents.

4.4.4.7 Solids Dewatering and Drying

After settling, the resultant sludge slurry is filtered to remove free liquids. A continuous belt vacuum filter or pressure filter may be affected by the flocculant used and the water content leaving the clarifier, as well as the mechanical variables of the equipment itself. While removal of free liquids is the primary goal to meet disposal criteria, drying the sludge thoroughly will reduce weight, which reduces shipping and disposal costs. Facilitating additional air drying after the filtering operation by turning or spreading the sludge may have a significant impact on cost.

4.5 Quality Assurance and Quality Control

Quality assurance (QA) and quality control (QC) are critical to the successful operation of a soil washing facility. They ensure the validity of data needed for process control and for evaluating system performance, determining the appropriate disposition of residue, and establishing regulatory compliance. QA/QC procedures will help to ensure that representative samples are collected, that introduction of contaminants during sampling and analysis is minimized, and that high-quality analytical data are produced. Without proper procedures, samples may become contaminated during collection, preservation, handling, storage, or transport to the laboratory. At the laboratory, additional opportunities for contamination arise during storage, in the preparation and handling stages, and in the analytical process itself. Unreliable, contaminated, or unrepresentative samples waste money and can jeopardize project success. Valid and useful results answer a question or provide a basis on which a decision can be made.

Because they are interrelated, QA/QC are typically thought of as one entity, but they do have different scopes. QA is a system of activities that assures the producer or user of a product or service that defined standards of quality are met. QC differs in that it is an overall system of activities that controls the quality of a product or service so that it meets the needs of users. QC comprises the internal, day-to-day activities, such as QC check samples, spikes, etc., that are performed to control and assess the quality of measurements. QA, on the other hand, is the management system that ensures an effective QC system is in place and working as intended.

The QA/QC program must be carefully planned in accordance with data-gathering needs to ensure that data will be of sufficient quality. The intended use of data measurements should be addressed explicitly in the sample planning process and reiterated in the analytical planning process. Careful planning is also required to ensure that samples adequately reflect the population being studied. QA/QC planning should define the problem and analytical program well enough so that the intended results can be achieved efficiently and reliably.

4.5.1 Sample Collection Issues

The objective in collecting samples for analysis is to obtain a small and informative portion of the population being investigated. If samples, individually and collectively, cannot provide the required information, they are seldom worth the time and expense of analysis.

All sampling methods should be reviewed. If questions arise during the review, additional confirmatory analyses may be needed, possibly using other methods.

Each sample should be reproducible. Variations caused by different operators, equipment, location, time, and conditions should be minimized. As part of the QA/QC program, sampling methods should be verified and validated to help ensure reproducibility. Verification is the general process used to decide whether a sampling method is capable of producing accurate and reliable data. Validation is an experimental process involving external corroboration by other laboratories, methods, or reference materials to evaluate the suitability of methodology for a particular application.

4.5.2 Laboratory QA/QC Specifics

A laboratory QA/QC program is an essential part of a sound management system. It should be used to prevent, detect, and correct problems in the measurement process and/or to demonstrate attainment of statistical control. The objective of QA/QC programs is to control analytical measurement errors at levels acceptable to the data user and to assure that the analytical results have a high probability of acceptable quality.

There are several key steps in establishing QA/QC:

- planning to define acceptable error rates;
- quality control to establish error rates at acceptable levels;
- quality assessment to verify that the analytical process is operating within acceptable limits; and
- reporting and auditing data quality within the laboratory.

Each laboratory should have an independent person who reports on and carries out the QA/QC program. All QA/QC programs should be documented, for example, in a manual or program plan better known as a Quality Assurance Program Plan (QAPP). QA/QC procedures help ensure valid analytical data. The plan documents the specific steps for implementing the sampling and analytical procedures which are designed to provide reliable data. The plan also describes the procedure for auditing QA/QC implementation to ensure that the work and documentation are being conducted in accordance with established procedures. The elements of an acceptable QA/QC program include:

- development of, and strict adherence to, principles of good laboratory practice;
- consistent use of standard operating procedures; and
- establishment of, and adherence to, carefully-designed protocols for specific measurement programs.

4.5.2.1 Controls/Audits

A QA/QC system includes consistent use of qualified personnel, reliable and well-maintained equipment, appropriate calibrations and standards, and the oversight of all operations by management and senior personnel.

Audits should be a feature of all QA/QC programs. Three kinds of audits are usually performed; these are systems, performance, and data audits.

A systems audit is qualitative and should be made at appropriate intervals to assure that all aspects of the QA program are operative. Performance audits, in which a laboratory is evaluated based on the analyses of performance evaluation samples, are quantitative. They also provide valuable quality assessment information. In data audits, a few samples are randomly selected from a project. During a data audit, all documentation, data entry, calculations, instrument calibrations, data transcription, and report formats are checked for accuracy and conformance to the project QA/QC plan from the time of receipt through the final report.

4.5.2.2 Samples for Controls/Audits

QC samples are the primary means of estimating intra-laboratory variability. Current US EPA laboratory requirements generally specify a uniform schedule of QA/QC sample analyses for chemical parameters. All laboratories that analyze samples for regulatory compliance must analyze one duplicate sample and one matrix spike sample for every 20 samples. A problem with this method is that the schedule may include too few QA/QC samples to control for analytical error. Other controlling standards may have different QA/QC requirements.

4.5.3 Data Quality Criteria for Soil Washing

4.5.3.1 Types of Data

Field screening data are the lowest quality, but yield the most rapid results. They can be used for health and safety monitoring to rapidly determine the potential human exposure to contaminants and particulates during soil washing site operations. Field data assist the operations team in daily process control and in preliminary performance evaluation.

Laboratory analyses are designed to identify and quantify compounds in samples of various matrices. This level of analysis typically provides data to support site characterizations, environmental monitoring, confirmation of field data, engineering studies, and, in specific cases, risk assessments. Results of the laboratory analyses will provide information on the soil washing system's ability to meet soil performance and cleanup goals. RCRA analyses can also be used to characterize the site media as nonhazardous or hazardous before, during, and after soil processing.

4.5.3.2 Data Quality Parameters

In the soil washing process, QA/QC provides the ability to confirm that the sampling and analytical activities are being performed correctly and that the data can be used confidently to make remediation decisions. Five characteristics of data quality are used to assess the data:

- precision,
- accuracy,
- completeness,
- representativeness, and
- comparability.

Precision is a measure of agreement among individual measurements of the same property under similar conditions. It is expressed in terms of relative percent difference (RPD) between duplicates, or in terms of the standard deviation when three or more replicate analyses are performed. Compared to other remediation processes, typical soil washing objectives for the RPD between field duplicates range between 20 to 50% for soil samples and 10 to 20% for water samples.

Accuracy is the degree of agreement between a measurement and an accepted reference or true value. Accuracy will be determined in the laboratory through the use of matrix spikes, surrogates, laboratory method blanks, and laboratory control samples. Trip and field blanks are also analyzed to ensure that samples have not been cross-contaminated and that concentrations measured at the laboratory represent the concentrations in the field samples. Results measure the preparation accuracy and serve as a check on any sample contamination that may be encountered during sample preparation. Statistical control is the first requirement that must be met before accuracy can be assessed.

Completeness is a measure of the amount of valid data obtained compared to the amount expected to be collected under normal correct conditions. Data points may not be valid and may be eliminated if a sample exceeds holding time, did not meet the acceptance criteria, or was broken or contaminated. A completeness criteria of around 80% is normal for a soil washing process.

Representativeness expresses the degree to which data accurately and precisely represent a characteristic of a data population, process condition, sampling point, or an environment. Representativeness is a qualitative parameter of the sampling program. It is highly dependent on proper sample collection techniques which can be evaluated through the analysis of field duplicate samples and comparison with previous data sets.

Comparability is a qualitative parameter expressing the confidence with which one data set can be compared to another.

5

CASE HISTORIES

Case 1 — Soil Washing Treatability Test at 100-DR-1 Operable Unit at the Hanford Site, Richland, Washington

General Site Information

Name: 100-DR-1 Operable Unit

Location: U.S. Department of Energy's Hanford Site,
Richland, Washington

Owner:

U.S. Department of Energy
P.O. Box 550
Richland, WA 99352

Owner Contact:

Julie Erickson
U.S. Department of Energy
P.O. Box 550
Richland, WA 99352
(509) 376-3603

Remediation Contractors(s)(Environmental Restoration Contractor [ERC] Team):

Bechtel Hanford, Inc.
450 Hills Street
Richland, WA 99352
(509) 372-9041

CH2M HILL Hanford, Inc.
P.O. Box 1510
Richland, WA 99352
(509) 375-9424

IT Hanford, Inc.
P.O. Box 1099
Richland, WA 99352
(509) 372-9419

TMA Hanford, Inc.
450 Hills Street
Richland, WA 99352
(509) 372-9241

Regulatory Factors

Authority

Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement between DOE, US EPA, and State of Washington) and CERCLA

Requirements/Cleanup Goals

Cleanup levels established after completion of the test. Cleanup level is 15 mrem/yr (cumulative total of all radionuclides summed together) above background. For metals, State of Washington MTCA B levels are the cleanup standard (chromium VI, 400 mg/kg).

Results

Cleanup goals for metals were met after treatment.

Exposure in clean treated soils was 15.3 mrem/yr without taking background into consideration.

Operation

Type (Cleanup Type)

Treatability test

Period

January 9-12, 1995

Waste Characteristics

Source

Nuclear reactor liquid effluent discharge trench

Contaminant(s)

Radionuclides:

- cesium-137, cobalt-60, europium-152 metals; and
- chromium.

Highest concentrations in feed soils:

- cesium-137 (22.7 pCi/g), cobalt-60 (0.67 pCi/g), europium-152 (8.63 pCi/g), chromium (9.8 mg/kg).

Exposure using average feed concentrations:

- 72.0 mrem/yr without background (residential scenario).

Type of Media Treated

Sands and gravels:

- average moisture content in feed soils is 7%.

Quantity of Media Treated

92.5 tonne (102 ton) of contaminated sand and gravels (99% less than 6 in.)

Technology

Description

Excavation and stockpiling:

- excavation of overburden and contaminated soils with a track mounted excavator (backhoe).

Soil washing system:

- design capacity: 9 tonne/hr (10 ton/hr); operating capacity this test: 4.5 tonne/hr (5 ton/hr);
- maximum treatable size: 6 in. minus;
- water-based system;
- coarse screening by grizzly with 6 in. bar spacing;
- wet Screening of 2 mm to 6 in.;
- attrition scrubbing of 0.25 mm to 2 mm sand;
- dewatering screen drys 0.25 mm to 2 mm sand;
- fines pumped to a clarifier for thickening of minus 0.25 mm sand and silt and clarification of process water;
- rotary drum filter dewaters minus 0.25 mm sludge; and
- filter cake stored in LSA boxes for disposal.

Significance

First pilot-scale test on 100 Area soils at the Hanford Site. Confirms bench-scale tests that soil washing is technically feasible in the 100 Area. Included test of real time monitoring for radionuclides on conveyors.

Cost Data

- Total cost (disposal not included) approximately $2.3 million (DOE-RL 1995).

Project Description

The 100 Area of the Hanford Site contains nine inactive nuclear reactors that were operated to produce fissionable material. Each water-cooled reactor situated along the southern bank of the Columbia River has been shutdown and is currently being evaluated for decommissioning. Waste streams that were generated during the operation of these reactors were disposed of into trenches and cribs, resulting in substantial volumes of contaminated soils.

Soils from the 116-D-1B trench in the 100-DR-1 Operable Unit were selected for bench-scale tests. These soils were expected to be representative of most liquid effluent waste sites. Results of the bench-scale tests indicated that soil washing may be a viable volume reduction treatment in the 100 Area, so a pilot-scale soil washing treatability test was performed.

The plant was designed, built and operated by the ERC team between September 1994 and January 1995. A total of 327 tonne (360 ton) of uncontaminated overburden and 92.5 tonne (102 ton) of contaminated soils were excavated. Approximately 73 tonne (80 ton) of the uncontaminated soils were processed during December 1994 and early January 1995 as part of the shakedown operations. The contaminated soils (all 92.5 tonne [102 ton]) were processed between January 9 and January 12, 1995.

Of the 92.5 tonne (102 ton) of contaminated soils processed, 85% by weight were returned to the excavation as clean and 15% by weight is stored in lined LSA boxes awaiting disposal. During the test 238 samples were taken and received various types of analysis. The uncontaminated soils were replaced back into the top of the excavation. The report, *Soil Washing Pilot Plant Treatability Test for the 100-DR-1 Operable Unit (DOE/RL-95-46)* (DOE-RL 1995), documenting the operations and test results was issued September 29, 1995.

All information for this case history as well as further details are contained in *Soil Washing Pilot Plant Treatability Test for the 100-DR-1 Operable Unit (DOE/RL-95-46)*(DOE-RL 1995) which has been approved for public release and issued in its final form.

Case 2 — Soil Washing Treatability Study for Operable Unit 5, U.S. Department of Energy, Fernald Environmental Management Project, Cincinnati, Ohio

General Site Information

Name: Fernald Environmental Management Project (FEMP)

Location: Butler/Hamilton County, 20 miles Northwest of Cincinnati, Ohio

Owner: U.S. Department of Energy

Owner Contact:

Michael Krstich
Flour Daniel Fernald
25 Merchant Street
Cincinnati, OH 45246
(513) 648-6231 or 648-3000

Remediation Contractors(s):

Primary Contractor — Flour Daniel Fernald,
Support Engineering — IT Corporation

Regulatory Factors

Authority

CERCLA

- ROD Date: 11/95

Requirements/Cleanup Goals

Cleanup level for total uranium was preliminary targeted at 35 pCi/g (ca. equal to 50 mg/kg^{-1} total uranium) as outlined in NRC guidelines (1981).

Results

Bench-scale results indicated that a physicochemical process incorporating sequential extraction steps using $Na_2CO_3/NaHCO_3$ and dilute H_2SO_4 could approach the 50 mg/kg^{-1} targeted cleanup level. Pilot-scale results showed a 90% reduction in total uranium mass for nearly 75% of the initial soil mass and final total uranium concentrations that were less than 40 mg/kg^{-1}. This process was extremely aggressive, resulted in process residues of nearly 40% (approximately 25% soils and 15% chemicals added) that required disposal, and was assessed to be not a cost-effective engineered approach to treatment of soils at the FEMP.

Operation

Type

Bench-scale and pilot-scale treatability testing

Period

Period of operation:

- bench-scale treatability test: April 1992 thru May 1993; and
- pilot-scale treatability test (Batch operation): May 1993 thru August 1993.

Waste Characteristics

Source

Surface soils (2 locations):

- Plant 1 Pad Area; and
- Incinerator Area.

Contaminant(s)

Target analyte — Uranium

Type of Media Treated

Soils (ca. 20% sand, 60% silt, and 20% clay for fraction less than 2 mm)

Quantity of Media Treated

Bench-scale treatability test: 50-250 g per treatment sample

Pilot-scale treatability test (Batch operation): 200-250 kg (441-551 lb) per batch

Technology

Description

Soil washing

Bench-scale testing:

- physical separation; and
- chemical extraction.

Pilot-scale testing:

- physicochemical treatment; and
- batch operated system (ca. 250 kg [551 lb] per batch).

Pilot-plant soil washing system equipment:

- 148.7 m^2 (1,600 ft^2), bilevel arrangement;
- trommel screen with high pressure sprayer (4.75 mm screen);
- vibrating duel-screen deck (2 mm and 0.3 mm screens);
- horizonal duel-scroll centrifuge (0.02 mm particle-size separation & dewatering);
- attrition scrubber (0.02-4.75 mm particle attritioning)(Na_2CO_3/ $NaHCO_3$ extractant);
- chemical extraction reactor vessel (H_2SO_4 extractant);
- processing tanks (1,893 L [500 gal] PVC tanks for interim storage); and
- plate and frame filter press (dewatering precipitate from spent extractant).

Significance

One of the first large-scale soil washing treatability testing efforts for removing radionuclides (uranium) from soils at a DOE site. Incorporated both extensive bench-scale testing (chemical extraction and physical separation) and subsequent pilot-scale testing and system design (physicochemical process).

Cost Data

Total cost for design, construction and operation of the soil washing pilot plant was approximately $1,000,000. Additional costs were incurred during the initial bench-scale testing and subsequent engineering evaluation and conceptual design.

Project Description

Soil washing was identified as a viable treatment process option for remediating soil at the FEMP Environmental Management Project (FEMP). Little information relative to the specific application and potential effectiveness of the soil washing process exists that applies to the types of soil at the FEMP. To properly evaluate this process option in conjunction with the ongoing FEMP Remedial Investigation/Feasibility Study (RI/FS), a treatability testing program was necessary to provide a foundation for a detailed technical evaluation of the viability of the process. In August 1991, efforts were initiated to develop a work plan and experimental design for investigating the effectiveness of soil washing on FEMP soil. In August 1992, the final *Treatability Study Work Plan for Operable Unit 5: Soil Washing* (DOE 1992) was issued.

Bench-scale testing was initiated by IT Corporation in April 1992 and completed in May 1993. Equipment procurment, skid-mounting, and installation on-site at the FEMP occured during the period between November 1992 and May 1993. Pilot-plant operations were conducted during the May through August 1993 time frame. The pilot-plant soil washing system was design to operate in batch mode with a processing rate of approximately 250 kg/week (55 lb/week).

A summary of the findings of this extensive testing established a baseline understanding of the FEMP soil-contaminant matrix, as well as the potential effectiveness of soil washing on FEMP soil. The primary considerations when determining the effectiveness of soil washing for decontaminating FEMP soil must be premised with an understanding of the diversity of soil types, contaminant concentrations, and the resulting soil/contaminant matrices. The effectiveness of soil washing with respect to a reduction in residual uranium mass and mobility, and this extrapolation to the concept of volume reduction, were evaluated based on the results from these extensive bench- and pilot-scale studies.

Based on a summary of the finding from bench- and pilot-scale testing, a hybrid soil washing system was engineered which emphased a sequential extraction process that incorporated a carbonate based reagent as a primary extractant followed by a sulfuric acid based secondary extraction process used on an as-need basis. Using a conservative estimate, extrapolated from pilot-scale results, for the potential effectiveness of a hybrid soil washing system for all of FEMP soils, it is estimated that greater than 90% of the soil can be treated to a residual total uranium concentration of 100 mg/kg^{-1} or less with a mobility of less than 1 mg/L^{-1} total uranium established through TCLP testing.

Case 3 — Soil Washing at The U.S. Army Corp. of Engineers, Saginaw River Site, Essexville, Michigan

General Site Information

Name: Saginaw River PCB Contaminated Sediment Site

Location: Essexville, Michigan

Owner: U.S. Environmental Protection Agency, Great Lakes National Program Office (GLNPO)

Owner Contact:

Dr. James Galloway
U.S. Army Corp. of Engineers
Detroit District
477 Michigan Avenue
Detroit, MI 48226
(313) 226-2056

Remediation Contractors(s):

Richard P. Traver
Bergmann USA
1550 Airport Road
Gallatin, TN 37066
(615) 230-2217
(615) 452-5525 (FAX)

Regulatory Factors

Authority

Assessment and Remediation of Contaminated Sediments (ARCS)

Requirements/Cleanup Goals

CERCLA cleanup levels:

- Clean coarse fraction (>45 microns);
- PCB's 0.188 mg/kg;
- Al 760 mg/kg;
- Ba 5.85 mg/kg;
- Ca 13,900 mg/kg;
- Cu 7.1 mg/kg; and
- Pb 12.0 mg/kg.

Results

Cleanup goals were achieved for PCBs and 5 heavy metals. As reported in the GLNPO Applications and Analysis report entitled *Pilot-Scale Demonstration of Sediment Washing for the Treatment of Saginaw River Sediments*, EPA 905-R94-019, the Bergmann Sediment Washing System performed with a 100% on-line duty factor.

Operation

Type

Full-scale field demonstration

Period

October 1991 to June 1992

Waste Characteristics

Source

Contaminated commercial waterway sediments from dredging operations

Contaminant(s)

Organics:

- polychlorinated biphenyl; and
- maximum concentration in feed 5-7 mg/kg.

Metals:

- Al 27,000 mg/kg;
- Ba 182 mg/kg;
- Ca 96,000 mg/kg;
- Cu 87 mg/kg; and
- Pb 70 mg/kg.

Type of Media Treated

Sediment

Quantity of Media Treated

454 tonne (500 ton) of slack dried sediments

Moisture content of approximately 21%

pH of approximately 6.5

Technology

Description

Coarse material and debris scalping with computer belt scale

Soil washing system:

- five components — deagglomeration, screening, dense media separation, attrition scrubbing, flocculation/sedimentation; rated feed capacity 4.9-9 tonne/hr (5-10 ton/hr);
- screening — multiple screens; coarse static grizzly scalping screen (>2 in.) Wet screening of <2 in. materials with five screening at 45 micron (325 mesh);
- separation — hydrocyclones separate coarse- and fine-grained materials;
- dense media separation — removal of contaminated light organic humic materials (leaves, twigs, roots, etc.) by upward rising water/elutriation;
- attrition scrubbing — high energy surface-to-surface particle contacting for release and separation of contaminated clay material from coarse (3/8 in. by 45 micron) material fractions; and
- flocculation/sedimentation — polymer addition for removal of -45 micron material within inclined plate clarifier.

Significance

Army Corp. of Engineers ARC's full-scale sediment remediation demonstration aboard self-contained support barge performed 2 miles off shore. System evaluated under US EPA Superfund Innovative Technology Evaluation Program.

Cost Data

As reported in the US EPA SITE Applications and Analysis report entitled, *Pilot-Scale Demonstration of Sediment Washing for the Treatment of Saginaw River Sediments*, EPA 905-R94-019, the Bergmann Sediment Washing System reported that estimated cost of soils/sediment washing operations were as follows (see Table 5.3.1).

Table 5.3.1
Costs in $/ton for Operation of Various Sizes of Bergmann USA/Soil Sediment Washing Systems*

Treatment Rate Total Treatment Time	5 ton/hr 1 year	15 ton/hr 2 years	25 ton/hr 3 years	100 ton/hr 5 years
Site Facility Preparation Costs				
Including Excavation	$20.00	$17.85	$15.78	$14.74
(Excluding Excavation)	($0.25)	($0.09)	($0.06)	($0.03)
Permitting & Regulatory Costs	–	–	–	–
Equipment Costs	$12.73	$8.51	$7.29	$5.04
Startup & Fixed Costs	$28.89	$19.64	$16.37	$11.12
Labor Costs	$58.10	$19.37	$11.62	$3.67
Supplies Costs	$7.92	$6.67	$5.42	$4.12
Consumables Costs	$4.10	$2.72	$2.50	$2.35
Effluent Treatment & Disposal Costs	–	–	–	–
Residuals & Waste Shipping, Handling & Transport Costs	–	–	–	–
Analytical Costs	$19.05	$6.35	$3.81	$0.95
Facility Modifications, Repair & Replacment Costs	$0.54	$0.36	$0.30	$0.17
Site Restoration Costs	–	–	–	–
Total Costs	$151.32	$81.46	$63.08	$42.16
(Total Costs Excluding Excavation)	($131.57)	($63.71)	($47.36)	($27.44)

*All costs estimated at 1993 prices

Project Description

Bergmann USA was invited to present an overview on river and harbor sediment treatment technology to the joint US EPA and Army Corps of Engineers' ARCS (Assessment and Remediation of Contaminated Sediments) Workgroup in March 1991. Bergmann was contracted by Jim Galloway, ACOE-Detroit for 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 4.5-9 tonne/day (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 by 10 m (120 ft by 33 ft) Army Corps of Engineers dredge support barge for the processing of approximately 454 tonne (500 ton) of PCB contaminated spoil.

Preliminary results indicate a reduction of 91% of the initial PCB concentration with only 0.2 mg/kg of PCBs remaining in the "clean" coarse +74 micron (200 mesh) fraction. The -74 micron 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 were scheduled for biodegradation during the Spring/Summer of 1992.

Working with Jack Hubbard of the US EPA Hazardous Waste Engineering Research Laboratory in Cincinnati, this Bergmann USA system was evaluated by the Superfund Innovative Technology Evaluation (SITE) Program in May/June 1992 by SAIC, Inc. Preliminary analytical test results were available in July 1992 to be followed by the Technology Evaluation Report and Applications Analysis Report in 1995.

This 9 tonne/hr (10 ton/hr) Bergmann USA plant processed approximately 181 tonne (200 ton) of PCB contaminated dredge sediments prior to winterization. An additional 272 tonne (300 ton) of material was washed during the May/June 1992 evaluation period.

Case 4 — Soil Washing and Hydrometallurgical Lead Extraction, Longue Pointe Garrison, Montreal, Quebec, Canada

General Site Information

Name: Longue Pointe Garrison, National Defence Canada

Location: East Montreal, Quebec, Canada

Vendor:

Bruce E. Holbein
Tallon Metal Technologies, Inc.
1961 Cohen
Ville Saint-Laurent, Quebec
Canada H4R 2N7
(514) 335-0057
(514)335-8279 (FAX)

Point of Contact:

Sylvain Lavoie
DCC Site Engineer
Canadian Forces Base Montreal
St-Hubert, Quebec
Canada J3Y 5T4
(514) 462-7400

Project Operating Company:

Tallon Environment Inc.
6769 Notre Dame Est
Montreal East, Quebec
Canada H1N 3R9
(514) 252-0735
SIC Code: 4593

Regulatory Factors

Authority

Department of National Defence

Defence Construction Canada (DCC)

Environment Canada

Supply and Services Canada

Ministry of Environment & Fauna (Quebec)

Requirements/Cleanup Goals

Environment Canada guidelines:

- less than 900 g/t lead (industrial); and
- less than 500 g/t lead (residential)

Results

Cleanup objectives are to return soil that meets either industrial or residential cleanup guidelines of Environment Canada and the Ministry of Environment and Fauna, Quebec. These guidelines are less than 900 ppm total lead for industrial reuse soils and 500 ppm total lead for residential reuse soils. Lead concentration is determined by XRF and/or AA analyses. Air and water emissions are monitored to conform to environmental specifications.

Operation

Type

Full-scale cleanup

Period

September 1994 to May 1996

Treatment Operation: June 1995 to May 1996

Waste Characteristics

Source

Lead smelter stack emissions

Lead battery recycling operations

Contaminant(s)

Lead

Scrap metal

Diesel fuel

Type of Media Treated

High clay soil (approximately 60% clay)

Classified as hazardous soil (fails TCLP test)

Lead content up to 50,000 g/t

80% of soil lead <10 µm

Moisture content approximately 20%

pH between 8 and 9

Quantity of Media Treated

149,685 tonne (165,000 ton) excavated

Technology

Description

Pretreatment: coarse scrubber, magnetic and gravity separations, size classification.

Lead Extraction: conditioning of minus 0.0394 in. size fraction, chemical extraction of lead, recovery of lead concentrate, recovery of cleaned fine soil fraction.

Site Restoration: return as backfill of 97% of clean soil, landscaping and seeding.

Significance

The Longue Pointe Project is significant as it represents the first full-scale integration of conventional soil washing with chemical extraction of metal from fine fractions of the soil. This enhanced process provides total treatment of the soil and reuse of 97% of the original soil after treatment. The high clay nature of the soil (>50%) and multiple contaminant sources permitted demonstrating of materials handling, dissagregation, physical separation, chemical extraction of metals and fine soil dewatering methods at industrial scale. The project is also demonstrating that clean soil products are produced which are returnable to the site or could be beneficially used off-site.

Lead contamination to hazardous (fails TCLP leach) levels was a consequence of industrial activities at the site at separate times. Lead smelting was conducted at the site until the early 1970's, producing a plume of aerial emissions of lead (60 to 65% of contaminated soil). In the late 1970's and early 1980's a second phase of contamination resulted from lead battery crushing and lead metal recovery operations. Metallic lead as well as battery solutions containing lead were spilled on the site.

Cost Data

The total project cost is US $18.8 million which includes the treatment cost for 116,120 tonne (128,000 ton) of hazardous soil, as well as excavation, civil work, and the construction of fixed facilities for the military base. Average treatment charge on a dry tonne (dry ton) basis is approximately US $123 ($112). This compares favorably with restricted landfill disposal at a cost of $148 to $192/tonne ($135 to $175/ton).

Project Description

The Longue Pointe Project included selective excavation of contaminated soil (hazardous classification) for temporary storage in a containment cell adjacent to the site designated for the treatment plant. The quantity of soil and time constraints, required a plant with the capacity to process 726 tonne/day (800 ton/day). Independently monitored bench-scale and pilot-plant treatability studies demonstrating treatment effectiveness were prerequisites to a competitive commercial bid. In addition to full treatment, the project also included civil work and infrastructure construction. Detailed engineering design, procurement and construction of the treatment plant commenced in July 1994 and the plant was commissioned in May 1995. The project specifications require that the site be landscaped and seeded at the conclusion of treatment.

Case 5 — Soil Washing and Soil Leaching at the Twin Cities Army Ammunition Plant (TCAAP), Site F, New Brighton, Minnesota

General Site Information

Name: Twin Cities Army Ammunition Plant (TCAAP), Site F

Location: New Brighton, Minnesota

Owner Contact:

Martin McCleery
Environmental Engineer
U.S. Army
Twin Cities Army Ammunition Plant
SMCTC-CO
New Brighton, MN 55112
(612) 633-2308

Remediation Contractors(s):

William E. Fristad
COGNIS, Inc.
2331 Circadian Way
Santa Rosa, CA 95407
(707) 575-7155

Regulatory Factors

Authority

CERCLA and RCRA

PRP Lead

Requirements/Cleanup Goals

Soil cleanup levels for 8 metals:

- Sb (4 mg/kg);
- Cd (4 mg/kg);
- Cr (100 mg/kg);
- Cu (80 mg/kg);
- Pb (300 mg/kg);
- Hg (0.3 mg/kg);
- Ni (45 mg/kg); and
- Ag (5 mg/kg).

Results

Cleanup goals were met for all 8 metals.

All soil remained at TCAAP.

No residuals were disposed of in a hazardous waste landfill.

Operation

Type

Full-scale cleanup

Period

September 1993 to July 1995

Waste Characteristics

Source

Ammunition burning/burial

Contaminant(s)

Metals:

- antimony, cadmium, chromium, copper, nickel, silver, lead, mercury; and
- highest metals concentrations in soil — lead (86,000 mg/kg), copper (>100,000 mg/kg), mercury (20 mg/kg).

Type of Media Treated

Soil and ammunition

Quantity of Media Treated

18,597 tonne (20,500 ton) of soil

Moisture content of approximately 15%

pH of approximately 7.0

>272 tonne (300 ton) of ordnance

Technology

Description

Soil washing/soil leaching

Materials handling:

- selective excavation of metals-contaminated soil using visual inspection and x-ray fluorescence.

Soil washing system:

- four components — deagglomeration, screening, sand and fines separation, density separation;
- screening — oversize screen (>1/4 in.);
- separation — elutriation separates coarse and fine-grained materials; and
- density separation — removes metallic particles.

Soil leaching system:

- leaching — both sands and fines leached; and
- metal recovery — all leached metals were recovered in elemental form and recycled.

Significance

First full-scale application of soil washing and soil leaching. Contaminant metals were removed, recovered, and recycled. All soil fractions were treated.

Cost Data

Total cost of $5,000,000 (including excavation, health & safety, ordnance removal, and treatment).

Project Description

COGNIS' TERRAMET soil leaching and Bescorp's soil washing systems have been successfully combined to remediate an ammunition test burn area at the Twin Cities Army Ammunition Plant (TCAAP), New Brighton, Minnesota. TCAAP is an industrial complex covering 2,370 acres in metropolitan Minneapolis, St. Paul that manufactured primarily small caliber rifle ammunition. Off-spec ordnance material and ordnance supplies were buried at Site F, the area remediated in this project. The cleanup is the first in the country to successfully combine these two technologies, and it offers a permanent solution to heavy metal remediation. Over 18,144 tonne (20,000 ton) of soil were treated in the project. The cleaned soil remained on-site, and the heavy metal contaminants were removed, recovered, and recycled. Eight heavy metals were removed from the contaminated soil achieving the very stringent cleanup criteria of <175 ppm for residual lead and achieving background concentrations for seven other project metals (antimony, cadmium, chromium, copper, mercury, nickel, and silver). Initial contaminant levels were measured as high as 86,000 ppm lead and 100,000 ppm copper, with average concentrations over 1,600 ppm each. Final average values for residual copper was 46 ppm and lead was 71 ppm. In addition, both live and spent ordnance (>272 tonne [300 ton]) were removed in the soil treatment plant to meet the cleanup criteria. By combining soil washing and leaching, COGNIS and Bescorp were able to assemble a process which effectively treated all the soil fractions so that all soil material could be returned on-site, no wastewater was generated, and the heavy metals were recovered and recycled. No hazardous waste requiring landfill disposal was generated during the entire remedial operation.

Case 6 — Soil Washing at The Toronto Harbour Commissioners, Contaminated Soil Recycling Facility

General Site Information

Name: Toronto Harbour Commissioners Cherry Street, contaminated soil recycling facility

Location:

Toronto Harbour Commissioners
Cherry Street
Toronto, Ontario
Canada

Owner Contact:

Dennis Lang
Toronto Harbour Commissioners
60 Harbour Street
Toronto, Ontario M5J 1B7 Canada
(416) 865-2047

Remediation Contractors(s):

Richard P. Traver
Bergmann USA
1550 Airport Road
Gallatin, TN 37066
(615) 230-2217
(615) 452-5525 (FAX)

Regulatory Factors

Authority

Toronto Harbour Commissioners & Ontario Ministry of the Environment

Requirements/Cleanup Goals

Toronto Harbour & Ontario ministry on the environment standards:

• BTEX	2.6 mg/kg;
• naphthalene	4.1 mg/kg;
• benzo(a)pyrene	<0.2 mg/kg;
• TPH	1,200 mg/kg; and
• Pb	37 mg/kg.

Results

As per the Toronto Harbour Commissioners designated criteria, cleanup goals were achieved for TPH (Oil & Grease) and copper, nickel, lead, zinc, benzene, toluene, xylene, naphthalene, phenathrene, pyrene, benzo(a)pyrene, chrysene, benzo(b&k)fluoranthene, dibenzo(a)anthracene.

Operation

Type

Full-scale field demonstration

Period

January 1991 to September 1991

Waste Characteristics

Source

Contaminated soil from industrial properties and contaminated sediment from the Toronto Harbour.

Contaminant(s)

Organics:

• BTEX	69 mg/kg;
• naphthalene	17.25 mg/kg;
• benzo(a)pyrene	2.75 mg/kg;
• TPH	37,833 mg/kg; and
• Pb	149 mg/kg.

Type of Media Treated

Soil and sediments

Quantity of Media Treated

4,536 tonne (5,000 ton) of contaminated soil and harbor sediments from 5 different industrial hazardous waste sites.

Technology

Description

Materials handling

Coarse material and debris scalping with computer belt scale

Soil washing system:

- six components — deagglomeration, screening, dense media separation, attrition scrubbing, flocculation/sedimentation; rated feed capacity 4.5-9 tonne/hr (5-10 ton/hr);
- screening — multiple screens; coarse static grizzly scalping screen (>2 in.) wet screening of <2 in. materials with five screening at 45 microns (325 mesh);
- separation — hydrocyclones separate coarse- and fine-grained materials;
- dense media separation — removal of contaminated light organic humic materials (leaves, twigs, roots, etc.) by upward rising water/elutriation;

- attrition scrubbing — high energy surface-to-surface particle contacting for release and separation of contaminated clay material from coarse (3/8 in. by 45 micron) material fractions;
- flocculation/sedimentation — polymer addition for removal of -45 micron material within inclined plate clarifier; and
- deep cone thickener for sludge densification to 35% solids for further treatment.

Significance

Full-scale demonstration of a totally integrated soils recycling facility incorporating soils washing, acid extraction/electro winning of heavy metals, and bio slurry reactors for organic contaminant destruction.

Cost Data

As reported in the report prepared by The Toronto Harbour Commissioners and Zenon Environmental Laboratories entitled, *The Toronto Harbour Commissioners' Soil Recycling Demonstration Project*, presented November 9, 1992 at the Cleanup of Contaminated Sites Conference in Toronto, Ontario, no cost of operation information was presented for the operation of the Bergmann Soil/Sediment Washing System. Bergmann's estimated cost for an 91 tonne/hr (100 ton/hr) or 272,155 tonne/yr (300,000 ton/yr) remedial project of the Toronto Harbour front area is approximately $27/tonne ($25/ton)(excluding excavation and residuals management).

Project Description

Bergmann USA was contracted by the Toronto Harbour Commission for the installation of a 4.5-9 tonne/hr (5-10 ton/hr) pilot-scale soils washing system for the demonstration of volumetric remedial operations coupled with an innovative metal extraction and biodegradation technologies for the treatment of the -74 micron fines fractions. With the receipt of permits from the Ontario Ministry on the Environment, Bergmann USA transported and erected in-place a complete modularized plant on the site. The system was completely shrouded by a Rubb Fabric Building, a tube heat exchanger was installed raising the temperature of process operations wash water to approximately 27-32°C (80-90°F). Canadian weather/temperature permitting, the demonstration commenced on January 6, 1992, and was operated for an initial 28 week period.

The Bergmann USA soils washing plant processed approximately 2,722 tonne (3,000 ton) of heavy metal, PNA and petroleum hydrocarbon contaminated soil materials. The Wastewater Treatment Technology Centre of the Ontario Ministry of the Environmental had Bergmann process approximately 454 tonne (500 ton) of contaminated dredge spoil from the Toronto Harbour. A total of 3,175 tonne (3,500 ton) of material was scheduled for Bergmann to provide effective volumetric reduction. The US EPA HWERL SITE evaluated the Bergmann plant at the Toronto project location in April 1992. The final US EPA report was released in April 1993 and can be obtained by contacting the National Technical Information Service at (703) 487-4600 and requesting EPA Report No. 540/AR-93/517, *Toronto Harbour Commissioner (THC) Soil Recycle Treatment Train.*

Following the completion of the Canadian demonstration project it is anticipated that a full-scale plant would then be designed for installation for a three year, 77 tonne/hr (85 ton/hr) or 272,155 tonne/yr (300,000 ton/yr) remedial project of the Toronto Harbour front area.

Case 7 — Soil Washing of Lead and Grease at Dead Horse, Alaska

General Site Information

Name: Prudhoe Bay, Alaska

Location: Dead Horse, Alaska

Owner Contact:

Merebad Nadem
State of Alaska
Department of Environmental Conservation
Fairbanks, AK
(907) 451-2360

Remediation Contractors(s):

TVIES, Inc.
(Tuboscope Vetco International Environmental Services, Inc.)
2835 Holmes Rd
P.O. Box 808
Houston, TX 77001

Regulatory Factors

Authority

State of Alaska — Department of Environmental Conservation

Requirements/Cleanup Goals

Total lead <500 ppm, TCLP lead <5 ppm, TPH by US EPA 8020 <500 ppm

Results

Cleanup goals met for 97% of the soil.

Average total lead 224 ppm, TCLP lead 2 ppm, TPH 207 ppm.

Fines (3% of mass) with TCLP lead <5 ppm were stabilized, and landfilled.

Cleanup achieved in less than 2 months in remote location with very difficult supply problems.

Operation

Type

Full-scale cleanup

Period

July to September 1992

Waste Characteristics

Source

Pipe dope which had contaminated the gravel pad of an oil field pipe inspection building when the building burned.

Contaminant(s)

Lead (total 3,330 ppm, TCLP 37 ppm) and grease (5,530 ppm)

Type of Media Treated

Gravel, sand and glacial till

Quantity of Media Treated

4,587 m^3 (6,000 yd^3)

2% <200 mesh

Technology

Description

Soil wash with counter-current scouring in augers with 27 atm (400 psi), 99°C (210°F) weakly acidic solution. Fines acid extracted, water settled and recycled — processing rate 9 tonne/hr (10 ton/hr) with 98 L/min (26 gal/min) water.

Significance

Remediate a RCRA metal in a remote and fragile Arctic wilderness. This was the first large-scale soil washing project in the United States in which a RCRA metal was remediated. The project was completed in a very remote location at less than 15-20% of the cost of alternative remediation methods.

Cost Data

Total project cost $1.2 MM, included equipment construction, 1991 pilot, 1992 mobilization, demobilization, and stabilization of nonhazardous fines.

Project Description

Tuboscope Vetco International operates oil field pipe inspection buildings in 45 countries. In 1991 their inspection facility at Dead Horse, Alaska serving a portion of the Prudhoe Bay oil field burned down. The pad of the building was found to be contaminated with lead and grease used for preparing pipe, some of which may have melted during the fire. The cost of alternative cleanup technologies, especially transport and burial in the lower 48 states was excessive, so TVI re-engineered sand and gravel washing augers to melt and scour contaminants from the soil.

Equipment was designed and built in Houston, Texas, and mobilized to the site in 1992 for a pilot. In 1992 the full-scale project was conducted.

Case 8 — Soil Washing at the Gustavus, Alaska Airport Site

General Site Information

Name: Gustavus Airport

Location: Gustavus, AK (99812)

Owner Contact:

Claire Jaeger
Chief, Construction Branch, USACOE, Alaska District
Richardson Resident Office
Anchorage, AK 99506-0898
(907) 384-7444

Remediation Contractors(s):

TVIES, Inc.
(Tuboscope Vetco International Environmental Services, Inc.)
2835 Holmes Road
P.O. Box 808
Houston, TX 77001

Regulatory Factors

Authority

State of Alaska — Department of Environmental Conservation

Requirements/Cleanup Goals

Diesel range organics <200 ppm

Results

Cleanup goals met — volume of soil taken off-site reduced 89%.

Cleanup achieved in less than 4 months in remote location with very difficult supply problems and unexpected contamination problems.

Operation

Type

Full-scale cleanup

Period

August to November 1994

Waste Characteristics

Source

Asphalt and diesel buried at the conclusion of two airport construction projects — 1940's and 1950's.

Contaminant(s)

Diesel, motor oil, asphalt and asphalt hardener — diesel range organics 4,000-12,000 ppm. Analysis indicated that portions of the soil contained an 80:20 mixture of diesel and asphalt.

Type of Media Treated

Glacial sand and till

Quantity of Media Treated

13,181 tonne (14,530 ton)

5% <200 mesh

pH approximately 8

Very abrasive mineral particles

Primary contaminant diesel mixed with asphalt

Technology

Description

Screen to <1 in. to remove large tar chunks.

Soil washing using three successive stages of counter-current scouring in augers with 13.5 atm (200 psi), 99°C (210°F) alkaline detergent solution.

Dewatering of sand on shaker screens — water cleaned by flocculation and centrifuge — water recycled — processing rate 13 tonne/hr (15 ton/hr), while using 227 L/min (60 gal/min) of water.

Significance

Cleanup of subsurface contamination that could potentially affect the drinking water supply of a school, public buildings and residences, and removal of surface tar and buried chemicals that were contaminating the resort center supporting Alaska's Glacier Bay National Park.

Cost Data

Soil washing cost $1.4 MM, including mobilization, pilot and demobilization — total project cost $8.0 MM includes revegetation of the site as well as excavating then shipping 20,000 drums, the buried asphalt batch plant, waste asphalt, and contaminated fines to Washington state for land filling.

Project Description

When the Gustavus, Alaska airport was built during World War II, the drums used to ship the asphalt were buried. The airport was expanded in the early 1950's. At that time empty and full drums of asphalt and asphalt hardener, and the asphalt batch plant were buried. Apparently diesel fuel used to clean equipment had been dumped on the sandy soil. In addition, a mixture of asphalt and diesel solvent propagated through the subsurface soil from the vicinity of the buried asphalt mixing building. A large fraction of the subsurface soil at the site had been contaminated by this source, that was unknown at the time of the RI.

Equipment was mobilized by truck and barge from Houston, Texas to the site 50 miles by sea from Juneau, Alaska — piloted and production began approximately 8/15/94. The project was completed 11/1/94. An on-site analytical lab was crucial to rapid appraisal of soil washing efficiency at this isolated site.

Case 9 — Soil Washing of Drill Cuttings at Kenai, Alaska

General Site Information

Name: Kenai Gas Field

Location: Kenai, Alaska

Owner Contact:

Bruce St. Pierre
Unocal Oil and Gas
Anchorage, AK
(907) 263-7615

Remediation Contractors(s):

TVIES, Inc.
(Tuboscope Vetco International Environmental Services, Inc.)
2835 Holmes Road
P.O. Box 808
Houston, TX 77001

Regulatory Factors

Authority

State of Alaska — Department of Environmental Conservation

Requirements/Cleanup Goals

Total petroleum hydrocarbons <500 ppm, total lead <500 ppm

Results

Cleanup goals met for 95% of the soil.

Average TPH 300 ppm.

Fines were injected along with excess process water.

Operation

Type

Full-scale cleanup

Period

August to September 1993

Waste Characteristics

Source

Oil based emulsions used to support sand removed during drilling of oil wells in Cook Inlet.

Contaminant(s)

TPH 3,000 to 20,000 ppm, 500 ppm lead

Type of Media Treated

Drill cuttings (ground sand) and glacial till

Quantity of Media Treated

459 m^3 (600 yd^3)

2% <200 mesh

Technology

Description

Soil wash with counter-current scouring in augers with 27 atm (400 psi), 99°C (210°F) alkaline detergent solution — silt and water injected in Class II disposal well. Production rate 9 tonne/hr (10 ton/hr) while using 98 L/min (26 gal/min) of water.

Significance

Clean up oil well drill cuttings that had been buried for many years, and which could have potentially threatened water supplies.

Cost Data

Total project cost $31,000.

Project Description

Oil field drill cuttings are shale, sand, and broken rock flushed from a well bore by a water in oil emulsion ("mud") as the well is drilled. They are separated from the "mud" with shakers and cyclones, then were commonly buried. The oil based "mud" used in the well is a mixture of diesel fuel, emulsifiers, dispersants, such as chrome lignosulfonate and barium sulfate added to maintain a dense mud which can safely control underground pressure.

After a time, diesel fuel used in the emulsion carrying the cuttings from the well can begin to leach from pit and threaten groundwater supplies. Thus, the old pits are gradually being cleaned up. In this full-scale test, cuttings were cleaned from 3,000 ppm TPH to <300 ppm, while the water and fines were injected into a Class II well. The project ended when the packer in the injection well failed.

Case 10 — Soil Washing of NORM Contaminated Gravel

General Site Information

Name: Newpark Environmental Services

Location: Port Arthur, Texas

Owner Contact:

"Pappy" Ruckstuhl
VP Operations
Newpark Environmental Services
Lafayette, LA
(318) 984-4445

Remediation Contractors(s):

TVIES, Inc.
(Tuboscope Vetco International Environmental Services, Inc.)
2835 Holmes Road
P.O. Box 808
Houston, TX 77001

Regulatory Factors

Authority

Texas Railroad Commission — Louisiana Department of Environmental Quality

Requirements/Cleanup Goals

Radium^{226} <5 pCi/g

Results

85% of the soil was cleaned.

The NORM was concentrated in the -1/4 ft to 50 mesh fraction, which was ground and injected into a Class II injection well.

Water and clay were also injected into a Class II injection well.

Operation

Type

Full-scale cleanup

Period

February-June 1995

Waste Characteristics

Source

NORM scale cleaned from oil field pipe and vessels.

Contaminant(s)

Radium^{226} 100-700 pCi/g

Type of Media Treated

Gravel, shell, and soil

Quantity of Media Treated

2,700 drums

Technology

Description

Soil wash with counter-current scouring in augers with 27 atm (400 psi), 99°C (210°F) water.

Production rate up to 150 bbl/day while using 98-151 L/min (26-40 gal/min) of water.

Significance

Gravel and shell was cleaned and did not have to be injected into a Class II injection well.

Cost Data

Total project cost $215,000.

Project Description

NORM (Naturally Occurring Radioactive Material) is radioactive carbonate, silicate or sulfate scale that concentrates wherever large volumes of hot water are processed. NORM is a common problem in oil fields where hot subsurface carbonated brines are brought to the surface, cooled and depressurized. NORM then collects in vessels and pipes. Before it was common knowledge that the scale was radioactive, the scale was cleaned from the pipe or vessels and used as fill. Thus, significant volumes of soil have been contaminated in pipe yards and oil fields.

Scale is a very low solubility solid, that generally occurs in a specific particle-size range, i.e., smaller than 1/8 in., but larger than 50-150 mesh. Thus, in clay soils with gravel or shell covers, the problem is very amenable to inexpensive volume reduction.

Case 11 — Soil Washing of Listed Waste Contaminated Railroad Yard Ballast and Soil

General Site Information

Name: Union Pacific Railroad

Location: Houston, Texas

Owner Contact:

Paul Person
Manager Environmental Remediation
Union Pacific Railroad
Omaha, NE
(402) 271-6572

Remediation Contractors(s):

TVIES, Inc.
(Tuboscope Vetco International Environmental Services, Inc.)
2835 Holmes Road
P.O. Box 808
Houston, TX 77001

Regulatory Factors

Authority

Texas Natural Resources Conservation Commission

Requirements/Cleanup Goals

TPH <500 ppm, VOC and SVOC to non-detect

Results

95% of the soil was cleaned.

TPH was reduced 99.5% and VOC/SVOC reduced to non-detectable levels.

Operation

Type

Pilot

Period

January 1994

Waste Characteristics

Source

Grease dripping from parked locomotives onto railroad ballast and spill of D,F,K, and U wastes at railroad yard.

Contaminant(s)

TPH 25,000 to 75,000 ppm, VOC and SVOC 225 ppm

Type of Media Treated

Pea gravel, traction sand, and fine sandy loam soil

Quantity of Media Treated

18 tonne (20 ton)

Technology

Description

Soil wash with counter-current scouring in augers with 27 atm (400 psi), 99°C (210°F) alkaline detergent solution.

Water cleaned and recycled during the pilot then disposed of in the city sewer.

Production rate up to 9 tonne/hr (10 ton/hr) while using 98 L/min (26 gal/min) of water.

Significance

Inexpensive cleanup of messy and dangerous contamination in railroad yards.

Cost Data

No charge, estimated cleanup cost of unlisted wastes <\$33/tonne (\$30/ton). Cost for characteristic and listed wastes \$82 to \$165/tonne (\$75 to \$150/ton).

Project Description

Because a variety of materials are transported on railroads, the soil near the tracks and in railroad yards can become highly contaminated with almost any material. The least obnoxious of these is grease dripping from locomotives when they are parked. This material is classified as commercial non-hazardous wastes, but must be regularly cleaned as a house keeping measure. Another waste is diesel spills in fueling area. A final type of wastes are spills of chemicals and listed wastes during transport to disposal sites.

TVIES processed over 18 tonne (20 ton) of greasy ballast and yard soil contaminated with listed wastes. TPH was reduced from 25,000 and 75,000 ppm to less than 500 ppm, and both VOC's and SVOC's were reduced below detectable levels with a few minutes of scouring with chemical solutions in its auger washing equipment.

Case 12 — Soil Decontamination Treatability Studies at the Warm Waste Pond, Idaho National Engineering Laboratory, Idaho Falls, Idaho

General Site Information

Name: Warm Waste Pond, Idaho National Engineering Laboratory

Location: Idaho Falls, Idaho

Owner: U.S. Department of Energy

Owner Contact:

Lisa Green
U.S. Department of Energy
Idaho Falls, ID

Regulatory Factors

Authority

CERCLA:

- ROD Date 12/5/91; and
- DOE Lead Agency and PRP.

Requirements/Cleanup Goals

12/5/91 ROD requiring 60% soil recovery by sieving, 90% removal of total contamination, and residual cesium contamination level ≤690 pCi/g in soil returned to excavation.

Results

Cleanup goals for cesium decontamination could not be met using any treatment tested. Even low surface area +8 mesh fraction partitioned by wet sieving did not pass cleanup criteria. Cesium decontamination of up to 90% could be achieved with hot acid, but almost one third of the soil mass was dissolved, generating unacceptable secondary waste volumes. Sequential extraction indicated little preferential distribution of cesium in any chemical phase, with most of the cesium residual bound in or on the mineral lattice.

Operation

Type

Treatability study

Period

1991-1993

Waste Characteristics

Source

Cooling tower and low level radioactive waste discharge to evaporation pond.

Contaminant(s)

- Cesium: -137 Ave 11,500 pCi/g, -8 mesh 22,000 pCi/g;
- Cobalt: -60 Ave 4,620 pCi/g, -8 mesh 6,200 pCi/g; and
- Chromium: 338 mg/kg.

Type of Media Treated

Coarse gravel/sand/silt mixture

Quantity of Media Treated

14,159 m^3 (500,000 ft^3)

Coarse gravel/sand/silt mixture, >70% +8 mesh

pH approximately 8

Technology

Description

Chemical:

- ambient and hot mineral acid extraction;
- selective sequential extraction; and
- ion exchange with salt brines.

Physical:

- wet sieving.

Significance

Extensive treatability study efforts were completed using a wide variety of chemical decontamination techniques which showed that cesium appears to be irreversibly bound in the silicate mineral matrix, and unavailable to recovery without substantial dissolution of the matrix. Preliminary scoping studies were not adequate to characterize potential for cleanup prior to ROD.

Cost Data

Estimated cleanup cost for acid extraction, including secondary waste treatment, but not disposal, was $1,414/tonne ($1,287/ton) for the simplest conceptual flowsheet using neutralization and precipitation of sludges. Total cost for this option was estimated to be almost $57,000,000.

Project Description

The Warm Waste Pond is located in the southwestern portion of the Idaho National Engineering Laboratory, an 890 mi^2 reservation 32 miles west of Idaho Falls, in southwestern Idaho. The Idaho National Engineering Laboratory is under the purview of the DOE, and operated to do nuclear reactor research and fuel storage and processing. The pond consists of three cells, excavated in 1952, 1957, and 1964 covering a total of approximately 4 acres. Normal annual precipitation is about 9 in., and the underlying strata are made up of interbedded basalt flows and mixed gravel, sand, and silt.

Over 40 years of operation, the pond is estimated to have received over 18.9 billion L (5 billion gal) of reactor cooling water, radioactive wastewaters, and regeneration solutions from ion exchange columns. Though samples have been characterized to ten feet below the surface in efforts extending from 1983-1990, contaminants were found chiefly only in the top 2 ft. The most prevalent contaminant found is chromium. Introduced to the pond as a hexavalent corrosion inhibitor until 1972, the chromium has been reduced over time to the less toxic trivalent form.

The ROD required treatment of the top 2 ft of sediment, or about 14,159 m^3 (500,000 ft^3) of material. Initial scoping studies indicated that about 60% (by weight) of the matrix could be separated by sieving at 8 mesh, and the relatively low surface-area material could be water washed and returned to the excavation. The finer material could be extracted with hot mineral acids to achieve the required overall decontamination, with about 8% (by weight) lost to dissolution. Follow-on studies to support the cleanup indicated that the large material separated by screening did not meet the required residual cesium limits, and far greater extraction efficiency would be required with the finer material to meet the overall goals stated in the ROD. Up to 90% decontamination was achievable with near boiling 3M nitric acid, but about 1/3 of the soil matrix was dissolved in the process. Parallel studies were performed with sequential extraction to determine how the cesium was bound in an effort to develop a more selective extractant to remove the cesium without gross dissolution of the matrix. The soil was first treated with a potassium brine to remove exchangeable cesium. Then the carbonate, hydrated metal oxide, and organic phases were removed as selectively as practical. Over 20% (by weight) of the soil was dissolved by the time the underlying mineral matrix was stripped and yet only about 18% of the cesium was removed. The cesium was apparently irreversibly fixed in or on the silicate matrix, unavailable to chemical decontamination without strong etching of the mineral surface.

Estimated costs, secondary chemical wastes, and the risks of processing with near boiling, strong nitric acid made the proposed cleanup unacceptable, and the lower risk, lower cost interim action chosen was capping. The difficulties shown for chemical extraction of cesium at this site are mirrored by data from many other locations including Oak Ridge, Tennessee and Hanford, Washington.

Case 13 — Soil Washing Pilot Study at the 300-FF-1 Operable Unit, The Hanford Site, Richland, Washington

General Site Information

Name: 300-FF-1 Operable Unit, North Process Pond, The Hanford Site

Location: Richland, Washington

Owner:

U.S. Department of Energy
P.O. Box 550
Richland, WA 99352

Owner Contact:

Ronald D. Belden
CH2M HILL Hanford, Inc.
450 Hills Street, Door 5
P.O. Box 1510
Richland, WA 99352
(509) 372-9601

Remediation Contractor(s):

Alternative Remedial Tecnologies, Inc.
14497 North Dale Mabry Highway, Suite 240
Tampa, FL 33618
(813) 264-3506

Regulatory Factors

Authority

CERCLA:

- On May 15, 1989 (amended May 1991 and January 1994), the DOE, the Washington State Department of Ecology, and the US EPA signed an agreement (Tri-Party Agreement) that contains a plan for cleanup; and
- DOE lead agency.

Requirement/Cleanup Goals

Cleanup Goals are shown in Table 5.13.1, the criteria for the clean fraction of soil was greater than 90% by weight. The criteria for the contaminated soil fraction resulting from the process was 10% or less of the total soil processed on a weight basis.

Table 5.13.1
Cleanup Goals

Constituent	Soil Cleanup Levels
Copper (ppm)	11,840
U-238 (pCi/g)	50
U-235 (pCi/g)	15
Cs-137 (pCi/g)	3.0
Co-60 (pCi/g)	1.0

Results

The soils met the principal objective of the study which was to determine if the physical separation approach would be effective in attaining a 90% volume reduction while meeting the defined test performance criteria. Volume reductions of 93.8% and 91.4% by weight were attained for the two soil types processed. Cleanup standards attained are shown in Table 5.13.2.

Table 5.13.2
Cleanup Standards Attained

	Concentration		
Contaminant	Process Oversize (Clean)	Sand (Clean)	Test Performance Standard
Cu (ppm)	199	1,180	11,840
U-238 (pCi/g)	5.5	28.5	50
U-235 (pCi/g)	0.3	1.4	15
Cs-137 (pCi/g)	0.05	0.3	3.0
Co-60 (pCi/g)	< 0.04	< 0.06	1.0

Operation

Type

Pilot study

Period

March 1994-June 1994

Waste Characteristics

Source

Soils underlying process ponds and trenches that held wastewaters from nuclear fuel fabrication operations.

Contaminant(s)

See Table 5.13.3

Table 5.13.3
Feed Concentration of Contaminants

Contaminant	Feed Concentration
Copper	2,800 ppm
U-238	132 pCi/g
U-235	4.5 pCi/g
Cs-137	0.13 pCi/g
Co-60	0.08 pCi/g

Type of Media Treated

Coarse granitic sands and gravels. Two soil types were treated during the testing: a natural soil contaminated with low levels of uranium, cesium, cobalt, and heavy metals, and a natural soil contaminated with a uranium-copper carbonate material that was visually recognizable by the presence of a green sludge material in the soil matrix. The "green" material contained significantly higher levels of the same contaminants.

Quantity of Media Treated

315.9 tonne (348.2 ton) total

Technology

Description

Soil washing/physical separation, physical separation is one member of a broad group of technologies referred to as soil washing. The 9-14 tonne/hr (10-15 ton/hr) physical separation plant consisted of the following units:

- 50 mm vibrating screen;
- feed hopper;
- >2 mm double-decked vibrating wet screen;
- hydrocyclone separation system;
- sludge settling tank;
- attritioning unit;
- process water tank;
- sludge holding tank;
- dewatering unit; and
- sludge dewatering unit.

Significance

This was the first soil washing pilot study performed at the Hanford Site. The study demonstrated that soil washing could effectively meet the principal objective of the study which was to determine if a physical separation approach could be effective in attaining a 90% volume reduction while meeting the defined test performance criteria. Also of significance was the decontamination and removal of the plant from the site.

Cost Data

Value of contract was $1.1 million.

Project Description

ART was contracted to the Westinghouse-Hanford Company for all phases of the pilot study which included:

- mobilization and set-up of the pilot plant;
- plant shakedown;
- preparation of site manuals including:
  - site operations manual;
  - quality assurance project plan;
  - test procedures;
  - performance of all phases of the soil washing pilot test;
  - plant decommissioning and decontamination; and
  - project technical report.

The test was conducted on soils contaminated with low-level uranium, metals and organics. Contamination originated from nuclear materials production operations at the site from World War II until 1975. Soils from two areas within the OU were processed (1) 272 tonne (300 ton) of soil containing metals, organic materials and low-level uranium and, (2) 73 tonne (80 ton)(excavated) of soil containing elevated concentrations of copper and uranium.

The tests for the 272 tonne (300 ton) of soil were conducted in three segments: (1) the pre-test run, (2) the verification run, and (3) the replication run, as follows:

(1) The pre-test run provided for startup of the equipment and initial processing of soil. Adjustments and fine-tuning to the plant were made, based on the results of the pre-test run. During this run, 45 tonne (50 ton) of soil were processed.

(2) The goal of the verification run was to demonstrate that the equipment and process could achieve the specified 90% reduction by weight of contaminated material, and to meet the treatment standards. During this run 113 tonne (125 ton) of soil were processed.

(3) The goal of the replication run was to confirm that the results achieved in the verification run could be replicated. During this run, an additional 113 tonne (125 ton) of soil were processed.

ART also performed a test on 73 tonne (80 ton)(excavated) of soil containing significantly higher levels of uranium due to the presence of a uranium-copper carbonate precipitate. Attrition scrubbing added to the process units to achieve improved treatment performance.

The pilot plant utilized at this site had a throughput capacity of 9-14 tonne/hr (10-15 ton/hr) in a mobile, easily erectable configuration. The plant consisted of a feed hopper, a double-decked wet screen, hydrocyclones, attrition scrubber, sand dewatering screen, sludge thickening and dewatering units, and the required supporting peripheral equipment. The pilot study was successful in meeting the goal of >90% reduction by weight and was also successful in achieving the specified test performance standards.

Upon completion of the tests, ART submitted a written report to Westinghouse-Hanford Company for incorporation into a Feasibility Study.

Reference

1. Westinghouse Hanford Company. 1994. *300-FF-1 Operable Unit Physical Separation of Soil Pilot Plant Study.* WHC-SD-EN-TI-277, Rev. 0. Prepared for the DOE Office of Environmental Restoration and Waste Management.

Case 14 — Full-Scale Soil Washing at the King of Prussia Superfund Site, Winslow Township, New Jersey

General Site Information

Name: King of Prussia Superfund Site

Location: Winslow Township, New Jersey

Owner: Winslow Township, New Jersey

Owner Contact:

Frank J. Opet, PRP Committee Chairman
Johnson Matthey
2001 Nolte Drive
West Deptford, NJ 08066
(609) 384-7000

Remediation Contractor(s):

Alternative Remedial Technologies, Inc.
14497 North Dale Mabry Highway, Suite 240
Tampa, FL 33618
(813) 264-3506

Regulatory Factors

Authority

CERCLA:

- ROD Date 9/28/90;
- Unilateral Administrative Order April 1991 issued to Potentially Responsible Party Committee; and
- US EPA lead agency and PRP.

Requirements/Cleanup Goals

9/28/90 ROD defined five components of remedial activities pertaining to contaminated media, including the area relevant to this case history (Component 1):

> *Component 1* — The metals-contaminated soils adjacent to the lagoons, the sludge in the lagoons, and the sediment in the swale (Operable Unit 1);
>
> *Component 2* — The buried drums and soils contaminated with volatile organic compounds located in the northwest section of the site (Operable Unit 2);
>
> *Component 3* — Two tankers and their contents located near the southeast sections of the site;
>
> *Component 4* — The groundwater at the site contaminated with organics and metals (Operable Unit 3); and
>
> *Component 5* — The surface waters, sediments and biota of the Great Egg Harbor River.

The 1990 ROD identified cleanup goals for 11 metals in the soil in the area adjacent to the lagoons, sediments in the swale, and sludges in the lagoons. These goals are presented in Table 5.14.1.

Results

The remedial activities for Component 1 were led by the PRPs with US EPA oversight. Cleanup goals were met for all eleven metals. Cleanup goals were achieved in less than four months. Cleanup standards attained for the primary contaminants are presented in Table 5.14.2.

Operation

Type

Full-scale

Period

June 18, 1993-October 10, 1993

Table 5.14.1
Cleanup Goals

Constituent	Soil Cleanup Levels (mg/kg)
Arsenic	190
Beryllium	485
Cadmium	107
Chromium (total)	483
Copper	3,571
Lead	500
Mercury	1
Nickel	1,935
Selenium	4
Silver	5
Zinc	3,800

Primary contaminants of concern were nickel, chromium and copper.

Table 5.14.2
Cleanup Standards Attained

Contaminant	Clean Product (avg. conc. mg/kg)
Nickel	25
Chromium	73
Copper	110

Waste Characteristics

Source

Six lagoons used to process liquid industrial waste.

Contaminant(s)

Metals

- beryllium, chromium, copper, nickel, zinc, lead, mercury;
- highest metals concentrations in sediments — chromium (8,100 mg/kg), copper (9,070 mg/kg), mercury (100 mg/kg); and
- highest metals concentration in sludge — chromium (11,300 mg/kg), copper (16,300 mg/kg), lead (389 mg/kg), nickel (11,100 mg/kg).

Type of Media Treated

Soil and sludge

Quantity of Media Treated

17,418 tonne (19,200 ton)

Moisture content of approximately 15%

pH of approximately 6.5%

Technology

Description

Soil washing

Materials handling:

- selective excavation of metals-contaminated soil using visual inspection, confirmed using on-site x-ray fluorescence.

Soil washing system:

- four components — screening, separation, froth flotation, sludge management; rated feed capacity of 23 tonne/hr (25 ton/hr);
- screening — multiple screens; coarse screen (>8 in.) and process oversize (>2 in.); wet screening of <2 in. materials;
- separation — hydrocyclones separate coarse- and fine-grained materials;
- froth flotation — air flotation treatment units; and

- sludge management — overflow from hydrocyclones sent through clarifier, sludge thickener, filter press; filter cake disposed off-site; water reused for wet screening.

Significance

US EPA's first full-scale application of soil washing to remediate a Superfund site. Innovative on-site monitoring technique; selective excavation techniques, including use of x-ray fluorescence, to screen soil for cleanup. Data from demonstration run expedited the design schedule of the full-scale unit by more than a year.

Cost Data

The total cost for this application was $7,700,000, including off-site disposal costs for the sludge cake. Selective excavation, confirmed using on-site x-ray fluorescence, reduced the overall costs for the application by reducing the amount of soil requiring treatment by a factor of two.

Project Description

Background

The King of Prussia Technical Corporation Site is located in Winslow Township, New Jersey, about 30 miles southeast of Philadelphia. The site is situated on approximately ten acres within the Pinelands National Reserve, and adjacent to the State of New Jersey's Winslow Wildlife Refuge. The KOP Technical Corporation purchased the site in 1970 to operate an industrial waste recycling center. The operation was not successful, and in 1985 the site was placed on the National Priorities List. In 1990 a Record of Decision (ROD) was issued for the site, and soil washing was specified as the cleanup technology to be used for remediating the soils. A group of Potentially Responsible Parties was issued a Unilateral Administrative Order to implement the requirements of the ROD.

Preliminary Activities

Two major preparatory steps were taken prior to beginning full-scale soil washing activities:

(1) *A Treatability Study to Determine the Applicability of Soil Washing to the Site.* During the Treatability Study, site soils were separated into particle-size fractions and particle-size distribution curves were constructed. Each resulting fraction was analyzed for the target contaminants, and bench-scale studies were conducted to determine the treatment unit operations to be implemented in the full-scale operation.

(2) *A "Demonstration Run" of Actual Site Soils Prior to Final Design of the Soil Washing Plant.* Because this was a new technology to the US EPA, some questions were left from the treatability and bench-scale studies. Therefore, to fully confirm the effectiveness of the technology on KOP soils, a "demonstration run" was planned and implemented for actual KOP site materials at Heidemij's full-scale fixed facility in Moerdijk, The Netherlands. With US EPA and VROM (the equivalent Dutch agency) approval, 150 tonne (165 ton) of KOP site soils were shipped to Moerdijk. A one-day treatment operation was performed with the equipment configured as recommended in the preliminary design for the KOP soil washing plant. The operation was successful in demonstrating the effectiveness of soil washing in treating the site soils. Soils were remediated to levels well below the ROD-specified standards.

Preparation for Full-Scale Operations

Following the demonstration run, the firm of SALA International was contracted by ART to manufacture a 23 tonne/hr (25 ton/hr) soil washing plant, and the plant was delivered to the site in May 1993. After erection of the plant on-site, a pilot run was conducted on 907 tonne (1,000 ton) of contaminated soils excavated from the site. The pilot run was successful, again with cleanup levels well below the ROD-specified standards. As a result, US EPA granted prompt approval to proceed with full-scale remediation.

Full-Scale Operations

Full-scale operations at the KOP site began on June 28, 1993. The project was performed with full US EPA oversight and in accordance with the approved Site Operations Plan. The process and products were controlled by on-site x-ray fluorescence using previously prepared site matrix-matched standards and confirmed by off-site CLP analysis. Correlation between the approaches was excellent. The soil washing operation was completed on October 10, 1993, and the facility was disassembled and removed from the site. The project treated 17,418 tonne (19,200 ton) of soil with a volume reduction of greater than 90% on a dry solids basis.

Reference

1. US EPA 1995. *Remediation Case Studies: Thermal Desorption, Soil Washing, and In Situ Vitrification.* EPA-542-R-95-005. Office of Solid Waste and Emergency Response. Washington, DC. March.

Case 15 — Soil Washing at the Monsanto Site, Everett, Massachusetts

General Site Information

Name: The Monsanto Site

Location: Everett, Massachusetts

Owner: The Monsanto Company

Owner Contact:

Bruce Yare
Monsanto Company
800 North Lindberg Boulevard
St. Louis, MO 63167
(314) 694-6370

Remediation Contractor(s):

Alternative Remedial Technologies, Inc.
14497 North Dale Mabry Highway, Suite 240
Tampa, FL 33618
(813) 264-3506

Regulatory Factors

Authority

Massachusetts Contingency Plan, Phase III Remedial Action Plan

Requirements/Cleanup Goals

See Table 5.15.1

Table 5.15.1
Cleanup Goals

Contaminant	Cleanup Requirements (mg/kg)	Cleanup Goals (mg/kg)
BEHP	< 10,000	3,000
Naphthalene	< 10,000	3,000
Phthalic Acid	< 1,000	300

Operation

Type

Full-scale

Period

May-November 1996

Waste Characteristics

Source

Chemical plant

Contaminant(s)

- bis (2-ethlhexyl) phthalate (BEHP);
- phthalic anhydride process residues (PAPR) containing Naphthalene; and
- phthalic acid.

Type of Media Treated

Soil

Quantity of Media Treated

8,709 tonne (9,600 ton)

Technology

Description

Soil washing and bioremediation feed preparation

Plant units:

- trommel;
- feed hopper;
- wet screen;
- hydrocyclones;
- attritioner;
- sand dewatering screen;
- sludge settling tank; and
- plate and frame filter press.

Significance

In addition to the fine fraction containing PAPR the oversize fraction, typically unimpacted, also contained PAPR. An innovative treatment train was designed for treatment of this fraction. The soil washing technology effected considerable cost savings over baseline technology.

Cost Data

Total cost was $900,000 for soil washing and bioremediation feed preparation.

Project Description

The Monsanto Company operated a chemical plant at this 84 acre brownfields site from the mid-1800s to 1992. Manufacturing activities resulted in soil impacted with naphthalene, BEHP, arsenic, lead and zinc. Since operations ceased, the plant facilities have been dismantled or demolished, and the site was being remediated for construction of a 60,408.9 m^2 (650,000 ft^2) shopping mall. Monsanto performed the cleanup at this site under the Massachusetts Contingency Plan. Brownfields are potentially contaminated industrial or commercial urban properties that have been abandoned or underutilized, but are suitable for redevelopment to help restore economic vitality to a community.

ART began preparations for soil treatment operations in May 1996 with a treatability study to determine the particle-size contamination and to provide data for design of the plant. The study showed that the fines fraction (<2 mm) contained BEHP, and the oversize fraction (>2 mm) contained PAPR. The process-flow diagram design included a trommel, feed hopper, wet screen, hydrocyclones, attritioning, secondary hydrocycloning, sand dewatering, fines thickening and consolidation, and sludge dewatering. Treatment of fines was achieved by bioremediation performed by another contractor.

ART mobilized its 13.6 tonne/hr (15 ton/hr) soil washing plant to the site and configured it in accordance with the optimized process-flow diagram. Soils consisting primarily of oversize and coarse material, with less than 20% silt and clay, including construction debris, demolition rubble and other fill, were excavated from several areas around the site and delivered to the plant for processing. The soil was field-screened to remove gross oversize material, producing a plant feed <2 in. The <2 in. material was fed into the plant and through the wet screening unit, producing a process oversize >2 mm, and a wet slurry <2 mm. The process oversize, containing PAPR, was staged outside the plant for further treatment. The wet slurry was fed to the hydrocyclone separation unit, producing a coarse sand fraction and a fines fraction. The coarse sand fraction was directed to a dewatering screen and, after testing, was returned to the site as clean backfill. The fines fraction was degraded in a bioslurry system operated by another contractor. The oversize material >2 in. contaminated with naphthalene concentrations higher than treatment targets was further treated by attritioning. Overall, a volume reduction of 93% was achieved for the project.

Case 16 — Soil Washing Pilot Study at the RMI Titanium Company Extrusion Plant Site

General Site Information

Name: RMI Titanium Company Extrusion Plant Site

Location: Ashtabula, Ohio

Owner:

RMI Titanium Company, Inc.
1000 Warren Avenue
Niles, OH 44446

Owner Contact:

James W. Henderson
RMI Environmental Services
P.O. Box 579
Ashtabula, OH 44005-0579

Remediation Contractor(s):

Alternative Remedial Technologies, Inc.
14497 North Dale Mabry Highway, Suite 240
Tampa, FL 33618
(813) 264-3506

Authority

RMI Decommissioning Project (RMIDP) sponsored by the DOE Office of Environmental Restoration (EM-40)

Requirement/Cleanup Goals

To determine the feasibility of using a physical separation/carbonate extraction process in a full-scale application at Ashtabula through conduct of a pilot study. The operational and performance criteria used to assess this pilot study included the following:

- the removal efficiency of the process as measured by the uranium activities in the feed soil versus the uranium concentrations in the treated soil,
- the ability to treat RMI soil to meet the 30pCi/g free release standard,
- the ability to achieve a significant volume reduction in the amount of soil requiring off-site disposal, and
- the ability to demonstrate a mass balance for uranium.

Results

The performance of the pilot testing validated earlier bench-scale findings, particularly with respect to the removal efficiencies and the performance of selected system components. Removal efficiencies of 84% to 90% were achieved, and the clean soil met the treatment standard of 30 pCi/g uranium. Table 5.16.1 demonstrates some of the results achieved.

Operation

Type

Pilot study

Period

January 7, 1997 to February 14, 1997

Table 5.16.1
Cleanup Results

Pile	Area	Uranium Activity of Feed by Alpha Spec (pCi/g)	Leaching Time (hr)	Treated Soil		Removal Efficiency	
				XRF (pCi/g)	Alpha Spec (pCi/g)	XRF (%)	Alpha Spec (%)
2	Run 1 Area D	129	1	8	12	94	91
3	Run 2 Area D	90	2	11	12	88	87
4	Run 1 Area C	133	1	10	13	92	90
5	Run 2	145	1	17	14	88	90
					Average	90	89

Waste Characteristics

Source

The primary management practice that contributed to contamination at the RMI site was the uranium manufacturing process. Particulate uranium was generated in the extrusion building during operation of uranium extruding and machining equipment. Hoods and fans were used to exhaust the fine uranium dusts and fumes outside the building. Particulate deposition from the exhaust system contaminated the surrounding soils with uranium.

Contaminants(s)

Uranium

Type of Media Treated

The contaminated media at this site are clay soils with a small sand fraction or non-native gravel that was used for plant service roads. The uranium at the RMI site is generally stratified within shallow topsoils with highest activities found in the top 6 in. of soil.

Quantity of Media Treated

58 tonne (64 ton)

Technology

Description

Physical Separation/Carbonate Extraction. The equipment used in this demonstration included a rotary batch reactor in which a heated carbonate solution is contacted with the feed soils, a liquid/soils separation unit to remove the soluble uranium, a dewatering system for the soils, and an ion-exchange system to allow removal of the uranium from the liquid. The pilot plant was installed in the existing Northwest Warehouse at the RMI Site. Existing electrical, water, and natural gas infrastructure were used. The plant required an area of approximately 30.5 m by 30.5 m (100 ft by 100 ft).

Significance

The pilot study provided data for a detailed cost-benefit assessment for production-scale operations. The cost/benefit assessment concluded that separation/chemical extraction will result in a significant cost savings over the baseline remedy of excavation, transportation, and disposal.

Overall, the results of the pilot testing verified the initial findings of the bench-scale testing. The expected optimum operating conditions identified in the bench studies were very near the determined conditions form the pilot study, which suggests that well-designed bench-scale studies can be used to identify full-scale operating conditions. The pilot operations did show that treatment of the soils at the site will have to be tailored to the type of deposition of the uranium contaminants. Therefore, the full-scale system will require processing flexibility to effectively treat all the soils at the site. The demonstration of XRF as an effective screening tool for residual uranium content in treated soils showed that a method exists to proved effective real-time process control for a full-scale soil treatment system.

Project Description

The RMI Extrusion Plant is located in Ashtabula Township, approximately one mile south of Lake Erie, in the northeast corner of the State of Ohio. The 28.5-acre property is privately owned by the RMI Titanium

Reference

1. U.S. Nuclear Regulatory Commission. 1981. *Disposal or On-site Storage of Thorium or Uranium Wastes from Past Operations.* Branch Technical Position. 46FR52601. October 23.
2. *Soil Washing Treatability Study Report of the RMI Extrusion Plant Site.* November 4, 1996.
3. *Soil Washing Pilot Project Report for the RMI Titanium Company Extrusion Plant Site.* 1997. Volumes I and II. Ashtabula, OH. April 22.

SOIL FLUSHING

6

APPLICATION CONCEPTS

In situ soil flushing is a process used to accelerate the movement of contaminants through unsaturated or saturated materials by solubilizing, emulsifying, or chemically modifying the contaminants. A treatment solution made up of water, enhanced water, or gaseous mixtures is applied to the soil and allowed to percolate downward and interact with contaminating chemicals (US EPA 1993). Contaminants are mobilized by the treatment solution and transported down to a saturated zone, or within the saturated zone, where they are captured in drains or wells and pumped to the surface for recovery, treatment, or disposal (Magee et al. 1991).

6.1 Soil Flushing Development

Virtually all in situ soil flushing relies on various applications of pump-and-treat technology. Pump-and-treat groundwater cleanup methods use natural groundwater flow through the aquifer to flush out the contaminants and capture them using one or more pumping wells. The contaminated groundwater is treated to destroy the contaminants or render them harmless. The treated water is then released to the environment or recirculated. In a recent American Chemical Society study, Shiau et al. (1995) suggest that "remediation of dense nonaqueous-phase liquid (DNAPLs) residual saturation (the residual saturation is defined as the degree of saturation of a soil sample at high capillary pressure) can require hundreds to thousands of pore volumes to achieve drinking-water-standards cleanup levels using conventional pump-and-treat methods." (A pore volume is the amount of mobile fluid that can be contained in the pores of the soil being flushed.) See Section 7.4 for details.

Technically, in situ processes are not limited to pump-and-treat technology. For example, the petroleum industry has devoted much effort to develop methods that enhance oil recovery from petroleum reservoirs containing a mixture of hydrocarbons and water. Oil in a petroleum reservoir is usually found floating on a water table at great depths. In the oil industry, an effort is made to pump above the oil-water contact line to prolong crude oil recovery and minimize dilution with water. The waste industry uses skimmer pumps to accomplish the same objective. After some time, pumping causes oil levels to drop in an oil reservoir and secondary recovery commences with water flooding. Water is separated from the oil-water mixture and the separated water is supplemented and, if necessary, reinjected. Advanced wellfield patterns are applied to drive the oil to collection. The reinjected water increases the pressure in the reservoir to renew the flow of water and oil to the collector wells. Surfactants, polymers, and chemical agents may be added to further enhance oil recovery.

Many waste sites are similar to petroleum reservoirs except for their depth. Virtually all waste sites have contaminants at depths less than 100 m (330 ft), while petroleum reservoirs are typically 1 km (3,300 ft) deep, or more. The petroleum remedial processes that are potentially applicable include:

- the injection of surfactants and/or thermal energy to efficiently mobilize contaminants from the soil pores;
- the injection of polymers; and
- the application of advanced wellfield pattern design and operation to increase the volume of contaminants swept from the aquifer.

Of these technologies, the application of advanced wellfield design and using surfactants are most promising. The U.S. Environmental Protection Agency (US EPA) noted that "surfactant-enhanced subsurface remediation was identified as a promising technology for expediting source-zone treatment" (Sabatini et al. 1995).

In the petroleum industry, the concentrations of chemical additives used are low because of the costs involved in oil recovery. The use of surfactant is a once-through process and it is common to inject as little as 10% of the pore volume with a 3% surfactant solution (an overall 0.3% solution of the volume of the oil reservoir). A ton of reservoir rock from an oil-bearing formation may contain 80 L (1/2 barrel) of recoverable oil at a selling price of $0.11/L ($17/barrel). The same amount of oil dispersed in an aquifer may require thousands of dollars to remove because, as noted by Pope and

Wade (1995), waste cleanup requires the injection of multiple pore volumes accompanied by recycling to recover as nearly as possible 100% of the organic contaminants. Clearly, the economics of aquifer cleanup are quite different from oil recovery.

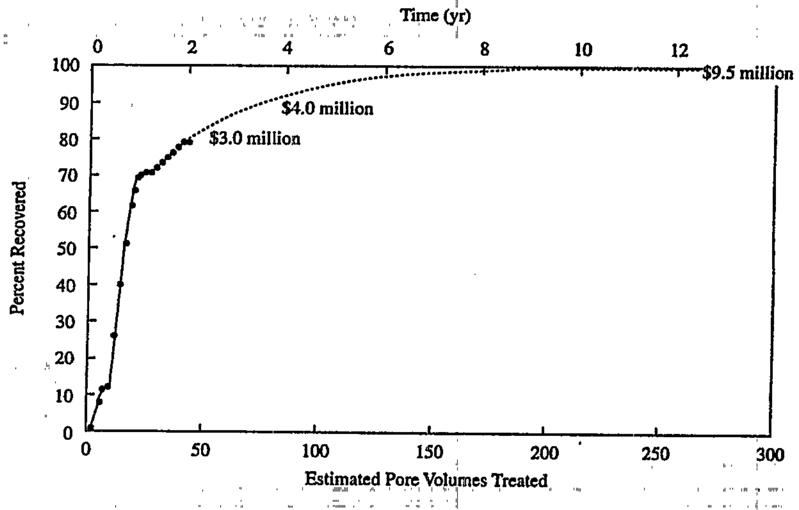
Surfactant treatment using continuous injection of a high-strength household surfactant solution (a dishwashing liquid) in concentrations greater than 0.3% can dramatically reduce the number of pore volumes required to clean an aquifer compared to standard pump-and-treat techniques. A recent study compared a surfactant enhanced flushing to water flushing for the removal of trichloroethylene (TCE)(McKee and Way 1994). With water alone, it was found that almost 50% of the TCE remained in the soil with no notable decline after 25 pore volumes of flushing. This occurred because a portion of the waste is held in the pores between the soil grains by capillary forces and dissolves slowly into the groundwater. With surfactant flushing, the TCE contaminant was dissolved at a much higher rate and flushed out to near zero concentration in fewer than four pore volumes. In practice, the surfactant concentration used will be somewhere between these two extremes, 0 and 3%, and foaming agents found in household products can be eliminated in site remediation applications.

In situ mining technologies for extracting uranium from deposits in aquifers developed on a large-scale in the 1970s have promise for groundwater cleanup. This technology uses oil-field well patterns with various chemical solutions. Circulation rates in the largest wellfields reached 40,000 L/min (10,000 gal/min), and extracted over a 450,000 kg (1 million lb) of uranium per year. These techniques have also been used to restore groundwater quality after in situ solution mining and have promise for in situ cleanup of radioactive waste sites.

The methods used in the petroleum and solution mining industries can be compared to the conventional pump-and-treat methods of soil remediation by graphically projecting the performance of each approach over time. In the examples which follow, a simple exponential model described by Zheng, Bennett, and Andrews (1992) generally reflects the performance of many of the processes used to extract materials from the ground.

Figure 6.1 illustrates the recovery rate achieved in a uranium solution mining project in Wyoming that operated for 1 2/3 years to extract 124,100 kg (273,700 lb) of uranium, about 77% of the reserves. The point at which solution mining of uranium is no longer economically feasible occurs at about 80% recovery and takes 35 to 40 pore volumes of treatment. In the Wyoming project, the exponential model closely fit the production data and can be used to forecast the time required for additional uranium extraction beyond economic recovery. Recovering 90% of the uranium would take 3.3 years of operation (about 70 pore volumes) and recovering 99.9% would take 12.7 years (about 274 pore volumes). As shown in Figure 6.1, the present-worth costs of the operation range from $3.0 million to $9.5 million.

Figure 6.1
Projection of Uranium Solution Mining Beyond the Economic Cutoff

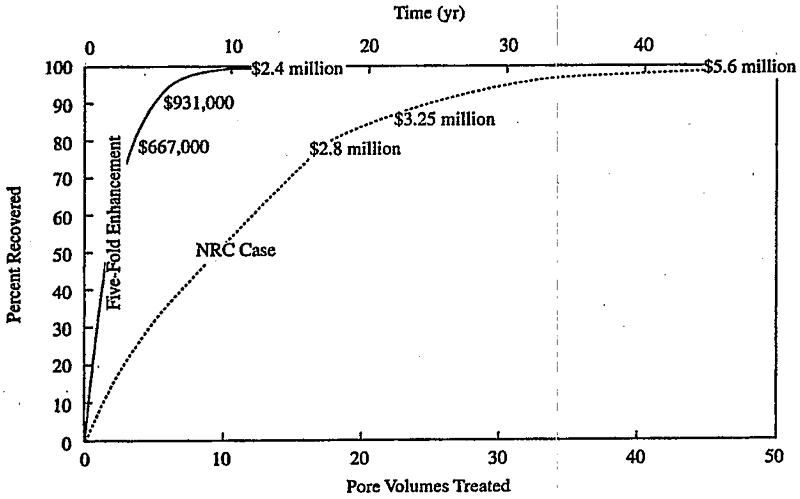


Uranium initially in place: 124,100 kg (273,700 lb)
Time to reach 99.9% recovery: 12.4 yr, 274 pore volumes
Remaining after 99.9% recovery: 6 ppm

Source: NRC 1994

The NRC presented a hypothetical case that illustrates soil remediation by pump-and-treat methods (NRC 1994). This conceptual example reflects the treatment of approximately 912 kg (2,011 lb) of DNAPLs in the water and on the soil. As shown in Figure 6.2, recovery of 80% to 99.9% of the material took from 15 to 63 years, at present-worth costs ranging from $2.8 million to $5.6 million.

Figure 6.2
Projection of Enhanced Performance with Improved Techniques Compared to Performance of Pump-and-Treat Methods



DNAPLs initially in place: 912 kg (2,011 lb)
Time to reach 99.9% recovery: No enhancement — 63 yr; Five-fold enhancement — 12.5 yr
Remaining after 99.9% recovery: 0.005 ppm

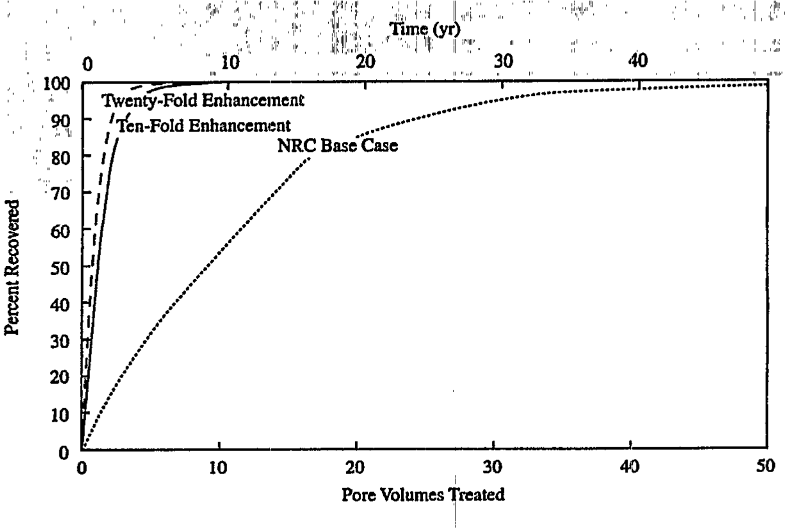
Source: NRC 1994

Application of solution mining or oil field experience, which includes optimizing wellfield patterns, might achieve a two-fold, five-fold, or greater increase in the rate of circulation in the ground which would, in turn, reduce the time required to recover material. Shortening the treatment time would substantially reduce the costs, particularly for recovery above 90%. The effect of a five-fold enhancement shown in Figure 6.2 is an illustration that does not account for the extra costs special treatment would require. The actual costs to achieve the enhanced performance would be more than those shown.

Treating the aquifer in the NRC example with an appropriate surfactant could greatly increase the solubilization of the DNAPLs. A five-fold increase in solubilization by surfactant addition would produce a corresponding five-fold decrease in the number of pore volumes needed to reach any specified level of recovery. Laboratory experiments suggest that surfactant addition could bring about a ten-fold or greater improvement in solubilization of many contaminants.

The combination of surfactant addition and increased circulation could potentially create a ten-fold to twenty-fold efficiency improvement in contaminant recovery as compared to conventional pump-and-treat technology.

Figure 6.3
Projection of Enhanced Pump-and-Treat Contaminant Recovery Performance with Improved Circulation and Surfactant Addition



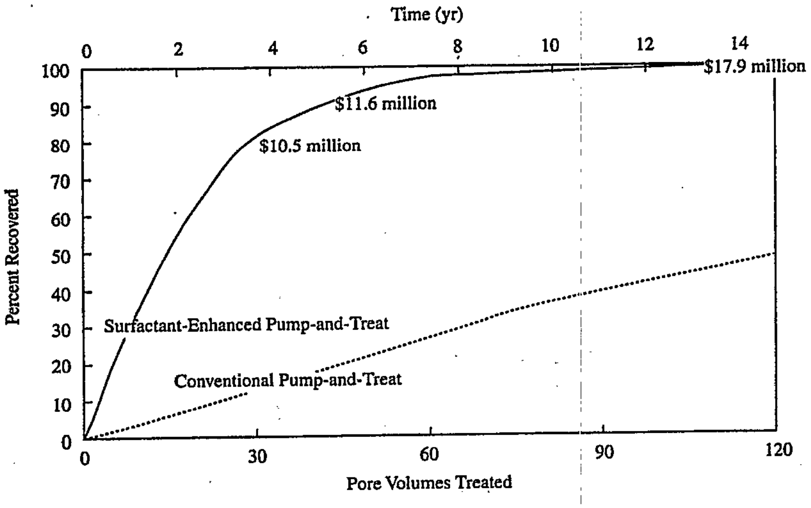
DNAPLs initially in place: 912 kg (2,011 lb)
Time to reach 99.9% recovery: No enhancement — 63 yr; Ten-fold enhancement — 6.3 yr; Twenty-fold enhancement — 3.2 yr
Remaining after 99.9% recovery: 0.005 ppm

Source: NRC 1994

Projection of contaminant recovery times with these soil flushing techniques is compared to the NRC example in Figure 6.3. Reducing the time necessary to reach 99.9% recovery from more than 40 years to less than 10 years would dramatically affect project costs.

Krebs-Yuill et al. (1995) discussed a situation involving large amounts of DNAPLs, a total of 7 million kg (15.4 million lb). With the use of surfactant, about 96% of the contaminants were recovered in 7 years. Figure 6.4 compares this surfactant-enhanced treatment using data derived from the exponential model with conventional pump-and-treat technology experience. The figure illustrates the benefit of using surfactants to remove such a large amount of DNAPLs.

Figure 6.4
Projected Performance of Surfactant-Enhanced Pump-and-Treat Methods Compared to Conventional Methods for Removal of a Large Amount of DNAPLs

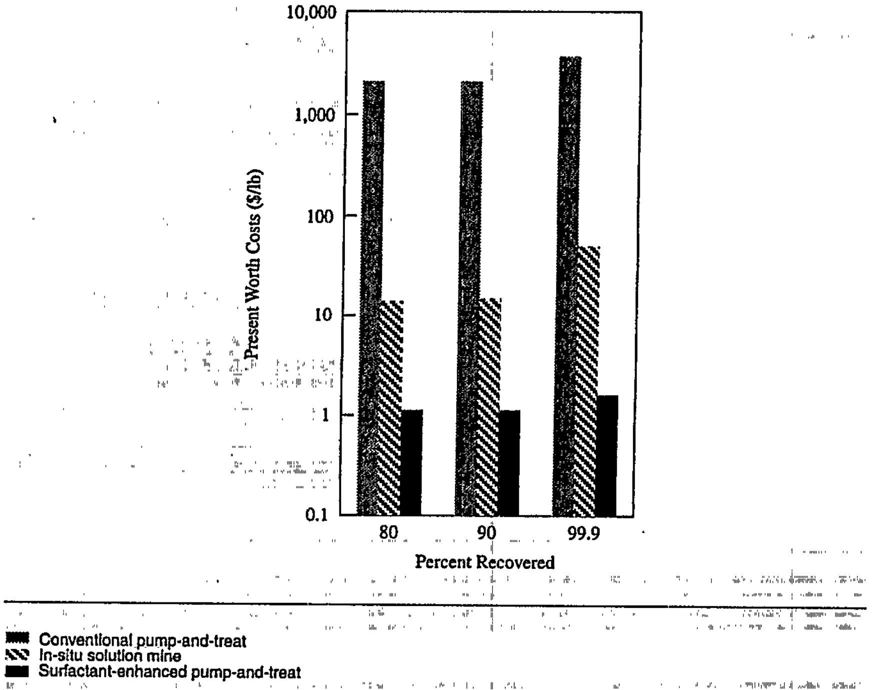


DNAPLs initially in place: 57 million kg (15.4 million lb)
Time to reach 99.9% recovery: 14.8 yr, 120 pore volumes
Remaining after 99.9% recovery: 190 ppm

Source: NRC 1994

Figure 6.5 provides a comparison of the cost effectiveness of conventional pump-and-treat methods and other processes that involve the use of chemicals and optimization of circulation.

Figure 6.5
Cost Comparison of Conventional Pump-and-Treat Methods to Other Available Technology

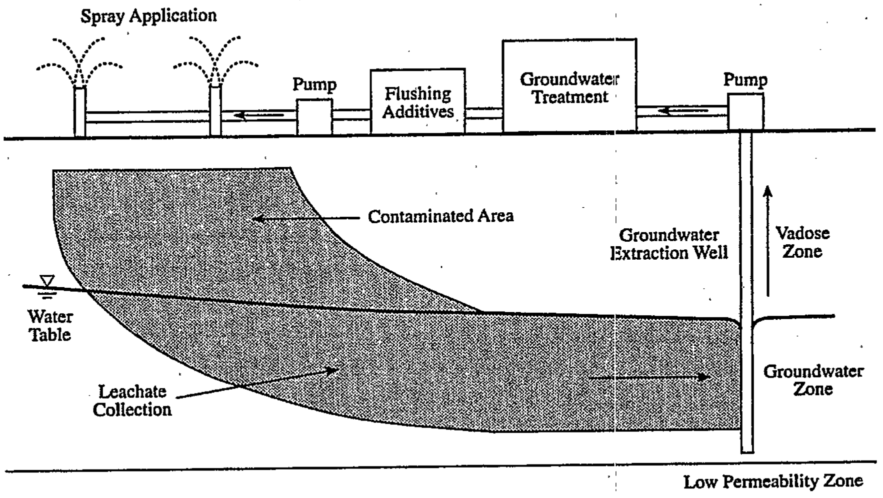


6.2 Scientific Principles

In situ soil flushing is generally used in conjunction with other treatment technologies, such as activated carbon, biodegradation, or chemical precipitation, which are used to treat contaminated groundwater that results from the soil flushing process. In some cases, the process can reduce contaminant concentrations in the soil to acceptable levels and may be the only soil treatment technology needed. In other cases, in situ biodegradation or other in situ technologies can be used in conjunction with soil flushing to achieve desired remediation objectives. In general, soil flushing is effective on coarse sand and gravel contaminated with a wide range of organic, inorganic, and reactive contaminants. Soils containing a large amount of clay and silt may not respond well to soil flushing, especially if it is applied as a stand-alone technology (US EPA 1991).

Figure 6.6 presents a general schematic of the soil flushing process (US EPA 1991). The flushing fluid is applied to the contaminated soil by subsurface injection wells, shallow infiltration galleries, surface flooding, or aboveground sprayers.

Figure 6.6
Schematic of Soil Flushing System



Soil flushing techniques used to mobilize contaminants are classified as conventional and unconventional (innovative). 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.

Innovative techniques consist of primary, secondary, and tertiary recovery techniques. Primary recovery encompasses, among other methods, neutral water drive and gravity drainage. Secondary recovery involves water flooding and pressure maintenance methods. Tertiary recovery employs gaseous and chemical processes and thermal methods.

The contaminants in the soil determine the type of flushing solution needed in the treatment process. Examples of three types of fluids are: (1) water only; (2) water plus additives such as acids (low pH), bases (high pH), or surfactants (e.g., detergents); and (3) organic solvents (US EPA 1992).

Water is used to treat contaminants that are water-soluble or water-mobile, such as inorganic salts of sulfates and chlorides. Acidic solutions are used to remove inorganic metal salts, such as carbonates or nickel, zinc, and copper, as typically found at sites engaged in battery recycling or industrial chrome plating. Basic solutions are used to treat phenols and certain metal species, such as zinc, tin, or lead. Surfactants can operate as detergents or as emulsifiers which can join substances that normally do not mix, such as oil and water. Surfactant solutions are effective at removing hydrophobic, immiscible organic contaminants, such as oil. Organic solvents are used to dissolve contaminants that water cannot. They are used to remove nonaqueous phase liquids (NAPLs).

The efficiency of soil flushing is related to two factors: (1) the increased hydraulic conductivity that accompanies an increase in water content of unsaturated soil and (2) the treatment solution selected based on the composition of the contaminants and the contaminated medium (Table 6.1). As shown in Figure 6.7, the hydraulic conductivity of soils decreases markedly with decreasing water content; therefore, the flow of liquids through unsaturated soils is extremely slow and the recovery of contaminants by conventional pumping techniques is not possible. With soil flushing, the water content and, consequently, the hydraulic conductivity of the soil is increased (Murdoch et al. 1990). However, heterogeneities in soil permeability may result in incomplete removal of contaminants.

The flushing fluid percolates through the contaminated soil removing contaminants as it proceeds. Contaminants are mobilized by solubilization into the flushing fluid, by the formation of emulsions, or through chemical reactions with the flushing fluid (Jin et al. 1994). Contaminated flushing fluid (or leachate) mixes with groundwater and is collected for treatment. Ditches open to the surface, subsurface collection drains, or groundwater recovery wells may be used to collect flushing fluids and mobilized contaminants. The flushing fluid delivery and the groundwater extraction systems are designed to optimize contaminant recovery. Proper design of the fluid recovery system is very important to a successful soil flushing program. In situ solution mining of uranium and copper is common and offers proven methods for circulating chemicals in the ground to remove target materials. The petroleum industry also has developed effective means to maximize fluid movement in soils.

Contaminated groundwater and flushing fluids, typically water or water with additives, are captured and pumped to the surface from the fluid recovery system. The rate of groundwater withdrawal is determined by the flushing fluid delivery rate, the natural infiltration rate, and the groundwater hydrology. These factors will determine the extent to which the *groundwater removal rate must exceed the flushing fluid delivery rate* to ensure recovery of all reagents and mobilized contaminants. The system must be designed so that hydraulic control of the remediation site is maintained.

The extracted groundwater and flushing fluid are treated using the appropriate wastewater treatment methods to reduce its heavy metal content, organics content, total suspended solids, and other parameters until it meets regulatory requirements. Metals may be removed by lime precipitation or by other technologies compatible with the flushing reagents used. Organics are removed with activated carbon, air stripping, or other appropriate technologies. Whenever possible, treated water should be recycled as makeup water to the front end of the soil flushing process.

Table 6.1
Soil Flushing Critical Factors and Conditions

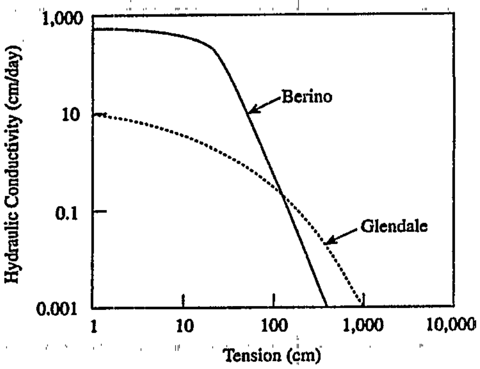
Factor Influencing Technology Selection	Conditions Favoring Selection of In Situ Treatment	Basis	Data Needs
Equilibrium Partitioning of Contaminant Between Soil and Extraction Fluid*	No action levels specified	• Contaminant preference to partition to the extractant is desirable • High partitioning of contaminant into the extortion fluid decreases fluid volumes	• Equilibrium partitioning coefficient
Complex Waste Mixture*	No action levels specified	• Complex mixtures increase difficulty in formulation of a suitable extraction fluid	• Contaminant composition
Soil-Specific Surface Area*	< 0.1 m^2/g	• High surface area increases sorption on soil	• Specific surface area of soil
Contaminant Solubility in Water*	> 1,000 mg/L	• Soluble compounds can be removed by water flushing	• Contaminant solubility
Octanol/Water Partitioning Coefficient*	Between 10 and 1,000	• Very soluble compounds tend to be removed by natural processes • More hydrophilic compounds are amenable to removal by water-based flushing fluids	• Octanol/water partitioning coefficient
Spatial Variation in Waste Composition*	No action levels specified	• Changes in waste composition may require reformulation of extraction fluid	• Statistical sampling of contaminated volume
Hydraulic Conductivity*	$> 10^{-3}$ cm/sec	• Good conductivity allows efficient delivery of flushing fluid	• Hydrogeologic flow regime

Clay Content*	No action levels specified	- Low clay content is desirable - Presence of clay increases sorption and inhibits contaminant removal	- Soil composition - Soil color - Soil texture
Cation Exchange Capacity*	No action levels specified	- Low cation exchange capacity is desirable - Cation exchange capacity increases sorption and inhibits contaminant removal	- Cation exchange capacity
Flushing Fluid Characteristics*	- Fluid should have low toxicity, low cost, and allow for treatment and reuse - Fluid should not plug or have other adverse effects on the soil	- Toxicity increases health risks and increases regulatory compliance costs - Expensive or non-reusable fluid increases costs - If the fluid adheres to the soil or causes precipitate formation, conductivity may drop, making continued treatment difficult	- Fluid characterization - Bench- and pilot-scale testing
Soil Total Organic Carbon Content	< 1% (by weight)	- Soil flushing typically is more effective with lower soil organic concentrations	- Total organic carbon content of soil
Contaminant Vapor Pressure	< 10 mm Hg	- Volatile compounds tend to partition to the vapor phase	- Contaminant vapor pressure at operating temperature
Fluid Viscosity	< 2 centipoise (cP)	- Lower-viscosity fluids flow through the soil more easily	- Fluid viscosity at operating temperature
Organic Contaminant Density	> 2 g/cm^3	- Dense insoluble organic fluids can be displaced and collected by soil flushing	- Contaminant density at operating temperature

*Indicates higher-priority factors

Source: US EPA 1993

Figure 6.7
Hydraulic Conductivity vs. Tension for
Berino Loamy Fine Sand and Glendale Clay Loam



6.3 Potential Applications

A number of chemical contaminants can be removed from soils using soil flushing (Table 6.2). Soluble (hydrophilic) organic contaminants are often easily removed from soil by flushing with water alone. Typically, organics with octanol/water partition coefficients (K_{ow}) less than 10 (log $K_{ow}<1$) are highly soluble. Examples of such compounds include lower molecular weight alcohols, phenols, and carboxylic acids.

Low-solubility (hydrophobic) organics may be removed from soils using a compatible surfactant. Examples of such organic compounds include chlorinated pesticides, polychlorinated biphenyls (PCBs), semivolatiles (chlorinated benzenes and polynuclear aromatic hydrocarbons), petroleum products (gasoline, jet fuel, kerosene, oils, and greases), chlorinated solvents (trichloroethene), and aromatic solvents (benzene, toluene, xylenes, and ethylbenzene).

Metals may require acids, chelating agents, or reducing agents for successful soil flushing. In some cases, all three types of chemicals may be used in sequence to improve the removal efficiency of metals. Many

Table 6.2
Applications of Soil Flushing on General Contaminant Groups

Contaminant Groups	Effectiveness
Organic	
Halogenated Volatiles	■
Halogenated Semivolatiles	▲
Nonhalogenated Volatiles	▲
Nonhalogenated Semivolatiles	■
PCBs	▲
Pesticides (halogenated)	▲
Dioxins/Furans	▲
Organic Cyanides	▲
Organic Corrosives	▲
Inorganic	
Volatile Metals	▲
Nonvolatile Metals	■
Asbestos	●
Radioactive Materials	▲
Inorganic Corrosives	▲
Inorganic Cyanides	▲
Reactive	
Oxidizers	▲
Reducers	▲

■ Demonstrated Effectiveness: Successful treatability test at some scale completed.
▲ Potential Effectiveness: Expert opinion that technology will work.
● No Expected Effectiveness: Expert opinion that technology will not work.

Source: US EPA 1993

inorganic metal salts, such as carbonates of nickel, zinc, and copper can be flushed from the soil with dilute acid solutions. Some inorganic salts, such as sulfates and chlorides, can be flushed with water alone.

In situ soil flushing has been used for treating soils contaminated with hazardous wastes, including pentachlorophenol and creosote from wood-preserving operations, organic solvents, cyanides and heavy metals from electroplating residues, heavy metals from some paint sludges, organic chemical production residues, pesticides and pesticide production residues, and petroleum/oil residues.

Table 6.3 lists some Superfund sites where in situ soil flushing has been selected as a treatment method. The table lists current sites, their location, the types of contaminants requiring treatment, and the status of each project.

6.4 Limitations

Studies of the effectiveness of pump-and-treat technology in groundwater restoration have been conducted by Keeley in 1989, Haley in 1991 and Palmer in 1992, and discussed in Sabatini et al. (1995). These studies indicate that pump-and-treat technology can intercept and contain waste plumes, but is incapable of cleaning up the waste with high adsorbing characteristics in a reasonable amount of time. The uncertainty about cleanup time is a major concern because it greatly affects the cost of remediation.

In 1994, the NRC reviewed the status of groundwater cleanup and identified several limitations that largely pertain to current industry pump-and-treat experience (MacDonald and Kavanaugh 1994) which are also relevent to soil flushing. These and other limitations are discussed in this section.

6.4.1 Physical Heterogeneity

The earth's subsurface is highly heterogeneous. Groundwater is stored in aquifers consisting of layers of sand, gravel, and rock, each having vastly different properties. Because of this geologic variability, determining the pathways by which contaminants spread is very difficult, complicating the design of cleanup systems.

Table 6.3
Soil Flushing Applications at Superfund Sites

Site	Location	Primary Contaminants	Status
Byron Barrel & Drum	Genesee County, NY	VOCs (BTX, PCE, and TCE)	Pre-design: Evaluating alternatives
Hooker Chemical/Ruco Polymer, Site OU1	Hicksville, NY	VOCs (PCE and TCE), Glycols	Pre-design
Peak Oil/Bay Drum	Tampa, FL	VOCs (PCE), BTEX, Metals (Chromium, Lead, Zinc)	Pre-design: In negotiation
Pester Refinery Company	El Dorado, KS	PAHs	Pre-design
South Calvacale Street	Houston, TX	PAHs	Pre-design: Considering bioremediation alternatives
Ormet Corporation	Hannibal, OH	Organic Cyanide	Design
Vineland Chemical	Vineland, NJ	Arsenic and VOCs (Dichloromethane)	Design: Project on-hold
Montana Pole and Treating Plant	Butte, MT	VOCs and SVOCs	Being Installed
Jadco-Hughes	North Carolina	Solvents	Installed
Lee Chemical	Liberty, MO	VOCs (TCE)	Operational: May 1994
Lipari Landfill	Pitman, NJ	VOCs, Metals (Chromium, Lead, Nickel, Mercury) Phenol	Operational
Rasmussen's Dump	Glen Oak Township, MI	Benzene and Vinyl Chloride	Operational
Umatilla Army Depot (Lagoons)	Hermistan, OR	Explosives (RDX and TNB)	Operational
United Chrome Products	Corvallis, OR	Chromium	Operational: August 1982
U.S. Naval Submarine Base	Bangor, WA	Explosives (RDX and TNT)	Operational: June 1995
Ninth Avenue Dump	Gary, IN	VOCs (BTEX, TCE), PAHs, Phenols, Lead, PCBs, and Total Metals	Completed: Operational, February 1992 to March 1994

Source: US EPA 1996

Solutions to some heterogeneity problems have been developed in the petroleum and in situ solution mining industries. The uranium in situ solution mining industry applied technology from the petroleum industry and hydrologic disciplines, adapting it to site-specific conditions associated with beach sands, barrier-bar marine sands, braided stream channels with clay, ancient river deltas, and fault zones. In-fill drilling, for example, has been used as a means of gaining access to oil in heterogeneous zones that are not well connected. Monitoring water levels in the wellfield to balance flow rates and optimize sweep efficiency is another method to handle heterogeneities.

6.4.2 Nonaqueous-Phase Liquids (NAPLs)

NAPLs are common groundwater contaminants that, like oil, do not dissolve readily in water. Light nonaqueous-phase liquids (LNAPLs), such as gasoline are less dense than water, whereas dense nonaqueous-phase liquids (DNAPLs), such as the common contaminant solvent trichloroethylene (TCE), are more dense than water. As an NAPL moves underground, it leaves small immobile globules trapped in the porous materials of the subsurface. These globules cannot be easily removed with conventional groundwater cleanup systems. Nevertheless, even with their low solubility contaminants continued to mobilize into the groundwater system.

In the petroleum industry, tertiary recovery methods use surfactants, polymers, and chemicals to mobilize NAPLs. One of these techniques, namely a surfactant flush, shows great promise for DNAPL flushing in waste cleanup. TCE, for example, has a solubility in water of 1.0 g/L (1,000 mg/L). Tetrachloroethylene's (PCE's) solubility is even lower at 0.08 g/L (80 mg/L).

Shiau et al. (1995) discussed solubilities of PCE increasing by 200 fold over water solubilities, using food-grade surfactants. They also reported microemulsification mobilization solubilities over 7,000 times higher than water solubilities for PCE. A core flush removed greater than 99% of the PCE in three flushes, rather than thousands for a water flush pump-and-treat system.

Similar laboratory test results using food-grade surfactants on PCE show microemulsion solubilization ranging from 80 g/L (80,000 mg/L) to 900 g/L (900,000 mg/L) and higher solubilities with optimization (Pope and Wade 1995). A column experiment conducted by Pope and Wade showed PCE mobilized with almost 100% of it displaced by only two pore volumes. Fountain et al. (1995) report field-test results in Corpus Christi, Texas, where carbon tetrachloride concentrations dropped from 1,000 mg/L to 10 mg/L after only three pore volumes. Other field trials of interest are being headed by Sabatini at the University of Oklahoma, and Fountain through the State University of New York (Fountain et al. 1995).

6.4.3 Diffusion of Contaminants into Inaccessible Regions

Contaminants may diffuse into very small pore spaces in the geologic formations of the aquifer. These small pores are difficult to flush with conventional groundwater cleanup systems. At the same time, contaminants in the pores can serve as long-term sources of pollution as they slowly diffuse from the pores when contaminant concentration in the groundwater decreases.

Potassium chloride has been used in the uranium industries to shrink the most troublesome smectite clays. Polyelectrolytes have also been used in the uranium industry to prevent clay migration and pore plugging and to maintain accessibility to the well bore (Stover and McKee 1995).

Surfactants are another possible means of gaining access to regions of lower permeability. Fountain et al. (1995) expressed concern that surface tension reduction of 100- to 10,000-fold "may allow DNAPLs to penetrate fine-grained layers that previously acted as barriers." The potential for surfactants to penetrate low-permeability areas requires site-specific laboratory and field studies before implementing this method.

Hydraulic fracturing has also been to improve accessibility in the oil and in situ uranium wellfields, and most recently, in waste cleanup (Stover and McKee 1995). In the extreme, explosives have also been used to improve accessibility in fractured media (Nichols 1992; Dorrier and Green 1993). Over-reaming of wells was used in the uranium industry to improve access of the formation to the well bore.

6.4.4 Sorption

Many common contaminants adhere to solid materials in the subsurface by chemical attraction or reactions. If a contaminant sorbs strongly to the aquifer solids, it is difficult to flush out.

Sorption depends upon the composition of the solid and the liquid. Changing the composition of the liquid by chemical additives can alter the sorption properties of the solid. For example, during the restoration of an in situ mine that employed ammonium carbonate to extract uranium, the desorption of ammonia from montmorillonite clay was enhanced by the addition of potassium to the flushing liquid. Sodium carbonate-bicarbonate uranium mining systems initially experienced difficulty in controlling the pH that resulted in large amounts of calcium carbonate being mobilized and precipitated. However, the industry learned how to effectively stabilize the pH and stop the calcium precipitation. By operating the sodium carbonate-bicarbonate system at the groundwater's natural pH and making a few changes to the natural groundwater chemistry, the post-mining groundwater restoration process became more predictable. Additional study is needed to identify other flushing agents that can preferentially replace contaminants on materials, especially to flush out low residual contamination.

6.4.5 Site Characterization

The subsurface of any contaminated site cannot be viewed in its entirety; observation is possible only through a finite number of drilled holes. It is difficult to design an effective cleanup system without knowing the site's subsurface characteristics (MacDonald and Kavanaugh 1994). This limitation affects all site remediation technologies.

Flow logging, incorporating conventional spinner tools based on thermal principles, enables subsurface characterization in highly heterogeneous environments by examining permeability through the subsurface region's flow profiles. McKee et al. (1981) noted that, "as flow rate declines uniformly it implies that permeability is approximately the same throughout the entire thickness of the aquifer. On the other hand, a sharp decline in flow indicates larger fluid acceptance of the adjacent zone and, therefore, higher permeability." With the availability of advanced instruments and technology, three-dimensional characterization of the formation can be evaluated (Way and McKee 1984).

6.4.6 Chemical Loss

Fluids containing the large amount of cosolvent required for NAPL mobilization have densities and viscosities that differ substantially from those of water, complicating prediction of transport behavior. Further, the movement of contaminants mobilized by the cosolvent movement generally requires pumping a larger volume of groundwater that the soil flushing system injects; this excess volume of extracted water must be treated and discharged elsewhere (NRC 1994). This limitation is of particular concern to regulators. Effective site characterization and properly designed hydraulic controls or other containment mechanisms are essential to prevent flushing from spreading, rather than capturing the contaminant(s).

6.4.7 Innovative Technologies

As the NRC (1994) noted, "a variety of barriers have discouraged those involved in groundwater cleanup from assuming the risks associated with using innovative technologies that lack proven track records." The most significant barriers include the following:

- allocation of liability if a technology fails;
- inability to raise sufficient capital for successful commercialization;
- lack of vendors for some innovations;
- federal regulations specifying that any contractor involved in the selection or testing of a technology is ineligible for construction;
- lack of testing facilities;
- lack of cost and efficiency information;
- lack of adequate technical expertise among consultants and regulators; and
- the requirement to construct a pump-and-treat system if the innovative technology fails to achieve cleanup goals.

While the US EPA, DOE, U.S. Department of Defense (DoD), and others are implementing programs to remove these barriers, the cumulative effectiveness of these efforts is unknown.

6.5 Treatment Trains

Treatment trains used in soil flushing are intended to make the target contaminants less toxic. In areas of high contaminant concentrations and deep vadose zones with no recharge, there may be value in diluting the contamination over a vertical profile to reduce surface impact or to allow intrinsic remediation to take place. In some cases, biological processes may be used as a polishing step to remove contaminants whose toxic effects have been reduced by the flushing action. When biological processes are used either during or after soil flushing, the effect of the flushing solution on the bacteria must be understood.

Bioremediation involves the delivery of required nutrients, co-oxidation substrates, electron acceptors, or other necessary enhancers of microbial growth. Various delivery techniques are used to add the required materials to the subsurface environment to enhance in situ bioremediation. Application methods consist of both surface and subsurface spreading.

Surface application methods include flooding, ponding, and the use of ditches or sprinkler systems. These methods are generally suitable for contamination at depths less than 4.6 m (15 ft). Flooding may be used at sites that are flat or gently sloped (i.e., less than 3% slope), have a uniform contour without gullies or ridges, and contain soils with high hydraulic conductivites (i.e., $>10^{-3}$ cm/sec, such as those found in sands, loamy sands, and sandy loams). Ponding can be used in sandy or loamy soils and in flat areas to increase the infiltration rate of the applied solution as compared to flooding. The depth of the solution in the pond drives the increase in infiltration rates. The ditch method of surface spreading uses flat-bottomed, shallow, narrow ditches to transport the solution over the land surface. The solution infiltrates the soil through the bottom and side surfaces of the ditch. Ditches are used at sites where it is best not to completely cover an entire area with the solution. Sprinkler systems can be used to deliver solutions uniformly and directly to the ground surface. These systems are less susceptible to topographical constraints than flooding and ponding. Sprinkler systems have been used successfully to deliver nutrients and moisture to bioventing systems where the site was contaminated to a depth of 15.3 m (50 ft).

Subsurface gravity delivery systems include infiltration galleries (or trenches) and infiltration beds. These systems are applicable at sites where there is deep contamination or where the surface layers have low permeability. Subsurface systems consist of excavations filled with a porous medium (e.g., coarse sands or gravels) that distribute solutions to the contaminated area. An infiltration gallery consists of a pit or pores through which the solution is distributed to the surrounding soils in both the vertical and horizontal directions.

Forced systems are another subsurface delivery system. They deliver fluids under pressure into a contaminated area through open-end or slotted vertical or horizontal pipes placed to deliver the solution to the zone requiring treatment (Amdurer et al. 1986). These systems are generally applicable to soils with hydraulic conductivities $>10^{-4}$ cm/sec (i.e., the fine sandy or coarse silty materials) and high effective porosities (i.e., ranging from 25 to 55%). A maximum injection pressure must be established to prevent hydraulic fracturing and uplift in the subsurface which would cause the fluid to travel upward rather than through the contaminated area. Unlike gravity systems, a forced-delivery system is theoretically independent of surface topography. Design considerations for gravity and forced delivery systems are presented in Amdurer et al. (1986). Innovative injection and extraction systems (as shown in Figures 6.8 and 6.9) have been developed by Horizontal Technologies, Inc., of Cape Coral, Florida.

For additional information on Bioremediation refer to Ward (1995) and Dupont (1998).

Figure 6.8
Horizontal Wells Used in Soil Flushing

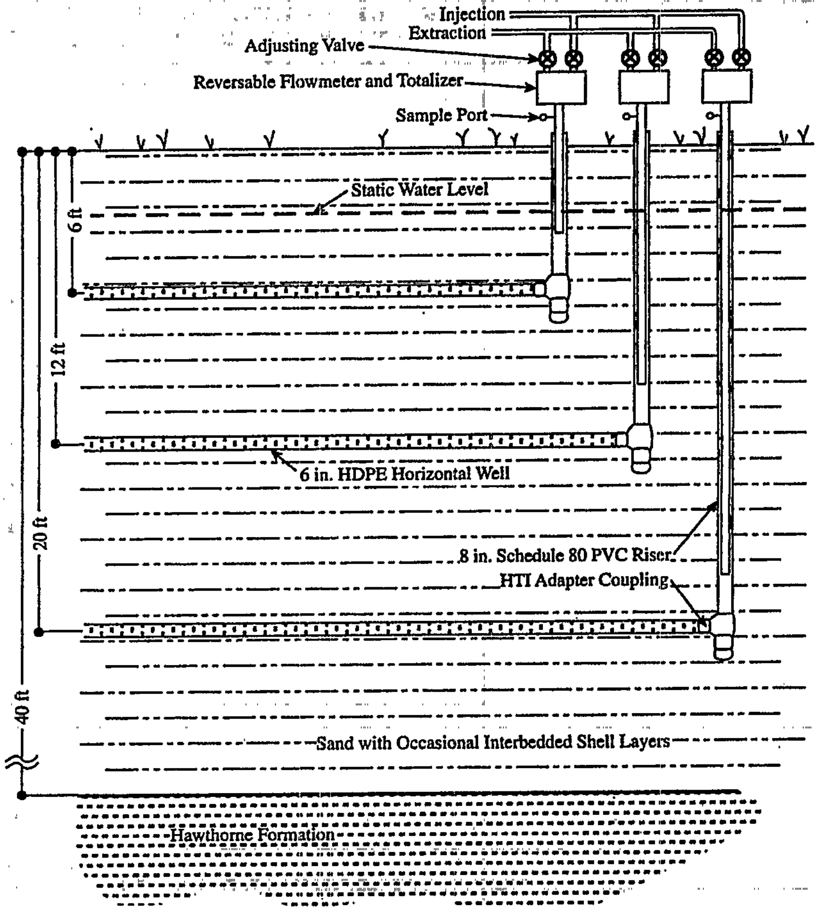


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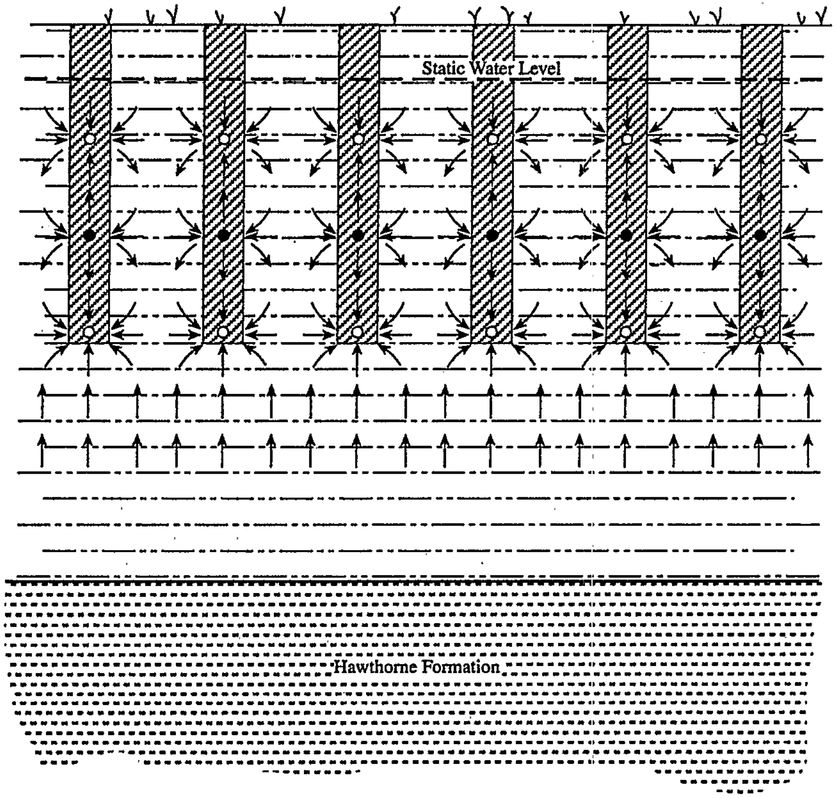
Figure 6.9
Extraction and Injection Horizontal Soil Flushing Wells



○ Horizontal well valved for extraction
● Horizontal well valved for injection
← Flowpath

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7

DESIGN DEVELOPMENT

7.1 Remediation Goals

The goal of remediation is to protect public health and the environment. While achieving drinking water standards is typically the primary goal, the true remediation goal should be determined based on health risk, technology feasibility, time, cost, government regulations, and site conditions to account for the variety of dynamics influencing any contaminated site.

The primary federal laws that govern groundwater cleanup are the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the Clean Water Act, and the Safe Drinking Water Act. Most commonly, groundwater remediation goals under RCRA and CERCLA are set at the levels of drinking water standards. However, the remediation goal for any given site may depend on the state in which the site is located and whether it is a RCRA or CERCLA site.

In addition to the water quality standards defined in various water-usage categories, the US EPA has established maximum contaminant-level goals (MCLGs) and maximum contaminant levels (MCLs) for drinking water supplied by public water agencies. The drinking water standards promulgated by the US EPA can be found in many publications, such as Contaminant Hydrology (Fetter 1993) and Alternatives for Ground Water Cleanup (NRC 1994). An MCLG is a non-enforceable goal set to prevent known or anticipated adverse health effects within a wide margin of safety. MCLs, however, are enforceable standards that take into account water treatment technologies and costs and are set as close as feasible to the MCLGs. US EPA also recognizes that attaining drinking water standards is not always possible at certain sites because of the technical limitations; thus, the agency may allow the original goals of drinking water standards to be waived. However, as of 1994, drinking water standards were the criteria at 270 out of 300 Superfund sites (NRC 1994).

There are several feasible alternatives to using drinking water standards as remediation goals. These include:

- *Remediation to Background/Detection Limit.* This alternative uses background concentration levels or analytical detection limits as the groundwater remediation goal.
- *Remediation to Water-Use Category.* This alternative returns the groundwater quality to its original usage category before the occurrence of groundwater (i.e., domestic water, water for fish and aquatic life, water for agriculture, water for livestock, or water for industry) as the remediation goal.
- *Remediation to Health-Based Levels.* This alternative employs predetermined water quality standards and disregards site-specific conditions.
- *Remediation to Technology-Based Standards.* This alternative is based on the capability of best available technology to destroy or recover contaminants.
- *Remediation to Standards Based on Acceptable Levels of Risk.* This alternative bases the remediation goal on a pre-determined acceptable risk of the contaminant left in place following remediation. The National Contingency Plan specifies an acceptable range of risk as one chance in 10,000 to one in 1 million (NRC 1994). To date, application of risk levels to establishing cleanup standards has yet to occur.

Remediation goals must also consider the two major factors that affect remediation success — the hydrogeology of the site and the contaminant chemistry. Table 7.1 examines the relative ease of cleaning up contaminated groundwater as a function of these two conditions. Sites rated "1" are the easiest to remediate and those rated "4" are the most difficult. The table shows that groundwater cleanup is likely to be extremely complex at the majority of sites (MacDonald and Kavanaugh 1994).

Regulatory agencies often mandate a particular set of remediation requirements as waste site cleanup goals. These requirements take into account specific site conditions and the site's specific contaminants. Table 7.2 shows MCLGs, MCLs, and remediation goals for selected remediation projects. State summaries of soil standards (Judge, Kostecki and Calabrese 1997) provides a summary of the cleanup standards for hydrocarbon contaminated soil in various states.

Table 7.1
Relative Ease of Cleaning Up Contaminated Groundwater

	Contaminant Chemistry					
Hydrogeology	Mobile, Dissolved (Degrades/ Volatilizes)	Mobile, Dissolved	Strongly Sorbed, Dissolved (Degrades/Volatilizes)	Strongly Sorbed, Dissolved	Separate Phase LNAPL[a]	Separate Phase DNAPL[b]
Homogeneous, Single Layer	1	1-2	2	2-3	2-3	3
Homogeneous, Multiple Layers	1	1-2	2	2-3	2-3	3
Heterogeneous, Single Layer	2	2	3	3	3	4
Heterogeneous, Multiple Layers	2	2	3	3	3	4
Fractured	3	3	3	3	4	4

The difficulty of cleanup is influenced by the hydrogeologic conditions and contaminant chemistry at a site. The NRC report classified the relative ease of cleanup as a function of these two conditions on a scale of 1 to 4, where 1 is the easiest and 4 the most difficult.

The 1-4 scale used in this table should not be viewed as objective and fixed, but as a subjective, flexible method for evaluating sites. Other factors that influence ease of cleanup, such as the total contaminant mass at a site and the length of time since it was released, are not shown in this table.

[a] Light nonaqueous-phase liquid
[b] Dense nonaqueous-phase liquid

Reprinted with permission from MacDonald and Kavanaugh, "Sustainable World Trade: Who Will Pay to Clean Up Britain's Past?," *Environmental Science & Technology*, Volume 28, Number 8, p 365A. Copyright 1994 American Chemical Society.

Table 7.2
Remediation Case Studies

Site Name, State	Contaminants	MCLG (g/L)[a]	MCL (g/L)[a]	Remediation Goal (g/L)
Savannah River Site, SC[b]	TCE	0	5	5
	PCE	0	5	5
	TCA	200	200	200
McClellan Air Force Base, CA[c]	TCE	0	5	0.55
	Cis-1,2-DCE	70	70	Not Applicable
	PCE	0	5	0.55
	TCA	0	5	0.55
	1,2-DCA	0	5	0.55
Langley Air Force Base, VA[d]	Benzene	0	5	1.4
	Toluene	1,000	1,000	2
	Ethelbenzene	700	700	1
	Xylene	10,000	10,000	3
Lawrence Livermore National Laboratory, CA[d]	Benzene	1	5	1
	Ethelbenzene	700	700	680
	Xylene	10,000	10,000	1,750
Twin Cities Army Ammunition Plant, MN[d]	TCE	0	5	5
	PCE	0	5	6.9
	1,2-DCE	70	70	70
	1,1,1-TCA	200	200	200
Verona Wellfield Superfund Site, MI[d]	Vinyl chloride	0	2	1
	1,1,2-Trichloroethane	3	5	1
	PCE	0	5	1
	Benzene	0	5	1
	Toluene	1,000	1,000	800

[a] Source: Fetter 1993
[b] Source: U.S. Department of Energy 1994
[c] Source: U.S. Air Force 1994
[d] Source: U.S. Environmental Protection Agency 1995

7.2 Design Basis

Soil flushing techniques for mobilizing contaminants are considered either conventional or innovative. Conventional soil flushing includes the following activities:

- natural restoration,
- well-and-capture methods in the vadose zone,
- pump-and-treat systems in the saturated zone, and
- a combination of pump-and-treat and vadose zone soil flushing.

Innovative soil flushing enhanced recovery includes:

- secondary recovery, and
- tertiary recovery.

Enhanced recovery methods draw upon the experience of the petroleum and mining industries for secondary and tertiary recovery techniques to remove greater than 90% of the contaminants. Secondary recovery methods include water flooding and pressure maintenance techniques. Tertiary recovery methods inject materials, such as surfactants, to desorb and/or dissolve contaminants bound within the soil matrix.

The recovery goal for petroleum and mining operations using enhanced recovery methods is different than that for remediation processes. In petroleum and mining operations, 90% recovery may be considered as sufficient; while in remediation processes, 99.9% recovery may be needed to satisy environmental concerns.

Table 7.3 presents a summary of screening criteria for enhanced recovery methods based on oil properties and reservoir characteristics. Table 7.4 provides a comparative summary of seven enhanced recovery processes used in the petroleum industry.

7.2.1 Site Characterization

One of the most basic needs of a groundwater remediation program is an understanding of the site's hydrogeology. This will help determine the water quality and water quantity characteristics of the formation, the degree of vulnerability of the formation to contamination at different locations, and the potential remediation technologies.

The characteristics of the vadose zone play a significant role in the potential for aquifer contamination. Aquifers overlain by permeable sand are highly vulnerable to surface contamination. Clay, on the other hand, is rather impermeable and retards contaminant movement.

Understanding the geology, hydrology, and geochemistry of the contaminated formation is the first major step in obtaining the required information for remediation design. Knowledge of the characteristics and boundaries of the aquifers themselves provides important information on the potential contaminant movement and transport. The flow of groundwater and transport of contaminants are functions of hydraulic gradient, hydraulic conductivity, effective porosity, and dispersivity which are dictated by the site's geology and hydrology. Table 7.5 identifies some of the principal types of information that must be gathered for site characterization.

Site characterization begins with understanding the geohydrology of the region. Geologic cross-sections prepared from well coring and geophysical logging information provide an excellent visual presentation of the general geology and delineation of the target area. Geologic maps, along with water level information, also furnish information on the recharge and discharge areas, and the regional groundwater flow. Well logs, water quality data, and well completion records may be available through federal and state agency databases. Careful review of these records can yield a general picture of past hydrologic activities in the site area.

A number of test wells should be drilled, cored, logged, and sampled at strategic locations to accurately delineate the area of contamination. Geophysical surveying may be useful in the study of some subsurface inorganic contamination distributions, especially where there is a good contrast between background and anomaly. Two of the most commonly-used geophysical survey techniques are resistivity and electromagnetic conductivity.

Hydrologic tests are performed to calculate the values of hydrologic parameters. The first hydrologic test to be performed is the slug test. By rapidly injecting a constant volume of water into the well and monitoring the recovery of the water level, the transmissivity of the formation can be calculated within reasonable limits. A constant rate single-well pump test can be performed to obtain values of transmissivity, hydraulic conductivity and well efficiency.

Table 7.3
Screening Criteria for Enhanced Recovery Methods

	OIL PROPERTIES				RESERVOIR CHARACTERISTICS					
	Gravity API	Viscosity (cp)	Composition	Oil Saturation	Formation Type	Net Thickness	Average Permeability	Depth (m)	Depth (ft)	Temperature
GAS INJECTION METHODS										
Hydrocarbon	> 35	< 10	High % of C_2-C_7	> 30% PV	Sandstone or Carbonate	Thin unless dipping	NC	600 (LPG) to 1,500 (H.P. Gas)	2,000 (LPG) to 5,000 (H.P. Gas)	NC
Nitrogen & Flue Gas	> 24 > 35 for N_2	< 10	High % of C_2-C_7	> 30% PV	Sandstone or Carbonate	Thin unless dipping	NC	> 1,400	> 4,500	NC
Carbon Dioxide	> 26	< 15	High % of C_5-C_{12}	> 30% PV	Sandstone or Carbonate	Thin unless dipping	NC	> 600	> 2,000	NC
CHEMICAL FLOODING										
Surfactant/ Polymer	> 25	< 30	Lighter intermediates desired	> 30% PV	Sandstone preferred	> 3 m (> 10 m)	> 0.2 m/sec (> 20 md)	< 2,400	< 8,000	< 80°C (< 175°F)
Polymer	> 25	< 150	NC	> 10% PV Mobile oil	Sandstone preferred; Carbonate possible	NC	> 0.1 m/sec (> 10 md) normally	< 2,700	< 9,000	< 94°C (< 200°F)
Alkaline	13-15	< 200	Some organic acids	Above waterflood residual	Sandstone preferred	NC	> 0.2 m/sec (> 20 md)	< 2,700	< 9,000	< 94°C (< 200°F)

Table 7.3 cont.
Screening Criteria for Enhanced Recovery Methods

	OIL PROPERTIES				RESERVOIR CHARACTERISTICS					
	Gravity API	Viscosity (cp)	Composition	Oil Saturation	Formation Type	Net Thickness	Average Permeability	Depth (m)	Depth (ft)	Temperature
THERMAL										
Combustion	< 40 (10-25 normally)	< 1,000	Some asphaltic components	> 40-50% PV	Sand or Sandstone with high porosity	> 3 m (> 10 m)	> 1.0 m/sec (> 100 md)*	> 150	> 500	> 65°C (> 150°F) preferred
Steam-Flooding	< 25	> 20	NC	> 40-50% PV	Sand or Sandstone with high porosity	> 6 m (> 20 m)	> 2.0 m/sec (> 200md)**	90-1,500	300-5,000	NC

NC Not critical
cp centipoises
md millidarcies
*Transmissibility >0.06/m^2 /sec/cp (or 20 md-ft/cp)
**Transmissibility >0.06/m^2/sec/cp (or 20 md-ft/cp)
Should not be taken as absolute values, but as rules of thumb only.

Table 7.4
Comparative Summary of Petroleum Industry Enhanced Recovery Processes

Process	Recovery Mechanism	Typical Recovery (%)	Typical Agent Utilization	Typical Agent Utilization
Immiscible Gas	Reduces oil viscosity; Oil swelling; Solutions gas drive	5-10	0.18 scM gas/L oil	10 Mscf gas/bbl oil
Miscible Gas	Same as immiscible plus development of miscible displacement	5-15	0.18 scM gas/L oil	10 Mscf gas/bbl oil
Polymer	Increase volumetric sweep efficiency by reducing mobility ratio	5	1.4-5.7 g polymer/ L oil	0.5-2 lb polymer/ bbl oil
Micellar/Polymer	Same as polymer plus reduction in IFT forces	15	43-71 g surfactant/ L oil	15-25 lb surfactant/ bbl oil
Alkaline/Polymer	Same as micellar/ polymer plus wettability alteration	5	100-128 g chemical/L oil	35-45 lb chemical/ bbl oil
Steam (drive or soak)	Reduces oil viscosity	50-65	0.5 L oil consumed/ L oil produced	0.5 bbl oil consumed/bbl oil produced
	Vaporization of light ends		5-10 L steam/L oil	5-10 bbl steam/bbl oil
In Situ	Same as steam plus cracking of heavy ends	10-15	0.18 scM gas/L oil	10 Mscf air/bbl oil

Table 7.5
Site Characterization Information for Remediation Design

Geology	Hydrology	Geochemistry
• Geologic cross-sections • Lateral continuity of saturated zones • Hydraulic communication between adjacent formations • Recharge areas • Discharge areas	• Hydrologic properties of aquifer • Water level in wells • Wellhead elevations • Dispersivity values • Regional groundwater use inventory • Primary contamination migration peak	• Adsorption characteristics • Biodegradation information

Multi-well interference pump tests are required to provide a more thorough analysis of hydrologic properties of the formations. The information that can be obtained from interference tests includes:

- directional transmissivity and hydraulic conductivity,
- storage coefficient,
- boundary effects,
- leakage, and
- groundwater flow.

Proper site characterization will enhance the success of many environmental engineering cleanup projects.

7.2.2 Contaminant Containment

Containment of the contaminant within the site is generally required. Groundwater cutoff walls and hydrodynamic control using a set of injection wells and pumping wells are two of the most commonly used methods.

7.2.3 Saturated Zone Wellfield Design

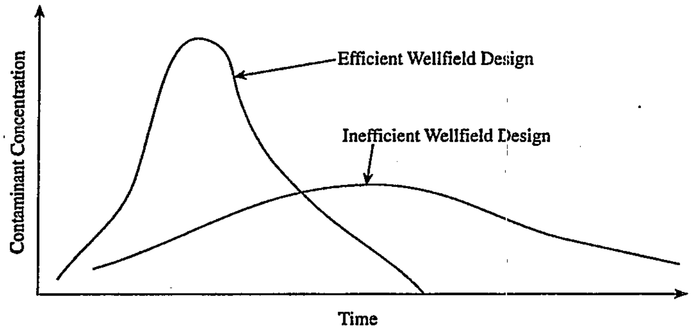
After contaminant migration due to groundwater flow is contained, the in situ removal and treatment (soil flushing) of the contaminant must be implemented. Often, a high percentage of the contaminants can be pumped from the subsurface and treated aboveground. The remaining contamination must be treated in situ, either by groundwater flushing, chemical flushing, bioremediation, or a combination of these. In situ waste recovery procedures are intended to accelerate the release of contaminants from the soil.

A good wellfield design can significantly lower the cost of in situ waste recovery. There are four major factors in wellfield design:

- amount of waste to be recovered,
- duration of operation,
- waste concentration in the recovered solution, and
- breakthrough time.

It is important to make the operation cost-effective through *efficient* wellfield design and operation. Figure 7.1 shows hypothetical soil flushing recovery curves from two different wellfield designs — one efficient and one inefficient.

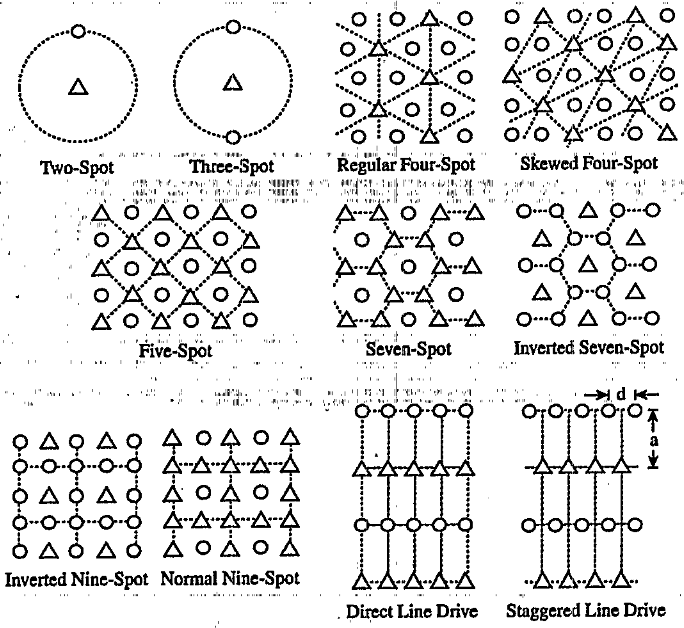
Figure 7.1
Hypothetical Contaminant Recovery from Two Wellfield Patterns — One Efficient and One Inefficient



Good wellfield design for in situ soil flushing incorporates the experience from enhanced oil recovery and in situ mining. Figure 7.2 shows the most basic wellfield patterns based on that experience (Craig 1971; Muskat 1971). These patterns are used when the contaminated area extends in all directions. Special wellfield patterns must be designed and applied when dealing with odd-shaped contaminated areas.

Table 7.6 presents the ratios of recovery to injection wells and areal sweep efficiency (the percentage of area contacted by the injected solution at a given time) at breakthrough in an isotropic homogenous formation for basic wellfield patterns (Craig 1971; Muskat 1971). For example, Table 7.6 shows areal sweep efficiency at the time of solution breakthrough at the recovery well in isotropic geologic formations. The values shown in Table 7.6 are based on the assumption that very large wellfield patterns have been used. A range of values is shown for areal sweep efficiency. Different studies have obtained different values for sweep efficiency depending on the method of simulation (Craig 1971; Muskat 1971).

Figure 7.2
Standard Wellfield Patterns



○ Injection well
△ Production well
---- Pattern boundary

Reprinted from Craig, "The Reservoir Engineering Aspects of Waterflooding," 1971, p 49, with permission of the Society of Petroleum Engineers.

Table 7.6
Ratio of Recovery Wells to Injection Wells and Sweep Efficiency

Wellfield Pattern	Ratio of Recovery to Injection Wells	Areal Sweep Efficiency at Breakthrough (%)
Two-spot	1:1	52-54
Three-spot	2:1	67-79
Regular four-spot	2:1	73-82
Skewed four-spot	2:1	70-80
Five-spot	1:1	67-73
Direct line drive (d/a = 1)*	1:1	55-60
Staggered line drive (d/a = 1)*	1:1	74-78
Seven-spot	1/2:1	73-80
Inverted seven-spot	2:1	73-82
Normal nine-spot	2/3:1	65-80
Inverted nine-spot	3:1	65-80

*a = distance between two adjacent rows of opposite wells; d = distance between two adjacent rows of like wells

Source: Craig 1971

7.3 Design and Equipment Selection

In addition to areal sweep efficiency and breakthrough time, there are several other controlling factors in soil flushing wellfield design. These include:

- well recovery rate and injectivity,
- formation anisotropy,
- regional groundwater flow, and
- geochemistry and contaminant recovery.

These factors will be discussed in the following sections.

7.3.1 Well Recovery Rate and Injectivity

Well recovery rate and injectivity provide a good indication of the type of basic wellfield pattern to be considered. For example, if a well in an aquifer can produce 190 L/min (50 gal/min), but can only inject 95 L/min (25 gal/min), the optimum wellfield pattern would consist of twice as many injection wells as recovery wells. Then, by referencing Table 7.6, a four-spot or seven-spot wellfield pattern should be selected. Additionally, injectivity and recovery rate determine the breakthrough time and economic feasibility of soil flushing. If injectivity and recovery are high, greater well spacing can be used.

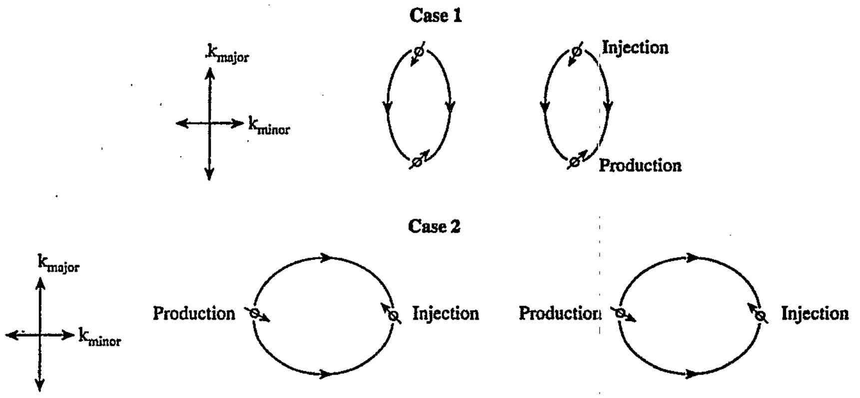
Injection pressure should not exceed the pressure at which hydraulic fractures would begin to develop and cause the injection and recovery wells to short-circuit. On the other hand, the water level in the recovery well should not fall below the top of the target horizon.

In estimating well pumping and injection rates, well efficiency (safety factor) should be considered. Wells do not usually operate at 100% efficiency because of well bore damage and well screen plugging. Individual well efficiency can be calculated from pumping test or slug test data. Wells tend to deteriorate during operation and well efficiencies decrease over time.

7.3.2 Formation Anisotropy

When the permeability of a formation is a function of direction, the formation is anisotropic. For example, in fractured rock units, the highest permeability is in the direction parallel to the direction of the fractures. The directional permeability of a geologic formation and the hydraulic gradient determine the preferential groundwater flow direction (Darcy's Law). Boundary conditions dictate the hydraulic gradient. To optimize the areal coverage, the direction of induced flow should be oriented along the direction of minor permeability. Figure 7.3 presents two different cases for direct-line-drive well patterns. In Case 1, the direction of minor permeability is perpendicular to the flow direction, and the areal coverage is small. Case 2 provides better coverage because the direction of minor permeability is parallel to the induced flow direction.

Figure 7.3
Effects of Horizontal Directional Permeability

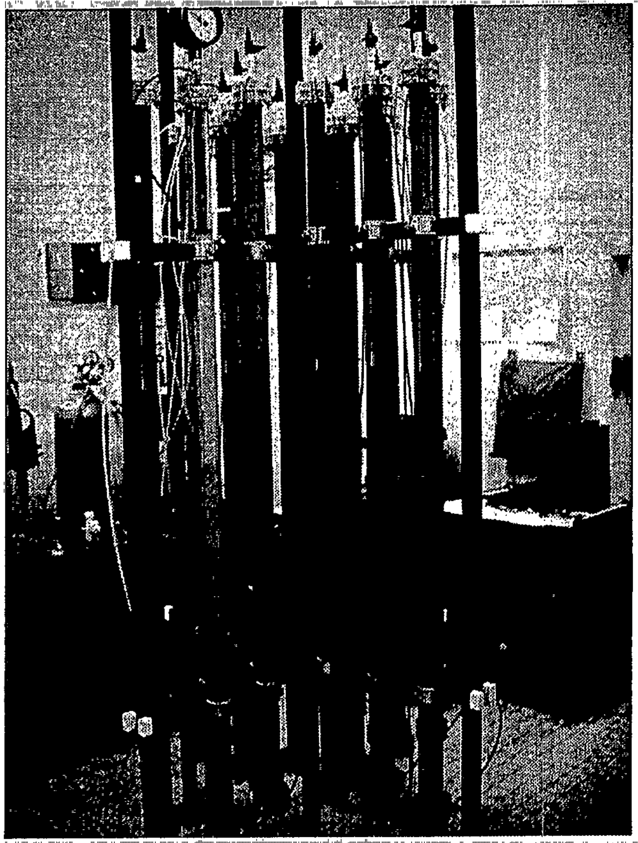


7.3.3 Streamlines and Pore Volumes

Before well spacing can be determined, it is necessary to examine how long the chemicals or nutrients can stay in the ground and how far they can travel before losing their effectiveness. A laboratory "stream tube" experiment is instrumental in selecting the proper chemical mix or nutrients (see Figure 7.4) Applying the results of this experiment should effectively minimize the number of streamline pore volumes to clean up the contaminant.

It is also essential to control the flow pattern in such a way that the breakthrough times for all streamlines will be close so that the peak concentration is high and the recovery time short.

Figure 7.4
Stream Tubes Consist of a Series of Long Columns



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7.4 Process Modifications

After designing the basic soil flushing system, it is appropriate to assess modifications to enhance the effectiveness of contaminant removal to minimize the time and cost to complete the remediation.

Geochemical procedures for the restoration of groundwater quality are tested in the laboratory, using beakers or columns and stream tubes, as each specific situation requires. The various contaminant recovery techniques that can be tested in the laboratory include ion exchange, reverse osmosis, electrolysis, bacteria conversion, and precipitation. Laboratory column tests also help determine the most suitable chemical (lixiviant), polymers, or surfactants for soil flushing.

7.4.1 Laboratory Tests

Batch tests are the simplest form of testing to screen processes for soil flushing. A contaminated soil sample in a container is saturated with selected solutions (natural groundwater or synthetic water spiked with specific solutes) and agitated by a shaker or a roller. The liquid samples are collected and analyzed at predetermined time intervals. The soil sample used in the batch test should be representative of the site soils. Batch tests should identify soil flushing processes that will not work in the field.

Column tests provide further screening and optimization of the soil flushing process. Column leach experiments are usually performed in a vertically oriented glass column. The contaminated soil sample is packed in the column. The solution (natural groundwater or synthetic water spiked with the solute of interest) is injected into the column at a predetermined flow rate (upward or downward flow). Liquid samples are collected at the column outlet. The results are evaluated to assess the effectiveness of the process. A water treatment circuit can be added to the testing program to examine the ability to recover contaminants from the contaminated liquid coming out of the column.

Stream tube tests employ a series of long columns having a variety of diameters and lengths, depending upon the application. These tubes should be sufficiently large to preclude edge effects which could compromise scale-up calculations. These are interconnected to provide a flow path of up to 60 m (200 ft) or longer, as appropriate, with sampling ports at each juncture (see Figure 7.4). Stream tube tests require much larger volumes of contaminated soil samples, often in the range of several kilograms. The flushing solution is injected into the stream tube at a predetermined flow rate. Liquid samples are taken at the sampling ports at predetermined intervals. The contaminant recovery rate of a particular process can be evaluated as a function of time and distance. The results from stream tube tests reveal how long and how far the chemical can travel underground before losing its leaching ability. This information is essential in determining well spacing between injection and recovery wells and, subsequently, the cost of the proposed soil flushing remediation program.

7.4.2 Soil Flushing Solutions

Flushing solutions may include water, dilute acids and bases, complexing and chelating agents, oxidizing and reducing agents, solvents for inorganic and metal contaminants, or surfactants for organic contaminants. The ideal flushing solution is inexpensive, common, and nontoxic, that rapidly mobilizes 100% of the target contaminant at low concentrations, releases no hazardous or toxic substances, causes no decrease in formation permeability, and remains unretarded in its transport through the formation. Chemically enhanced soil flushing is applicable at many remediation sites with metals or radioactive material contaminants.

It is important to remember that each site is unique and each contaminant has its own physical and chemical properties. No single flushing solution can satisfy all requirements and be effective for all contaminants.

7.4.2.1 Organic Contaminants

Soil flushing with surfactant solutions to extract hydrophobic organic contaminants appears to be one of the most promising in situ cleanup technologies. Aqueous surfactant solutions are superior to water alone in extracting hydrophobic contaminants. The detergency of aqueous solutions and the efficiency by which organics are transported by aqueous solutions are improved by the addition of surfactants. 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 increases the efficiency by which organics are transported by the flushing fluid, compared to the injection of water only.

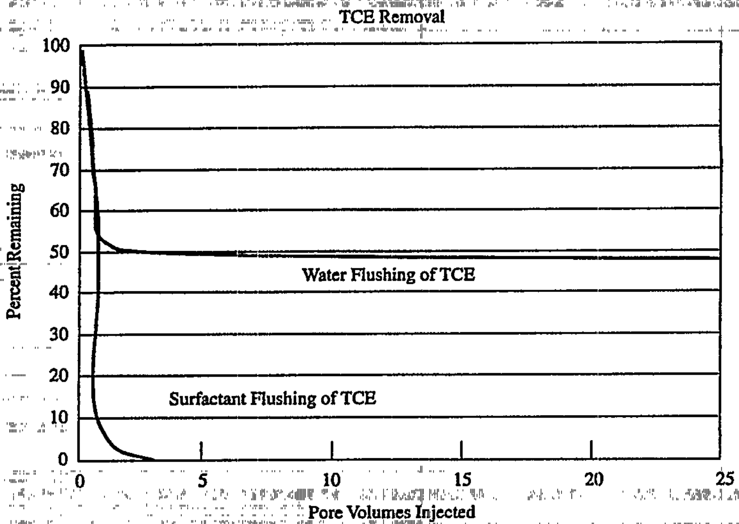
When only water is injected, contaminants are extremely difficult to remove because they have become trapped in the pore spaces. Also, flow rates and pressure gradients in standard pump-and-treat processes may not be high enough (on the order of hundreds of meters per meter of pressure gradient) to force immiscible contaminants, such as DNAPLs, through the soil matrix. With the introduction of surfactants, the interfacial tension of the system is substantially reduced. Tiny droplets of organics that are surrounded by the surfactant are subsequently "dissolved" into the water phase and are then more readily transported through the soil pores. Another reason the use of surfactants for in situ soil flushing appears promising is that numerous environmentally-safe and relatively inexpensive surfactants are readily available commercially (Edwards, Luthy, and Liu 1991).

The use of surfactants to enhance oil recovery from subsurface oil reservoirs has been practiced by the petroleum industry for many years. Research has recently been conducted on the use of surfactants for soil washing and soil flushing. Figure 7.5 shows the effectiveness of one surfactant (one brand of dishwashing liquid) compared to that of water flushing alone in removing TCE from contaminated sand (McKee and Way 1994). The surfactant used in the experiment was injected at a relatively high concentration that may not be cost-effective in field applications. However, the actual results of TCE recovery remain consistently higher when flushing is performed with a surfactant solution as compared to water only. Table 7.7 shows the results of several laboratory and field tests using surfactants to recover contaminants. The results demonstrate that surfactant use dramatically increased the removal of hydrocarbons and chlorinated hydrocarbons from contaminated sand. In each of the experiments shown, the recovery of the organic contaminant increased when high concentrations of surfactant and/or larger treatment quantities were injected.

Figure 7.6 shows the results of a laboratory experiment testing the recovery of diesel fuel from a coarse-sand soil column (94% <14 mesh) using a variety of flushing liquids. The first experiment used a 100% dishwahing liquid. The second used only water (note that the curve is flat after five pore volumes). The third used a 1% Drispac, an oil field polymer solution. The 100% dishwashing liquid was continually added until all the diesel fuel was recovered. In the other two tests, only 80% of the diesel fuel was recovered. The coarse sand retained 20% of the diesel fuel in the pores which is available to slowly leach out and continue to contaminate the groundwater. As the sand becomes finer, the pores become smaller and a much higher amount of contaminant will be retained in the pores.

In addition to surfactant flushing, there is a spectrum of technologies in various states of evolution or commercialization. There are cases where surfactants and cosolvents are being successfully used (AATDF 1997).

Figure 7.5
The Effectiveness of a Dishwashing Liquid in Removing TCE from Contaminated Sand Under Laboratory Conditions



Steam is another soil flushing enhancement that has been used to clean up organically-contaminated soils. The injection of steam tends to volatilize and reduce the viscosity of contaminants by increasing their vapor pressure. This phenomenon, combined with the pressure differential caused by the steam pressure and vacuum extraction, increases the mobility of contaminants in the media (Noffsinger 1995). In a pilot-scale of steam injection for soil flushing conducted in California, steam was injected into six wells that surrounded a single vacuum recovery well. After a relatively short treatment time of 140 hours, average contaminant concentrations were reduced by a factor of 50 in comparison to the standard pump-and-treat method (Noffsinger 1995).

7.4.2.2 Inorganic Contaminants

Inorganic contaminants can be flushed from soil by chemical solutions or they can be stabilized in situ by changing them into a form that is not soluble in posttreatment conditions. For example, uranium readily forms soluble complexes with bicarbonates, carbonates, and sulfates when it is oxidized to the hexavalent state. However, uranium in the tetravalent state is not soluble and will not be transported by water. As water moves through soil, its chemistry can be altered by reactions between the components in the water and in the soil. Understanding and controlling the reactions between the water (soluble phase) and the soil (insoluble phase) is important for successful contaminant removal or in situ stabilization.

Contaminants can be flushed from soil and transported in a water-based solution if the solution chemistry favors the soluble form of the contaminant. However, if the solution chemistry changes by contact with soil or by groundwater dilution, it is then possible for some contaminants to precipitate or be adsorbed from the solution. Many inorganic contaminants are present in solutions in a soluble form as well as in the soil in an insoluble form. The amount of contaminant in the solution and soil is controlled by equilibrium considerations. If the solution containing the contaminant is removed and replaced by a similar solution without a contaminant, then a portion of the remaining contaminant in the soil will dissolve and seek to establish a new equilibrium concentration in the water. Hence, repeated flushing is often needed to extract inorganic contaminants.

Natural groundwater can be either mildly oxidizing or reducing, depending upon the properties of the soil with which it has come in contact. As soil composition changes, so do its properties. Typically, the natural movement of groundwater disperses contaminants into larger volumes of groundwater and through larger masses of soil, thus reducing the downgradient contaminant concentration in solution and in the soil. Natural restoration processes are useful for low concentrations of inorganic contaminants, but contaminant confinement and more aggressive flushing is normally required near the contaminant source.

Table 7.7
Summary of Results from Surfactant Experiments

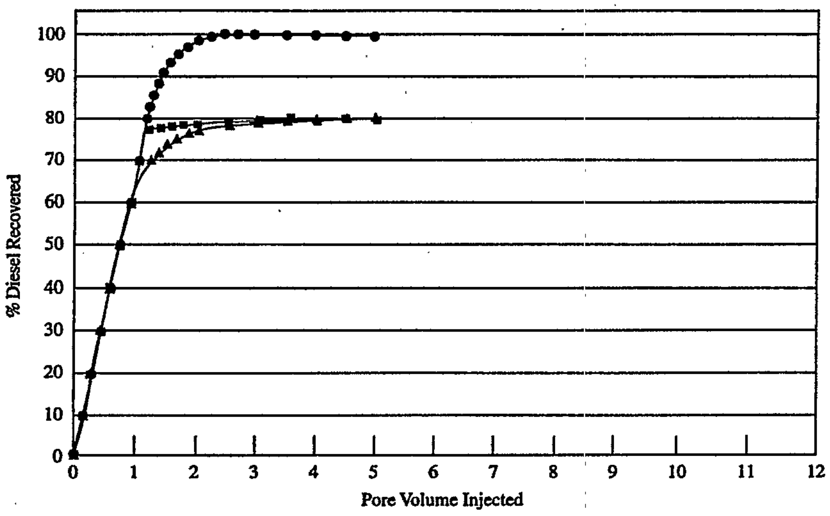
Lab/Field	Material/ Formation Type	Surfactant	Contaminant	Number of Pore Volumes	% Recovery	Reference
Lab (large concrete tank)	Sand	2% Richonate-YLA and 2% Hyonic PE-90	Automatic Transmission Fluid (ATF)	single application	6	American Petroleum Institute 1985
		2% Richonate-YLA and 2% Hyonic PE-90	Automatic Transmission Fluid (ATF)	multiple *(daily)* application by percolation	76	
		2% Richonate-YLA and 2% Hyonic PE-90	Automatic Transmission Fluid (ATF)	multiple *(daily applications by direct injection into the water table)*	83	
Lab (column)	98% Sand	Adsee 799 and Hyonic PE-90	Total Organic Carbon (TOC)	12	50	US EPA 1988
			Volatile Organic Analysis (VOA)	12	99	
			Biochemical Oxygen Demand (BOD_5)	12	50	
Lab (beaker)	Sandy Soil	Water	Automatic Transmission Fluid (ATF)	Beaker	22.9	Abdul , Gibson, and Rai 1990
		0.5% Witconol 1206	Automatic Transmission Fluid (ATF)	Beaker	83.8	
		0.5% Witconol SN70	Automatic Transmission Fluid (ATF)	Beaker	82.2	
		0.5% Witconol SN90	Automatic Transmission Fluid (ATF)	Beaker	81.3	
		0.5% Witconol NP100	Automatic Transmission Fluid (ATF)	Beaker	71.9	
		0.5% Witcamide 5130	Automatic Transmission Fluid (ATF)	Beaker	63.4	
		0.5% Adsee 799	Automatic Transmission Fluid (ATF)	Beaker	33.1	
		0.5% Witcolate D51-51	Automatic Transmission Fluid (ATF)	Beaker	81.1	
		0.5% Witcolate DS-10	Automatic Transmission Fluid (ATF)	Beaker	63.4	
		0.5% Emphos CS1361	Automatic Transmission Fluid (ATF)	Beaker	56.7	
		0.5% Witconate A0S	Automatic Transmission Fluid (ATF)	Beaker	71.0	

Lab (column)	Sandy Soil	Water	Automatic Transmission Fluid (ATF)	28	25.5	Ang and Abdul 1991
		0.5% alcohol ethoxylate	Automatic Transmission Fluid (ATF)	28	55	
		1% alcohol ethoxylate	Automatic Transmission Fluid (ATF)	28	60	
		2% alcohol ethoxylate	Automatic Transmission Fluid (ATF)	28	72.8	
Lab (column)	Sand	Water	1,1,2 Trichloroethylene (TCE)	3	51	In-Situ, Inc., unpublished report 1994.
		Water	1,1,2 Trichloroethylene (TCE)	25	52	
		A dishwashing liquid	1,1,2 Trichloroethylene (TCE)	3	99.9	
		Water	Diesel	3	80	
		1% Drispac	Diesel	3	80	
		Ivory dishwashing liquid	Diesel	2	100	
Field Pilot Test	Sandy to Silt	0.75% Witconol SN70	Polychlorinated Biphenyls (PCBs)	5.7	10	Abdul and Ang 1994
			Polychlorinated Biphenyls (PCBs)	8.0	25	
			Oil	5.7	10	
			Oil	8.0	32	
Lab (column)	Sandy to Silt	0.075% Witconol SN70	Polychlorinated Biphenyls (PCBs)	5.7	7	Abdul and Ang 1994
			Polychlorinated Biphenyls (PCBs)	8.0	19	
			Polychlorinated Biphenyls (PCBs)	105.0	85	
			Oil	5.7	9	
			Oil	8.0	15	
			Oil	105.0	90	
Lab (column)	Ottawa Sand	Sodium sulfosuccinate	Perchloroethylene (PCE)	1.0	87	Pope and Wade 1995
				2.0	96	
				6.0	97	
Lab (column)	Silty Alluvial Soil	Alcodet MC 2000	Total Petroleum Hydrocarbon (TPH)	14	80	Bourbonais, Compeau, and MacClellan 1995
		14	49			
		Wilcodet 100	TPH	14	90	
		Wilcodet 100	PAHs	14	99	
		Tap water	TPH	14	6	
		Tap water	PAHs	14	0-37	

Table 7.7 cont.
Summary of Results from Surfactant Experiments

Lab/Field	Material/ Formation Type	Surfactant	Contaminant	Number of Pore Volumes	% Recovery	Reference
Canadian Forces Base Borden Field Test	Clean Sand	Water Flushing	PCE	6.2	9	Fountain et al. 1995; Freeze et al. 1995
		1% NP 100 and 1% Rexaphos 25-97	PCE	10	46	
			PCE	14.4	52	
Corpus Christi, Texas Field Test	Fine-Grained Sand	Surfactant	Carbon Tetrachloride (CTET)	3.0	Effluent CTET concentration dropped from > 1,000 ppm to < 10 ppm.	Fountain et al. 1995; Freeze et al. 1995
Travis City, Michigan Field Test	Medium Sand	Dowfax 8300	PCE and Aviation fuel	NA	Mass extracted increase seven-fold over water alone	Knox et al. 1995

Figure 7.6
Results of Diesel Fuel Recovery Experiments Using Surfactant, Water, and Drispac Solution



- ● 100% Surfactant *(a dishwashing liquid)*
- ▲ Water
- ■ Drispac

The composition of the injected solutions can be controlled to favor the mobilization or stabilization of a contaminant. Injection of oxidizing solutions tends to mobilize contaminants. Injection of reducing agents tends to precipitate contaminants. However, it is important to ensure that all of the soil's components will be treated by the injected chemicals, while also noting that the final groundwater composition will be influenced by the final composition of the treated soil.

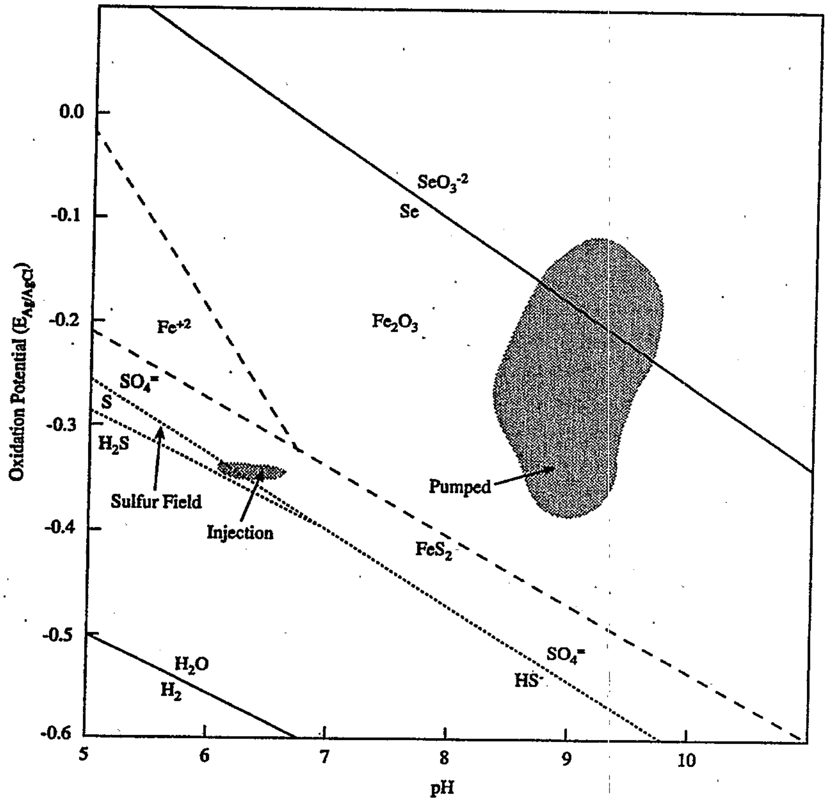
Under mildly oxidizing conditions, uranium can be converted from its insoluble state to a form that can be transported in water. If uranium in solution contacts a reducing zone in a soil, then the uranium can be reduced to an insoluble form. To accelerate the flushing of uranium from a soil, oxidants and complexing agents (such as carbonate or sulfate) can be added to the injected solutions. In most cases, a stronger oxidizing solution speeds the dissolution of uranium and helps keep uranium in solution by oxidizing zones in the soil where hydrocarbon or other reduced minerals are present. Once the uranium and oxidizing solution have been removed from the soil, it may take additional time for the groundwater composition to stabilize. Sometimes trace minerals, such as selenium, arsenic, and molybdenum, may become soluble during uranium flushing.

In situations where a contaminant solution has created an oxidizing condition in an aquifer which was previously in a reduced state, a reductant, such as hydrogen sulfide, can be added to the flushing solutions being injected into the contaminated part of the aquifer. The reductant will reverse the effects of oxidation and will cause many inorganic components in the soil and the water to become insoluble. If the ambient condition of the aquifer is reducing, then the inorganic components precipitated during the flushing with a reductant will remain insoluble and immobile. However, if a reductant is used to flush a soil, but the treated area does not remain in a reducing state, then as the oxidation of the area resumes, more contaminants will again be mobilized.

When using injected solutions to alter chemical conditions in situ, it is important to remember that the composition of the injected solutions change as they move between wells. Figure 7.7 shows the results of injecting a reducing solution in a wellfield for the purpose of reducing selenium to an insoluble form. The injected solution began with a pH of 6.1 and an oxidation potential of approximately -0.35. However, by the time the injected solution reached the recovery wells, the pumped solutions ranged from a pH of over 8 with an oxidation potential of about -0.35 to a pH of over 9 with an oxidation potential of nearly -0.1. Somewhere between the injection wells and the recovery wells, the chemical conditions as measured by oxidation potential and pH supported several different chemical forms of iron, selenium, and sulfur. When using in situ treatment with wellfield pumping, acceptable results are possible only with good site characterization and technical planning (Merritt 1971; Laman 1989).

Chemicals which enhance the flushing of contaminants from soils can mobilize other soil constituents and increase the dissolved solid content in the groundwater. Whether or not these additional mobilized constituents pose a problem for the surface treatment process depends upon the surface process and treated water discharge requirements at each site. In general, the use of oxidants or additives which enhance the mobility of contaminants will

Figure 7.7
Oxidation Potential and pH of Injected Solutions and Pumped Solutions (Based on Equilibrium Data)



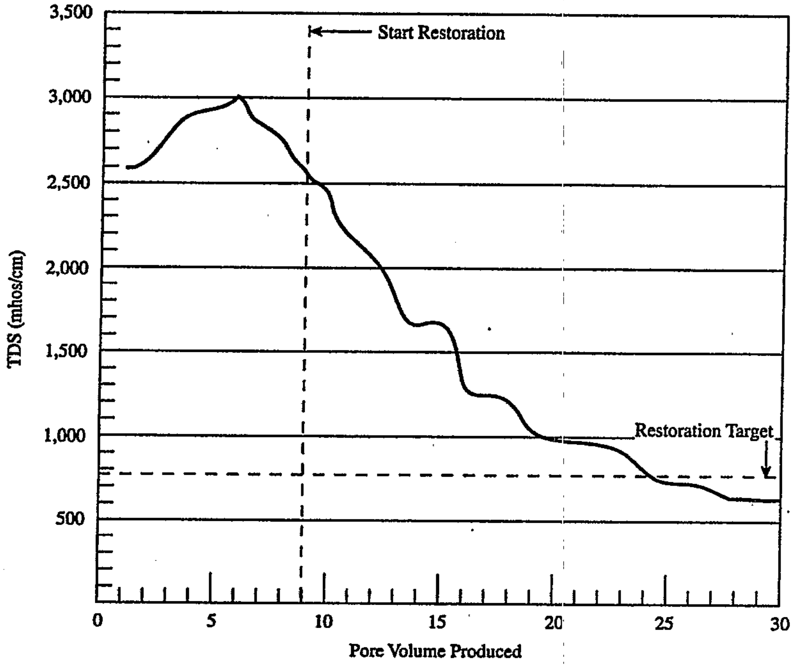
increase the total dissolved solid content of the groundwater more than the use of reductants. However, under some conditions, reductants can also increase total dissolved content of groundwater if the reductant reacts to form a soluble byproduct. For example, hydrogen sulfide might form sulfate and the sulfate can increase the total dissolved solid content of the groundwater. The design of the surface process needs to anticipate the possible mobilization of more than just the target contaminant.

Uranium in situ solution mining provides a good example of the application of innovative soil flushing to remove inorganic contaminants. It includes: (1) isolating a portion of the groundwater system from the regional flow, (2) using chemicals to extract minerals from a groundwater system, and (3) groundwater restoration after mining. Chemicals are injected into a wellfield that hydrologically confines the movement of the chemical solutions to the mined zone. The wellfield is surrounded by a ring of carefully spaced monitoring wells and sometimes a second ring of "trend" wells. The purpose of the monitoring wells and trend wells is to detect any movement of chemicals outside the mined zone and to ensure separation of the ambient groundwater from the chemical solutions used to dissolve the uranium contained in the mined zone. During active solution mining, uranium and other metals, such as arsenic, selenium, or molybdenum, are dissolved in a chemical solution. After active mining, traces of the chemical solutions, uranium, and any other byproduct metals are removed from the groundwater system and the groundwater in the mine zone is restored to a composition similar to the premining composition.

Restoration of groundwater after in situ uranium solution mining has been completed at several sites in the U.S. Figures 7.8 and 7.9 show the decrease in total dissolved solids as measured by specific conductance, and the decrease in uranium concentration at one restored site as an example. Since the displacement of water from pore spaces in the mined zone is not uniform, it is common to circulate several pore volumes to restore the water quality in the mined zone.

The restoration goal was the acceptable residual concentration of uranium and total dissolved solids determined by the appropriate regulatory agency. The cost-effectiveness of a restoration process depends upon the restoration targets for each contaminant because, as the contaminant concentration decreases, the costs increase; the cost to remove the last kilogram is much more costly to remove than the first kilogram. Another factor is downgradient geochemistry of the aquifer. If the aquifer geochemistry is appropriate, the groundwater quality will approach its pre-mining water quality by natural processes. Cost-effective groundwater restoration requires the use of treatment processes, groundwater management, and a knowledge of natural processes active in the mined zone and downgradient. Since groundwater information is limited by the number of wells and is usually sparse, monitoring wells should be used to detect any unexpected movements of contaminated groundwater outside the mined zone during active restoration. After active restoration, monitoring wells should be used to confirm the chemical stability of the groundwater.

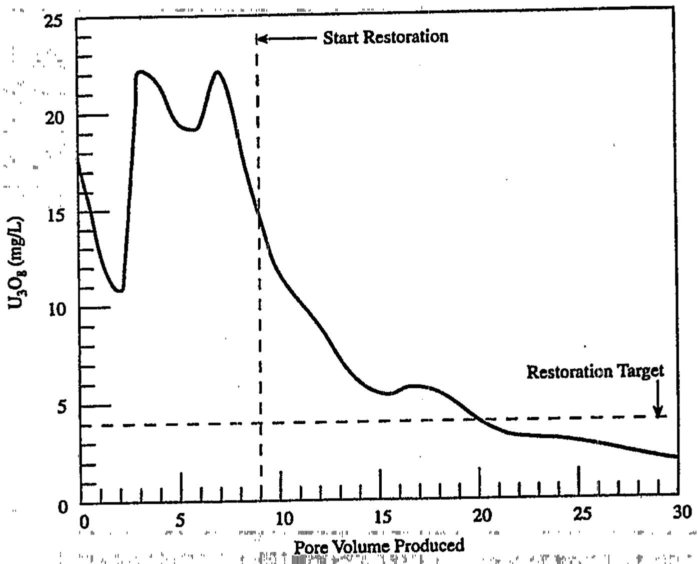
Figure 7.8
Reduction of Total Dissolved Solids at a Restored In Situ Uranium Solution Mining Site



Specific conductance 10 pore volumes to restoration

Occasionally, chemical solutions used in mining are detected in a monitoring well. This is called an *excursion.* Horizontal excursions are corrected by reversing the hydraulic gradient to favor flow toward the wellfield and away from the monitoring well by adjusting the volume of water pumped

Figure 7.9
Uranium-Contaminated Aquifer Restoration at an In Situ Uranium Solution Mining Site

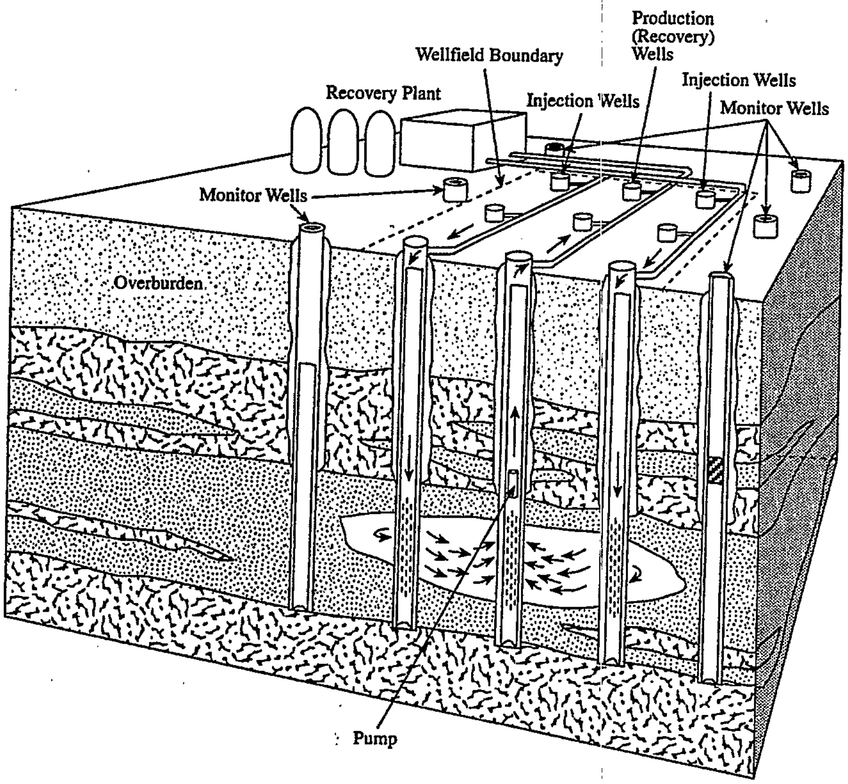


10 pore volumes to restoration

and injected. Use of hydraulic gradients and flow nets to control solution movements is an element of solution mining technology and can be used for improved recovery of contaminant plumes.

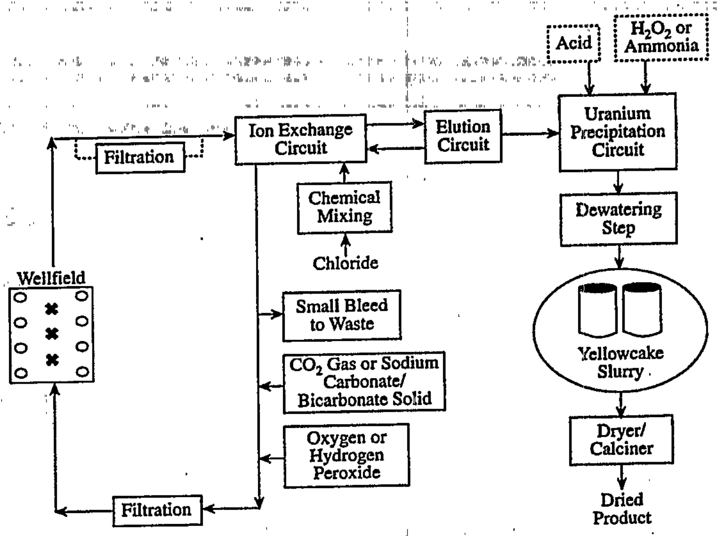
Figure 7.10 illustrates the in situ uranium mining process. The technology has evolved over many years and can easily be applied to groundwater cleanup and soil flushing. The chemistry of the chemical solutions used in active mining is normally an oxidant, such as oxygen gas or hydrogen peroxide, and sodium carbonate-bicarbonate (baking soda) and is designed to work with the ambient groundwater to create Eh and pH ranges in the mining solutions favorable to the oxidation and mobilization of uranium.

Figure 7.10
The In Situ Mining Process



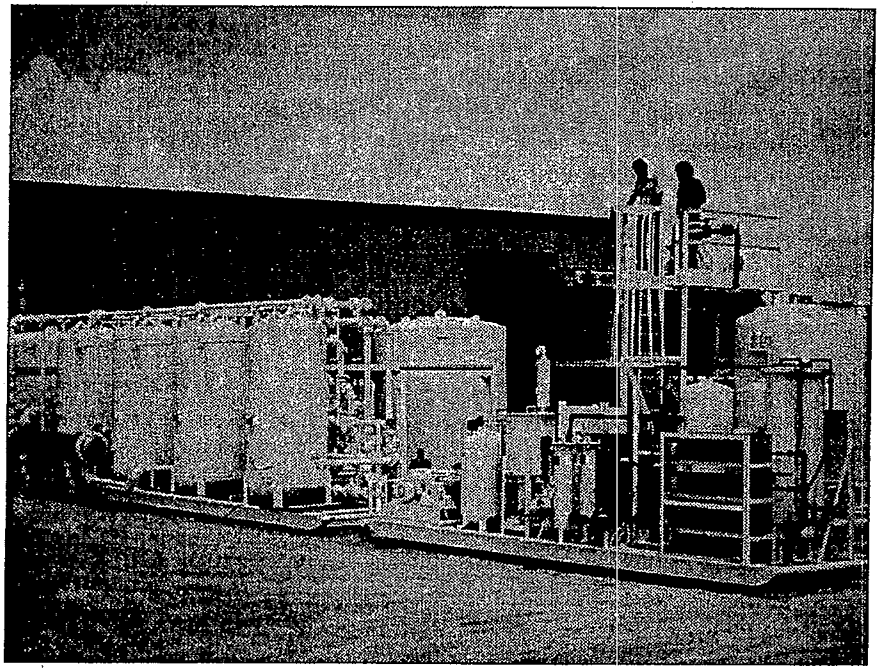
Different chemicals designed to stabilize or extract contaminants can be used for different objectives. Other chemistries have been used by the uranium mining industry. The best chemistry for each site depends upon site-specific considerations. Figure 7.11 shows a simplified in situ uranium solution mine flow chart. The best chemistry for a soil flushing project is also dependent upon the site-specific conditions.

Figure 7.11
Simplified In Situ Uranium Solution Mine Flow Sheet



The surface equipment used for uranium in situ solution mining is designed to remove small concentrations of uranium from water and recycle about 95% or more of the water to the wellfield. Ion-exchange processes, similar to those used in the water softening industry, remove the uranium from solution and concentrate the uranium in a much smaller water volume. The uranium is removed from the concentrated solutions by chemical precipitation and the uranium precipitate is dewatered and drummed. Various types of ion-exchange equipment are used including up-flow, down-flow, moving-bed, and fixed-bed devices. Figure 7.12 shows a four-column, skid-mounted, fixed-bed, down-flow ion-exchange plant and associated equipment. Fixed-bed, down-flow ion-exchange columns are for processing clear solutions, like those that come from a gravel-packed well. For a soil flush application, resin-in-pulp is a better design. In the resin-in-pulp design, the pulp is a mixture of the contaminated soil and the chemical water. The resin is added to the pulp and the uranium from the contaminated soil is loaded onto the resin. The advantage of resin-in-pulp is that the uranium-bearing resin can be screened from the pulp more easily than the soil can be dewatered or filtered. The capacity of uranium in situ leach plants is a function of the diameter of the ion-exchange vessels, the number of vessels, and the amount of product.

Figure 7.12
Ion-Exchange Plant and Associated Equipment

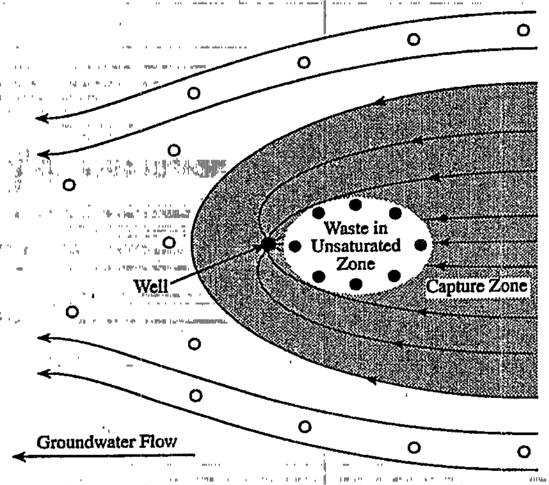


7.4.5 Soil Flushing in the Vadose Zone

The vadose, or unsaturated, zone is the region above the water table in which the pore space is partially filled with air and water. Contaminants contaminated sites have some portion of their contamination in the unsaturated zone. In order to quantitatively assess the behavior of contaminate transport in the unsaturated zone and optimize the design of a vadose zone recovery system, it is necessary to obtain representative soil-moisture characteristic curves for each specific soil, such as (a) soil suction and saturation and (b) hydraulic conductivity and saturation.

The concept underlying soil flushing in the vadose zone is the injection of water-leach solutions or surfactants through horizontal or vertical wells that are installed above the contaminated zone. The injected fluids mobilize and move the contaminants to the groundwater table. The contaminants can then be recovered by pumping. A hypothetical example is shown in Figure 7.13.

Figure 7.13
Recovery of Contaminants by Pumping in the Saturated Zone



○ Monitor Well
● Vadose Zone Flushing Injection Well

Under steady percolation conditions, the injected fluid tends to spread with depth. Significant spreading generally occurs in finer sand/silt formations and at low saturations. The vadose flow proportion of the subsurface environment must be understood when designing injection well patterns. Figure 7.14 shows an injection well design with flow injected into two horizontal wells. Figures 7.15 and 7.16 show effective saturation profiles in silt loam, resulting from injection of 30 L/min (8 gal/min) per minute from two horizontal wells. The figures demonstrate that shorter well spacings of 10 m (30 ft), as shown in Figure 7.15, provide better coverage (McKee and Whitman 1991).

Figure 7.14
Injection Well Design with Two Horizontal Wells

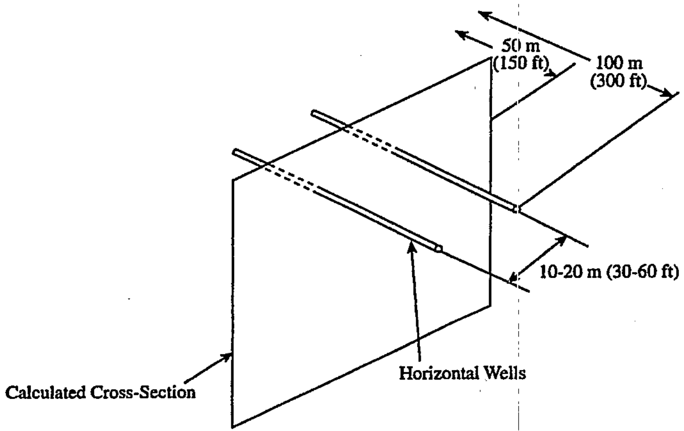
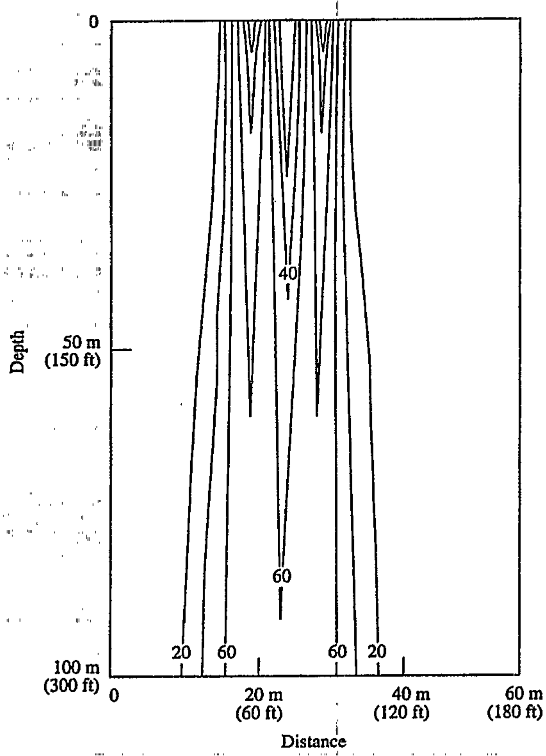
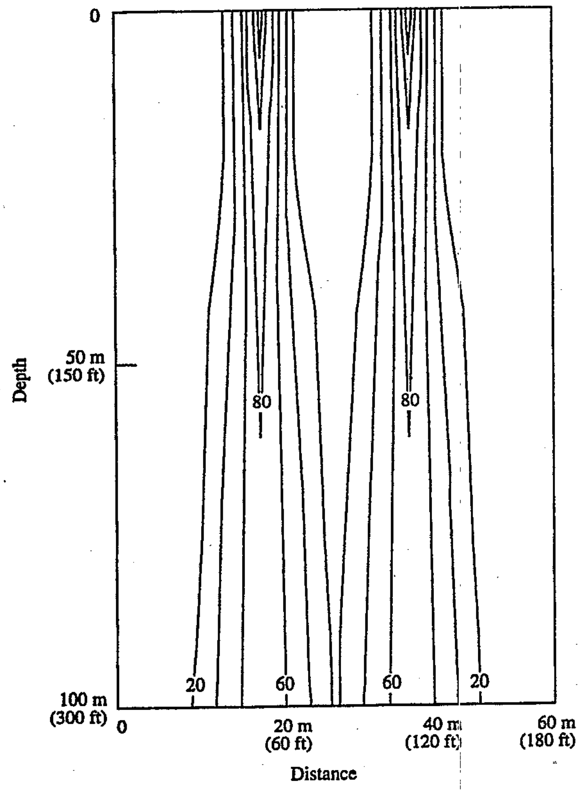


Figure 7.15
Saturation in Silt Loam Using Two Horizontal Injection Wells with Well Spacing at 10 m (30 ft)



Spacing: 10 m (30 ft)
Length: 100 m (300 ft)
Flow: 30 L/min (8 gal/min)
Effective saturations are values shown in central field of the chart.

Figure 7.16
Saturation in Silt Loam Using Two Horizontal Injection Wells with Well Spacing at 20 m (60 ft)



Spacing: 20 m (60 ft)
Length: 100 m (300 ft)
Flow: 30 L/min (8 gal/min)
Effective saturations are values shown in central field of the chart.

7.5 Pretreatment Process

In general, the vadoze zone serves as a conduit for the contaminant to reach the saturated groundwater region. The decision to select either horizontal swept or vertical swept depends on the depth-to-water table, the soil characteristics, and the ratio of horizontal to vertical permeability. Horizontal swept, using a set of pumping/injection wells, is generally employed in the saturated groundwater region (see Sections 7.2 and 7.3). For aquifers with a shallow water table, horizontal swept is adequate.

As an important step in the pretreatment process, the pump-treat-reinject system will be operated without adding any chemicals and/or surfactants in the injection stream. This initial step is to accomplish two major purposes:

- to check the entire soil flushing system and repair/modify any deficiencies; and
- to establish hydraulic control and hydraulic communication between wells.

7.6 Posttreatment Process

Since treatment of flushed contaminants is an integral part of the soil flushing process, posttreatment as defined for this series of monographs is not required. However, after the waste site has been cleaned and all hazardous wastes have been reduced to acceptable levels, it is necessary to implement a long-term monitoring program to ensure and verify the effect of remediation.

Legislation governing groundwater monitoring in the United States includes RCRA, CERCLA and its reauthorization, the Superfund Amendments and Reauthorization Act (SARA), the Clean Water Act, the Safe Drinking Water Act, and the Underground Storage Tanks Technical Standards and Requirements Act. These regulations provide general guidelines and monitoring requirements for waste sites. RCRA requires owners and operators to monitor groundwater quality for at least 30 years after the hazardous site has been remediated.

At a minimum, RCRA requires a four-well monitoring network (one upgradient well and three downgradient wells) be installed and sampled. However, since detecting the reappearance of substances at the site is as important as detecting the migration of hazardous substances off the site, the monitoring network may include sampling points within and surrounding the site. The design of the monitoring network is site-specific and depends on the conditions to be monitored.

For monitoring off-site contaminant migration, RCRA regulations require a sufficient number of downgradient monitoring wells, spaced according to the groundwater flow rate of the aquifer, the size of the site, and the value of dispersivity, be installed to ensure that any off-site migration is detected. An upgradient well located in each distinct aquifer is necessary to provide a water quality background reference. To monitor the possible reappearance of contaminants in the remediated zone, wells used in the soil flushing processes during remediation can be used again. These should be supplemented by new wells to monitor questionable areas in the site.

7.7 Process Instruments and Controls

The process instrumentation and controls necessary for wellfield and soil flushing control are all commercially available and relatively easy to obtain.

Instruments and controls that should be considered for wellfields include:

- submersible pumps;
- injection pumps;
- filters;
- valves;
- pipes;
- pressure gauges;
- flow meters:
- control panels;
- tanks;

- safety equipment; and
- water-level and water-quality monitoring instruments.

Instruments and controls that should be considered for water treatment facilities include:

- columns;
- pumps;
- filters;
- valves;
- pipes;
- pressure gauges;
- flow meters;
- control panels;
- tanks; and
- safety equipment.

7.8 Safety Requirements

Safety is an important concern in any operation; soil flushing is no exception. The safety requirements for soil flushing are common to many site remediation technologies including soil washing. Accordingly, the reader is referred to Section 3.8 in this monograph for a detailed description of generally applicable safety considerations and requirements.

7.9 Specification Development

Soil flushing requires pumping, water treatment, and reinjection of liquid through a series of pumping/injection wells. The idea is simple, but the process if often lengthy. During pumping/injection, aquifers behave like sponges, giving out water easily, but releasing contaminants reluctantly.

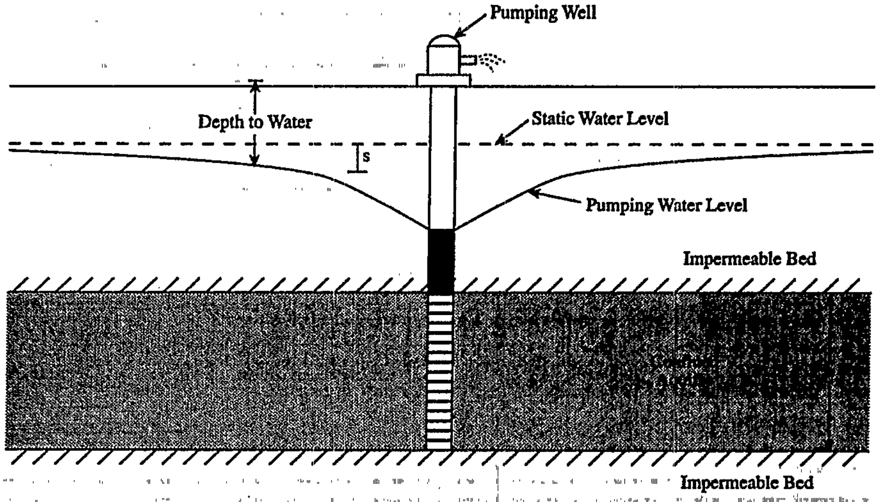
Development of specifications for a soil flushing projects requires consideration of the following:

- *Geology.* Contaminants generally enter the groundwater system in the vadoze zone and gradually reach the saturated groundwater region. The area of contamination can be estimated by the coring and sampling program. Two-dimensional and/or three-dimensional geologic cross-sections showing the area of contamination are useful in calculating the pore volume of a contaminated zone.
- *Geochemistry.* Laboratory tests (Section 7.4) provide screening and optimization of the soil flushing process (what chemical at what concentration should be used). The optimized process serves as the basis for the design of chemical/surfactant injection facilities and a water treatment plant.
- *Hydrology.* While the soil flushing process controls the contaminant plume and reduces contaminant concentration in the formation, it still may be necessary to circulate many pore volumes of water before substantial reduction of contamination in the groundwater is observed, depending on the geochemical parameters affecting remediation of the contaminant. Therefore, one of the most important design parameters is the approximate total amount of water that must be circulated during the soil flushing process over the life of the project.

The next step is to estimate flow injection rate and well pumping rate (see Sections 7.2 and 7.3) for the site aquifer(s). Well flow rates are limited by the formation's ability to transmit water in the aquifer. The ability is defined as transmissivity and is determined from aquifer tests. Figure 7.17 shows radial flow to a well in a confined aquifer.

In addition to transmissivity, the well pumping rate is limited by available drawdown above the pump in the well, and the well injection rate is limited by wellhead injection pressure. The hydrologic information is used to design a wellfield (see Section 7.3).

Figure 7.17
Radial Flow to a Well in a Confined Aquifer



7.10 Cost Data

There are many factors that affect the costs of individual soil flushing projects and, therefore, each site should be evaluated individually. This section summarizes the range of costs involved in soil flushing programs and should only be used as a baseline reference. Cost ranges cover a vast degree of sites and considerations; specific breakdowns are not of use and therefore, will not be covered here.

The factors generally considered in the cost evaluation are:

- licensing,
- site characterization (including drilling of test wells, coring, logging),
- baseline water quality conditions,
- wellfield design,

- laboratory testing,
- modeling,
- well drilling,
- well accessories (pump, wire, control panels),
- chemicals/surfactants,
- water treatment plant, and
- long-term monitoring program.

The above list of factors involved in various soil flushing programs is primarily useful to develop a program cost estimate. However, it does not include transaction tasks, including legal or technical personnel. Further, a contingency should always be included in any estimate to account for unforeseen circumstances.

The NRC (1994) has calculated present-worth costs for a pump-and-treatment system as a function of the percentage of waste removed and these are shown in Figure 7.18. The cost of operating a pump-and-treat system as a function of the contaminants' retardation factor (its tendancy to sorb to solid material in the aquifer) ranges from approximately $2.8 million to approximately $9.2 million for the year 1994, see Figure 7.19. Together, Figures 7.18 and 7.19 provide a realistic estimate of soil flushing costs.

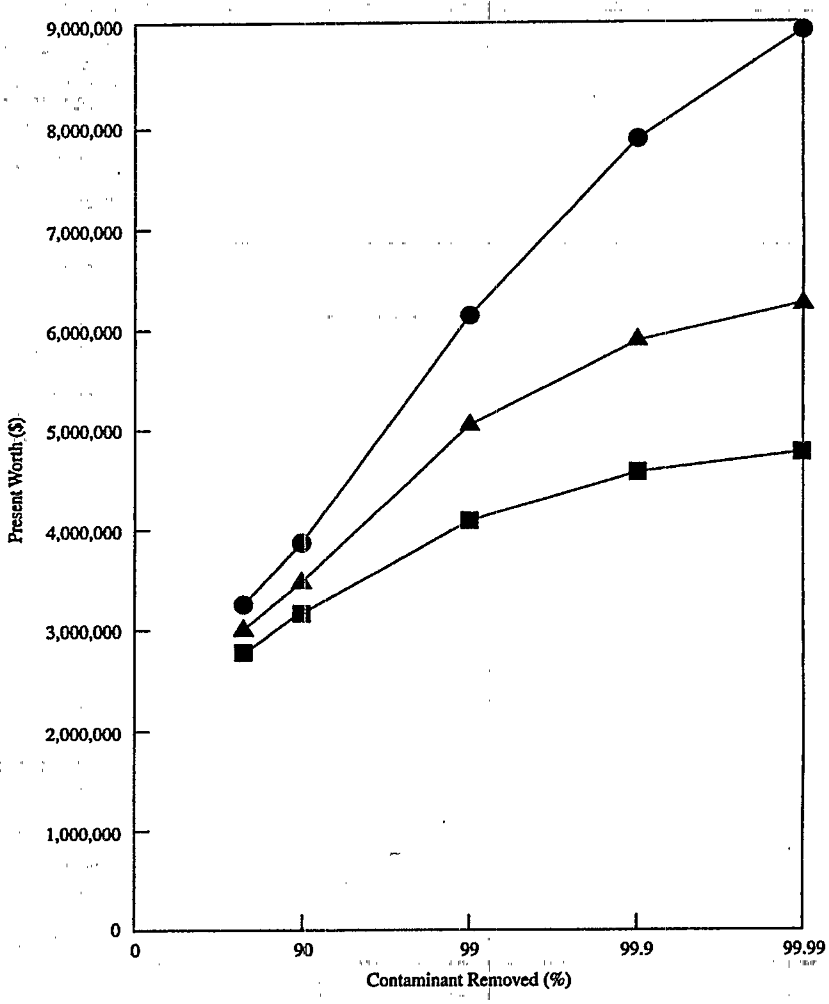
7.11 Design Validation

After the process and solution are selected based on laboratory studies, it is prudent to validate the effectiveness of the process in the field — on a smaller scale and under controlled conditions — prior to launching the full remediation program.

7.11.1 Push-Pull Test

The push-pull test is a simple injection and pumping sequence of groundwater spiked with solutes of interest (Drever and McKee 1980). Laboratory studies are usually conducted under ideal conditions, but can be useful in determining the relative effectiveness of the process and in planning the field

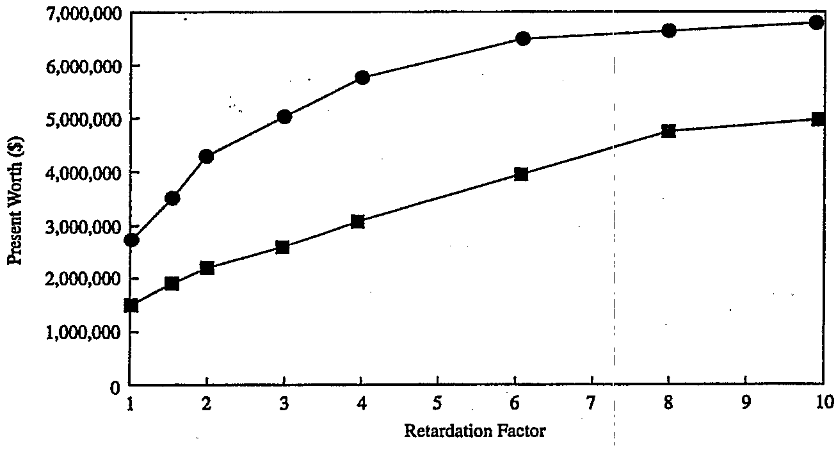
Figure 7.18
Present Worth as a Function of Percentage of Contaminant Removed on Three Discount-Rate Curves



- ● 2% discount rate
- ▲ 3.5% discount rate
- ■ 5% discount rate

Source: NRC 1994

Figure 7.19
Range of Costs in Present Worth for the Year 1994 Based on Two Contaminant Removal Retardation Factors of 99.9% and 90%



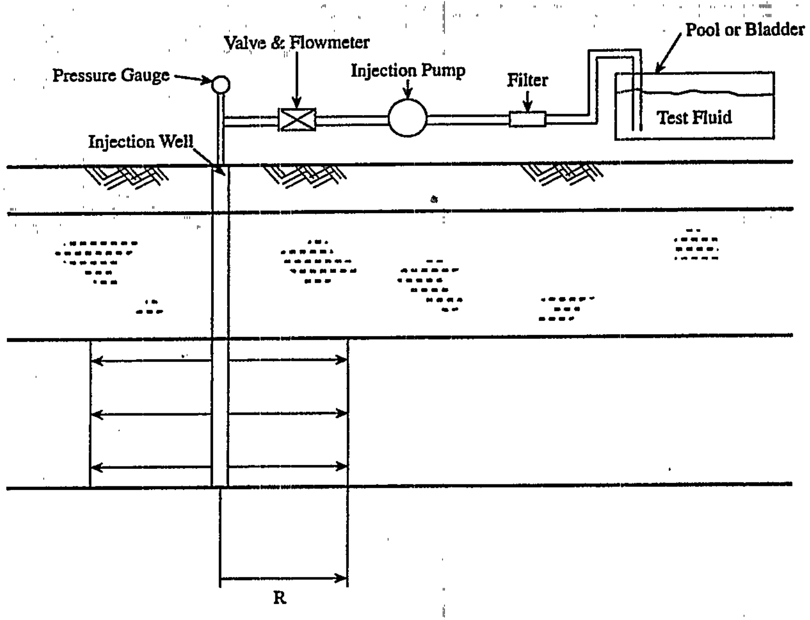
● 99.9% removal
■ 90% removal
Retardation Factor—The total quantity of a contaminant in a unit volume of aquifer relative to that dissolved in the groundwater.

Source: NRC 1994

experiment. Laboratory measurements are conducted on small samples and therefore may not be representative of the site. In addition, hydrogeologic conditions in the subsurface environment are very complicated and are difficult, if not impossible, to simulate in the laboratory. Push-pull tests are a logical step in validating laboratory results in the field.

Figure 7.20 shows a vertical cross-section of a push-pull test arrangement in the injection mode. Figure 7.21 provides a plan view of push-pull tests in an isotropic formation (Drever and McKee 1980). The test solution is injected into the formation and is allowed to reside for a few days. Next, a pump is lowered into the well to recover the solution, and the contaminant concentration is measured as a function of volume produced. Typically, 10 times the injection volume is recovered. The results are then analyzed to determine the effectiveness of the process and the retardation effect that can prolong the cleanup process.

Figure 7.20
A Vertical Cross-Section of a Push-Pull Test Scheme in the Injection Mode



The advantage of push-pull technology is that, with the proper design, up to 100 tonne (110 ton) of in situ soil can be tested, therefore, providing a larger test than can be normally obtained in a laboratory.

7.12 Permitting Requirements

The permitting requirements for using soil flushing processes (or any other technologies) to remediate a subsurface waste site depend on the following considerations:

- **Is the contaminant hazardous?**

  The US EPA will be involved in the permitting process if the contaminant is classified as hazardous waste.

- **Is the contaminant radioactive?**

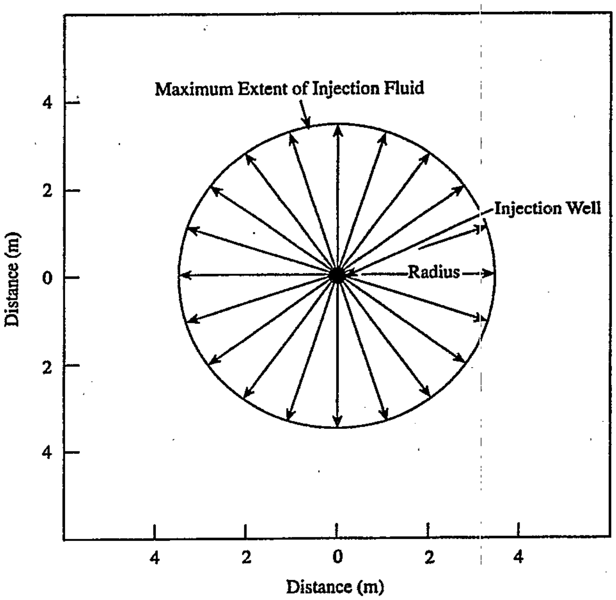
  The Nuclear Regulatory Commission will be involved in the permitting process if the contaminant is classified as radioactive waste.

- **Is the waste site located on federal land?**

  The owner of the federal land in question, e.g., the Bureau of Land Management, will be involved in the permitting process if the waste site is located on federal land.

Figure 7.21

Plan View of a Push-Pull Test in an Isotropic Formation



The state permitting authority will always be involved in any waste site remediation located in its jurisdiction. Table 7.8 shows the general guidelines for permitting requirements. Figure 7.22 provides a general flow chart for permitting requirements. The soil flushing project site manager should consult with the appropriate permit-granting authorities for each specific project.

In an effort to avoid dual permitting applications and to streamline permitting processes, US EPA has authorized some states ("approved state") to apply their state rules and regulations to the management of hazardous waste within the state, in lieu of the federal regulations.

Table 7.8
General Guidelines in Permitting Requirements

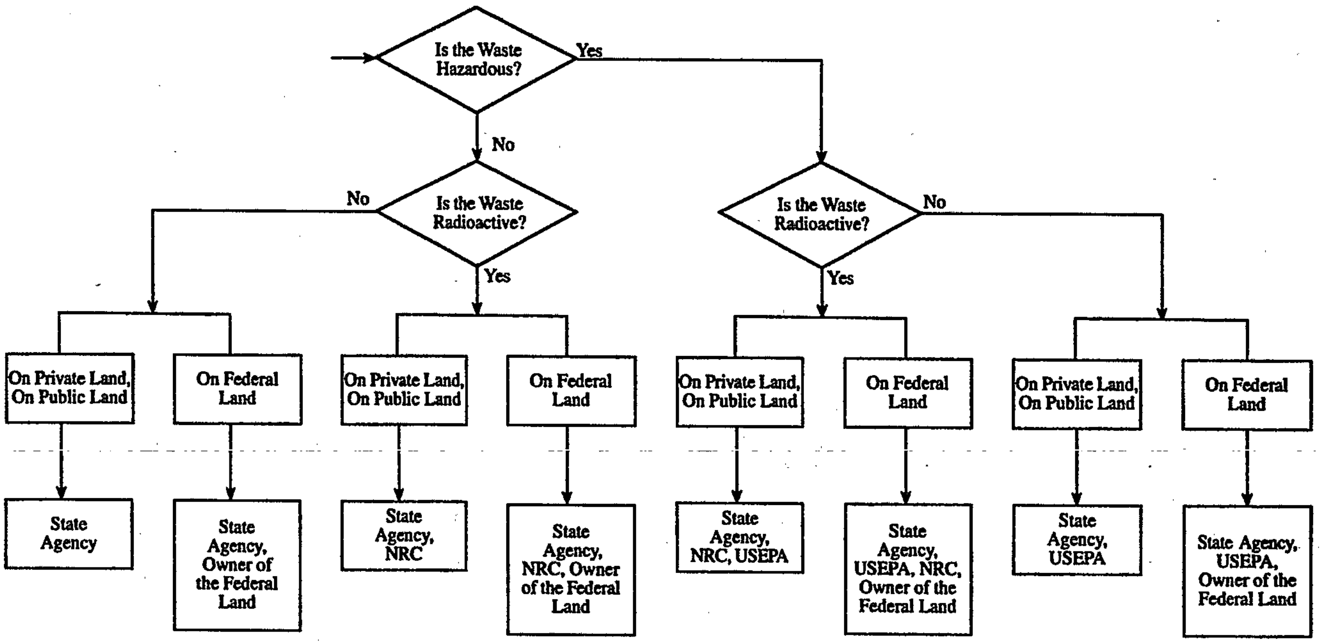
Agencies involved in permitting	Conditions: Is the contaminant hazardous? Yes	No	Is the contaminant radioactive? Yes	No	Is the waste site located on Federal land? Yes	No
State Agency	✓	✓	✓	✓	✓	✓
US EPA	✓					
NRC			✓			
Owner of the Federal Land					✓	

7.13 Performance Measures

The performance objectives are to control contamination plumes and to achieve cleanup goals within prescribed time frames, while protecting public health and environmental standards. Performance measures include:

- **Operational Performance Measures:**
  - well flow rates,
  - system throughput,

Figure 7.22
General Flow Chart for Permitting Requirements



- system downtime,
- operation schedule/milestones, and
- Quality Assurance/Quality Control (QA/QC).

- **Hydrodynamic Performance Measures:**
  - plume control, and
  - modeling conformance.
- **Water Treatment Performance Measures:**
  - rate of reduction of contaminant concentration,
  - contaminant removal efficiency, and
  - waste disposal.
- **Cost Performance Measures:**
  - capital costs, and
  - operating costs.
- **Safety Performance Measures:**
  - safety records.

7.14 Design Checklist

The following is a design checklist for a soil flushing project.

1. **Geology**
   - Well logs
   - Geologic cross-sections
   - Recharge areas
   - Discharge areas
2. **Hydrology**
   - Hydraulic conductivities
   - Transmissivity
   - Storage coefficients

- Leakage between aquifers
- Water levels
- Well survey records
- Baseline water quality

3. **Geochemistry**
   - Adsorption characteristics
   - Biodegradation characteristics
4. **Contaminant**
   - Type of contaminant
   - Contamination source
   - Amount of contaminant
   - Size and boundary of contamination
5. **Wellfield**
   - Well location
   - Well size, depth, screen intervals, and material
   - Well production rate
   - Well injection rate, injection pressure
   - Well completion and well integrity
6. **Computer Modeling**
   - Model verification
   - Hydraulic modeling of site
7. **Flushing Solution**
   - Concentration
   - pH
8. **Water Treatment Plant**
   - Throughput
   - Process-flow diagram
   - Amount of solid waste generated

8

IMPLEMENTATION AND OPERATION

8.1 Implementation

8.1.1 Site Characterization

Before beginning a soil flushing project, background information about the site should be reviewed with particular emphasis on the geology, hydrology, and nature of contamination. The field implementation program starts with test-well drilling. Many factors must be evaluated when choosing well locations, well-completion techniques, and sampling and aquifer testing programs. These factors generally include:

- The material of the well casing — will it react with groundwater or contaminated groundwater?
- Cement or other material used in the well completion — will these materials introduce contaminants to the groundwater?
- Well completion techniques — will they promote inter-flow between aquifers?
- Drilling fluid — will it contaminate the groundwater?
- Well screen intervals — will they be able to isolate the contaminated zone?
- Well size — will it be large enough for setting the pump, bailer, or other sampling devices?

A study to assess the present contamination should identify the following parameters:

- kind of contaminant,
- contamination source,
- amount of contamination,
- size and boundary (three-dimensional) of the contamination, and
- environmental impact of the contamination.

Figure 8.1 shows the sequence of information acquisition. In addition to the information on the contaminants of interest, the site-specific geology and hydrology should be defined.

8.1.2 Wellfield Design

The wellfield patterns discussed in Section 7.2.2 are used when the contaminated area extends in all directions over a large area. Formation geology, hydrology, and characteristics of chemicals of concern should be considered in selecting one of the standard patterns . Because of the anisotropy, heterogeneity, and spatial variation of formations, computer models are used to optimize the wellfield design. A computer model, called "Tracer™" (developed by C.R. McKee) was used to study the effectiveness of wellfield designs for in situ uranium operations. This model illustrates the importance of wellfield design in effective mineral recovery, and, therefore, the associated contaminant cleanup (soil flushing) scenarios. The same concept and principles can be applied to a number of DOE sites and sites with uranium contamination.

The importance and effect of wellfield design is amplified by three summaries of uranium extraction which are presented on the following pages.

Figure 8.1
Information Acquisition Sequence

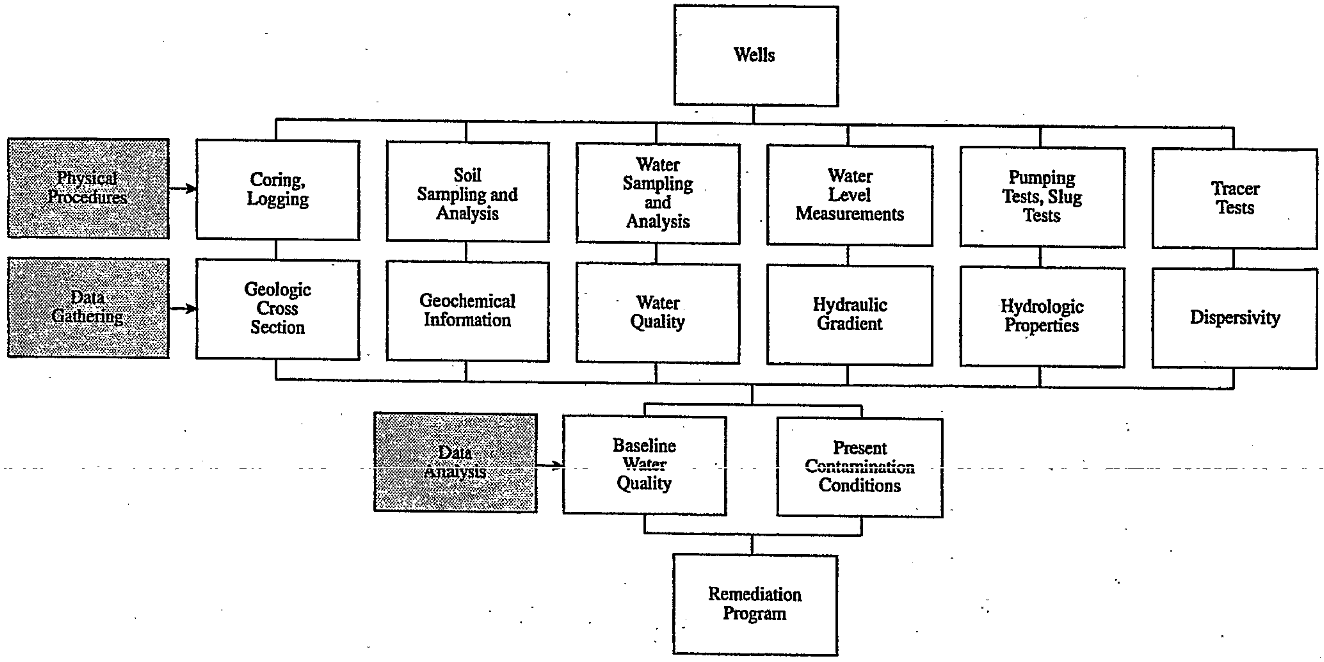
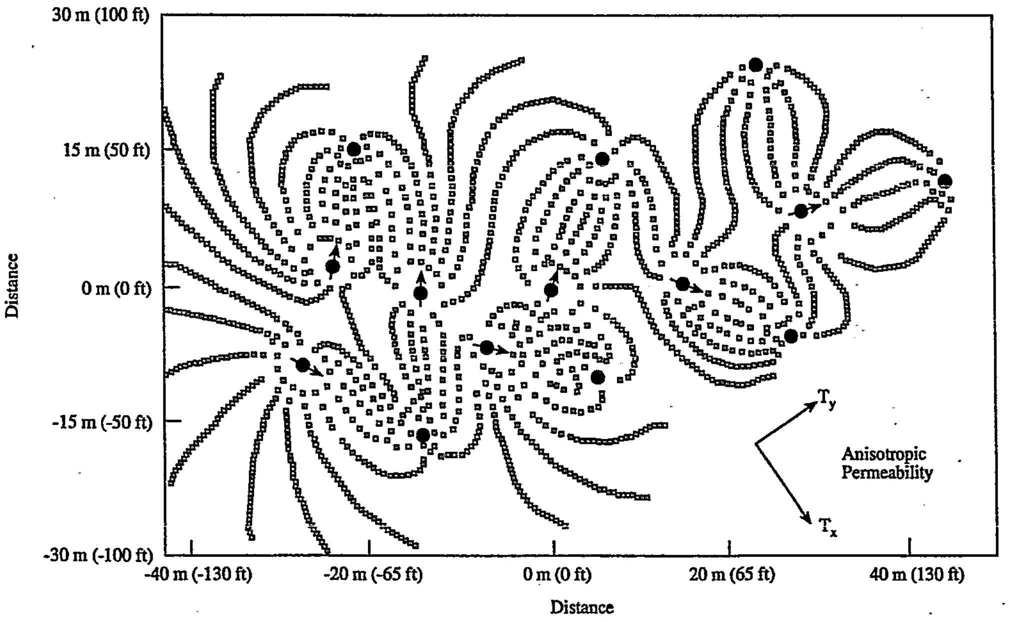


Figure 8.2
Fourteen-Well Production Match, Bruni, Texas

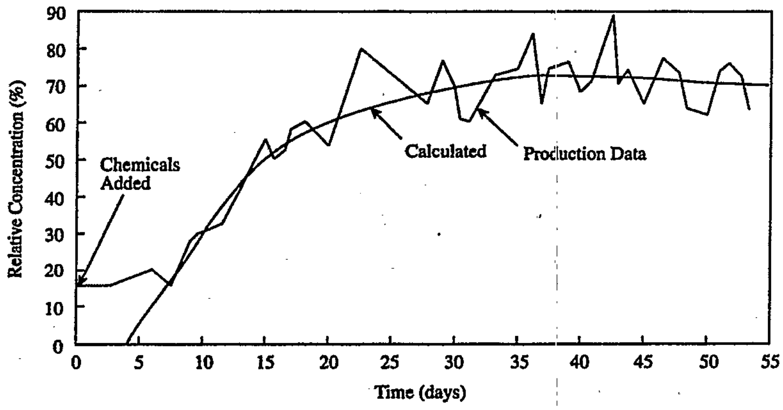


●➤ Injection
● Production
Tracers plotted at 1-day intervals; Total Time: 56 days; North is at top of figure.

8.1.2.1 Bruni, Texas

This is one of the oldest in situ uranium mining operations. The wellfield consisted of seven injection wells and seven recovery wells. The wellfield was designed based on speculation rather than engineering considerations. Figure 8.2 shows the fluid migration path and history. A number of hypothetical particles, or tracers, were placed at the circumference of injection wells and released at the moment when the leach solution was supplied to the injection wells. The tracers moved along streamlines and were plotted at one-day intervals. The resulting plot shows the path followed by the leach solution in a given direction. A high density of paths indicates slow fluid velocity. It was not a good design. Figure 8.3 is a time plot of actual uranium production and computer match generated by the "Tracer™" computer program. The relative concentration of uranium products was plotted to preserve the confidentiality of the project. The actual uranium concentration produced was low, and the production time was long. The large amount of lixiviant (the chemical solution used to mobilize uranium) leakage to the northwest, west, and southwest side of the wellfield contributed to the poor recovery of uranium in this wellfield operation.

Figure 8.3
Production Match to Fourteen-Well Pattern, Bruni, Texas

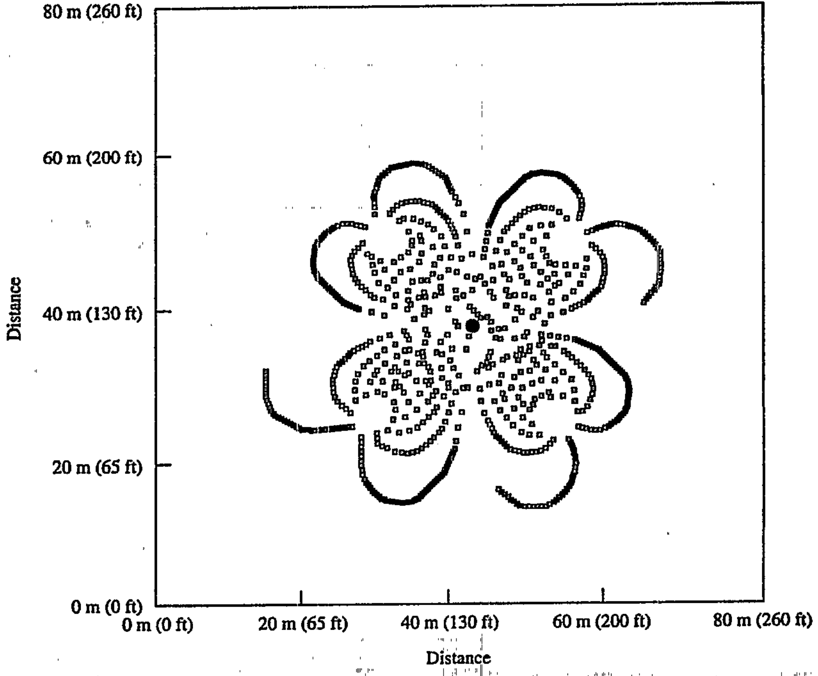


Assumes that 10 streamline pore volumes are required to leach uranium.

8.1.2.2 Irrigary, Wyoming

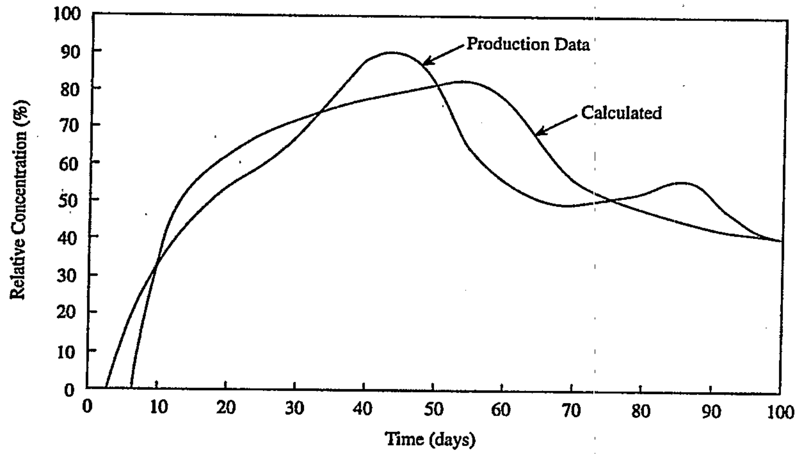
The isolated five-spot pattern (four injection wells and one production well) is a very popular design for in situ uranium pilot operations, especially in formations where well injection capability is limited. A computer model projected the flow paths that the lixiviant followed as it moved through the aquifer (see Figure 8.4). Figure 8.5 shows the computer match of the production curve.

Figure 8.4
Five-Spot Production Match, Irrigary, Wyoming



●➤ Injection
● Production
Tracers plotted at 1-day intervals; Total Time: 100 days; North is at top of figure.

Figure 8.5
Production Match to Five-Spot Well Pattern, Irrigary, Wyoming

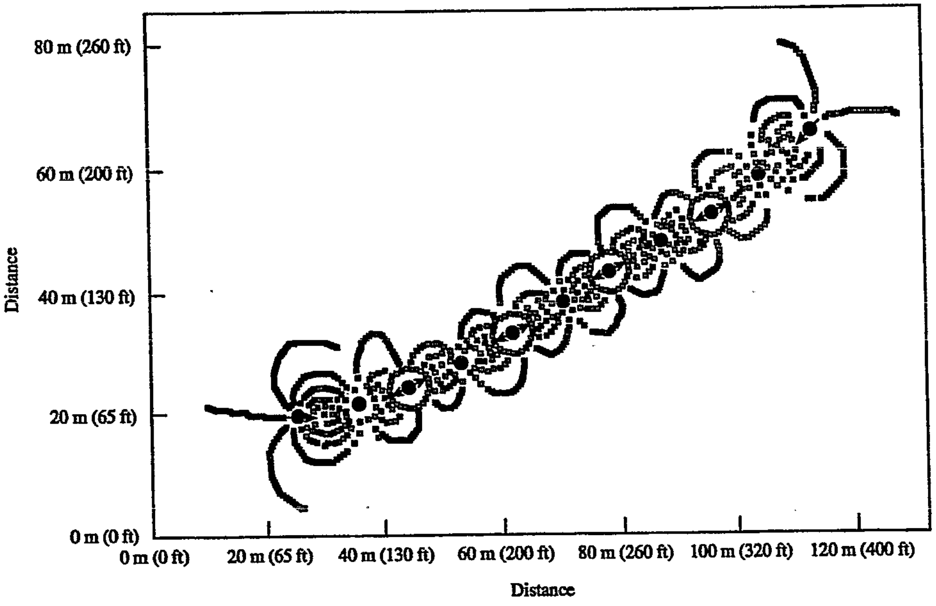


Assumes that 8 streamline pore volumes are required to leach uranium.

8.1.2.3 Zamzow, Texas

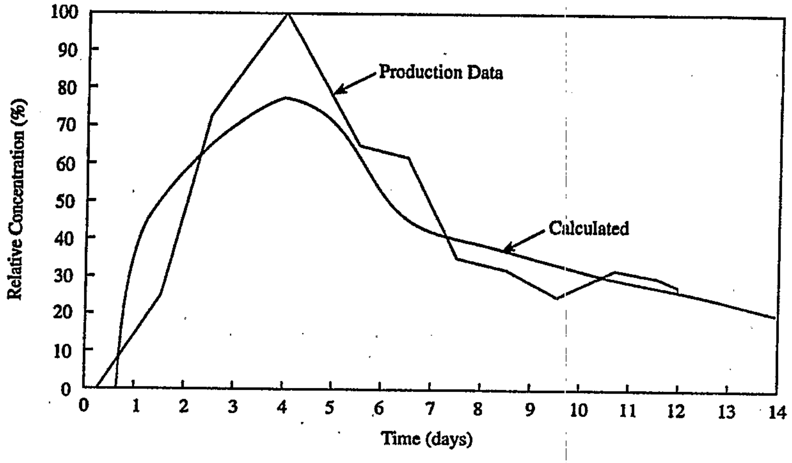
This project employed an uncommon design dictated by the unusual configuration of the project's physical layout — the high-grade uranium was deposited in a long and narrow strip (See Figure 8.6). Under these conditions, conventional wellfield design would not work very well. The wellfield was designed to accommodate the deposit with the help of a computer model. The production curve reflected the effectiveness of the operation — high uranium concentration and short operation duration (see Figure 8.7).

Figure 8.6
Eleven-Well Production Match, Zamzow, Texas



●➤ Injection
● Production
Tracers plotted at 0.1-day intervals; Total Time: 15 days; North is at top of figure.

Figure 8.7
Production Match to Eleven-Well Pattern, Zamzow, Texas



Assumes that 6 streamline pore volumes are required to leach uranium.

8.2 Start-up Procedures

8.2.1 Baseline Water Quality

To define the degree of contamination, the baseline water quality in the formation of concern must be established. Baseline information is obtained by determining water quality in the affected aquifer either:

- prior to suspected contamination events; or
- outside of the contaminated region once contamination has occurred.

The information is most useful if it has been collected over an extended period of time during different seasons of the year. This enables the user to properly assess monitoring data in light of temporal fluctuations in water quality.

It is important that all information in the baseline study be obtained through proper procedures for the sampling, handling, storage, and analysis of aquifer waters. The sampling program should continue throughout the remediation program.

8.2.2 Equipment Shakedown and Calibration

To minimize unforeseen problems, all equipment must be calibrated and subjected to performance shakedown before the start of the remediation. Power supplies, flow lines, valves, gauges, meters, lighting, data loggers, computers, sampling devices, and other equipment should be tested.

8.3 Operations Practices

8.3.1 Pilot Tests

Pilot tests usually involve a small number of injection wells and recovery wells. The most popular wellfield patterns are single two-spot, single three-spot, or single five-spot patterns (see Section 7.3). A small-scale water treatment plant, usually with a flow rate of less than 400 L/min (100 gal/min), is part of the pilot test.

Selected coring/soil samples in the test area are pilot tested to validate the remediation process. The pilot test will evaluate:

- the effectiveness of the process to remove the contaminant from the subsurface environment;
- the ability of the water treatment plant to recover contaminant from the pumped solution;
- the consumption rate of chemicals/surfactants in the soil flushing process;
- the operation of testing equipment; and
- the spacing between wells.

Once the results of the pilot tests are compiled, the data may be applied to the complete remediation site. Between the injection wells, recovery wells, and the cored soil samples, sufficient data will be available to implement the remediation.

8.3.2 Traverse City, Michigan Pilot Test

A surfactant pilot field test was conducted at the U.S. Coast Guard facility in Traverse City, Michigan, during June 1995. The contaminants had undergone a decade of bioremediation, with moderate levels of tetrachloroethylene (PCE) and aviation fuel contamination remaining, specifically, up to 1,000 μg/kg (ppb) and 1,000 mg/kg (ppm), respectively. PCE concentrations less than 10 μg/kg (ppb) were common in the groundwater. The surfactant test occurred in a highly permeable sand formation, with natural groundwater velocities of 0.91 to 1.52 m/day (3 to 5 ft/day) and minor drawdowns realized at pumping rates exceeding 56 L/min (15 gal/min).

The primary objectives of the test were to maximize surfactant recovery and evaluate the vertical circulation well (VCW) system. A secondary objective was to enhance contaminant removal; this was a secondary objective because prior remediation activities had minimized contaminant concentrations. Laboratory, batch, and column studies were conducted to evaluate the interactions of surfactant, contaminant, media, and groundwater. Modeling studies were used to design the field-scale implementation of the VCW system. Preliminary tracer studies were conducted to verify the proper installation of the VCW and characterize system hydraulics. The design was based on 95% recovery of the surfactant, with the actual recovery exceeding this value. The hydraulics of the VCW system were less than optimal in this highly conductive formation because an extraction rate of 10 to 15 times the injection rate was necessary to achieve >95% surfactant recovery.

The surfactant (Dowfax 8390) was injected at 10 times the critical micelle concentration to promote solubilization. A total of 2,043 L (540 gal) of (3.8% by weight) Dowfax 8390 was injected during the course of the study. Surfactant-enhanced solubilization increased the mass of contaminant extracted by a factor of five to seven versus water alone for PCE and methylated alkanes; this was especially encouraging, given the relatively low levels of contaminant present (Knox et al. 1995).

8.4 Operations Monitoring

8.4.1 Scope

Environmental monitoring is typically the subject of negotiations between responsible parties and agencies, based on statutes and regulations. There are two basic approaches to examining and selecting what to monitor. These are:

- monitoring for all substances relevant to the waste type; or
- applying key indicators that give early warning of leakage.

For example, Plumb (1991) studied 500 contaminated sites and concluded that VOCs are the most significant contaminants in groundwater associated with disposal sites. Rather than conduct a complete water-quality analysis for all organic contaminants, which can cost up to thousands of dollars, Plumb suggested that analyzing samples for only VOCs alone can successfully provide an early-warning of excursions that then justify more extensive laboratory analysis. The key indicators for VOCs are listed in Table 8.1. Such an approach can save both time and money.

Some other key indicators advocated for detecting water-quality problems associated with particular contaminants are:

- VOCs for organic priority pollutants;
- pH for acid mine waters;
- specific conductivity for inorganic contamination;
- total hydrocarbon content for petroleum in soil;
- total nitrogen and phosphates for agricultural contamination;
- total organic halogen (TOX) for pesticides;
- total organic carbon (TOC) for general organic substances; and
- flame ionization detection (FID) or photo ionization detection (PID) responses of soil vapor for volatile organic components (Murphy 1991).

Table 8.1
Key Indicators for Volatile Organic Compounds

VOC	H (V ppm/W ppm)
Methylene Chloride	29.2
Trichloroethene	88.8
Tetrachloroethylene	161.8
Trans-1,2-Dichloroethene	57.4
Chloroform	33.9
1,1-Dichloroethane	59.2
1,1-Trichloroethane	252.9
1,1,1-Trichloroethane	206
Toluene	69.0
1,2-Dichloroethene	11.9

$H = C_v / C_w$
where: C_v = VOC concentration (mg/L) in vapor above water level; and
C_w = VOC concentration in water.

8.4.2 Procedures

Environmental site monitoring usually requires taking samples by pumping water from wells and analyzing them in a laboratory. The time between sampling and receipt of the analysis results can be weeks. It is difficult to make a real time decision regarding an excursion from a site. In addition, most of the samples taken at sites throughout the United States do not show any contamination. Monitoring is expensive; it includes sampling equipment, containers, labor, transportation, and a per-parameter charge for each test the laboratory conducts. Therefore, if this monitoring cannot provide timely data for operations, it wastes limited resources.

This situation has generated substantial interest in rapid, real-time, cost-effective field analysis and in situ monitoring methods. Field screening of soils and water samples for appropriate indicator parameters can be used to indicate the presence of contamination. Such methods offer the promise of better decisions as to whether or not to collect a sample, where to collect a sample for laboratory analysis, and how to define the boundaries of contamination. Two key objectives in developing field screening and remote environmental analysis technologies are identifying a substance of interest and providing necessary quantitative information about the substance within the site. Field determination of what to do with the sampling and monitoring program is called field screening.

Advanced command-and-control systems that use sophisticated communications technology will be used extensively in the future (see Figure 8.8). These systems can also include computer programs providing for automatic notification of regulatory agencies and key site personnel, or trigger alarms to address various situations that may arise (McKee, Schabron, and Way 1995).

In addition to the ring of monitoring wells depicted in Figure 8.8, the in situ uranium mining industry uses an inner ring of trend wells for early detection. In the event of contaminant migration, the inner ring monitoring provides advance warning enabling corrective action before contamination migrates beyond the outermost boundary.

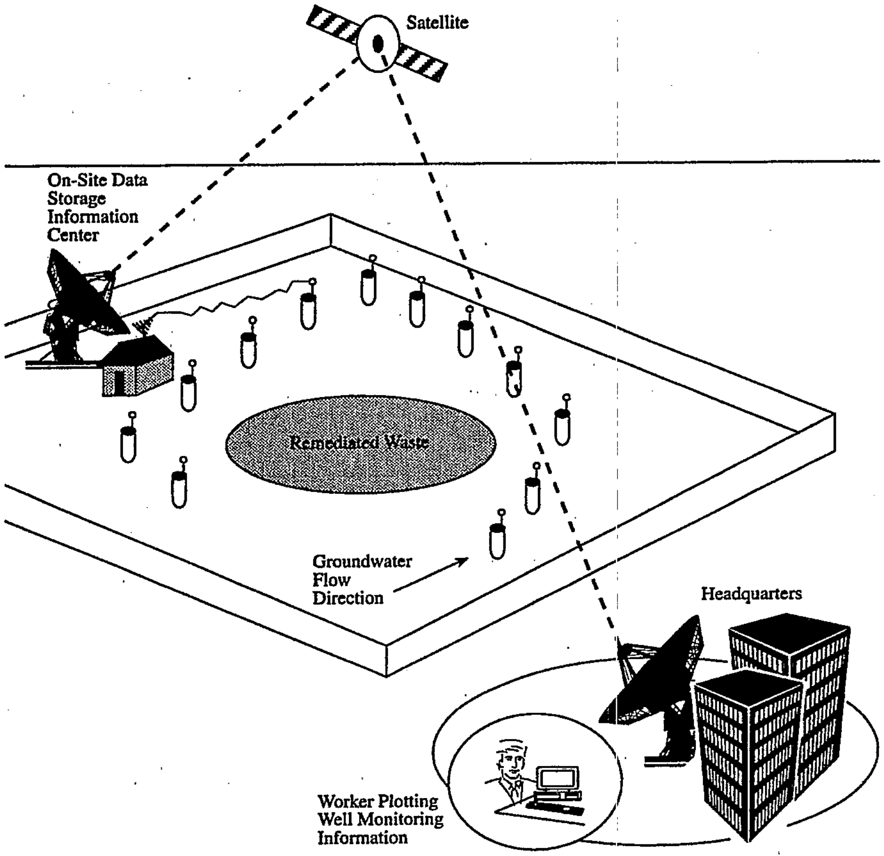
8.5 Quality Assurance/Quality Control

A QA/QC program is essential when soil flushing is used. The program should address several major areas, including the following considerations:

- *Responsibility.* Quality assurance involves the entire organization, from top management to the individuals participating in every phase of work.
- *Training and Certification.* Proper training and certification of individuals will ensure that soil flushing data is collected and interpreted correctly.
- *Documentation.* Standards and procedures for collecting and interpreting data must be developed and documented.
- *Instrument Calibration.* Establishing instrument calibration standards and procedures is important, especially for comparing data collected at different times, under different environments, and with different instruments.

Table 8.2 identifies several specific items that should be included in a soil flushing QA/QC program.

Figure 8.8
Multi-Aquifer Monitoring



Monitoring wells at the remediated waste site are in communication with personnel responsible for the site via communication links.

Table 8.2
Features of a QA/QC Program for a Soil Flushing Project

Item	QA/QC Program
Hydrologic measurements	Measure to certain accuracies
Sample collection	Ensure representative samples, not biased samples
Sample preservation	Preserve samples in the field as soon as possible after collection
Sample storage/transport	Minimize the chemical alteration of samples prior to analysis/chain of custody
Verification of sampling methods and analytical procedures	Use field blanks/standards/duplicate samples
Chemical/surfactant/contaminant concentrations	Measure to certain accuracies/mass balance

9

CASE HISTORIES

This chapter presents seven soil flushing cases.

- A ground water clean-up project conducted in the United Chrome Products site in Corvallis, Oregon. Chromium was recovered from a contaminated aquifer using a network of extraction/pumping wells, two infiltration basins and one infiltration trench.
- A pilot study using surfactant to recovery polychlorinated biphenyls (PCBs) and oils from contaminated soil.
- A laboratory column study conducted to investigate the potential of using soil flushing for the remediation of sandy loam contaminated with either lead, lead sulfate, lead carbonate or lead and naphthalene.
- A field pilot test at the Borden Canadian Forces Base near Alliston, Canada. Surfactant-enhanced, pump-and-treat remediation of aquifers contaminated with tetrachloroethylene (PCE), a dense-non-aqueous-phase liquid (DNAPL) was evaluated.
- A remediation project at the Fairchild Semiconductor Corporation in San Jose, California. Pump-and-treat soil flushing was employed to recover organic contaminants (xylene, acetone and 1,1,1-trichloroethane).
- The current groundwater clean-up program at the Savannah River Hazardous Waste Management Facility. Enhanced recovery techniques were used to remove were 1,1,2-trichloroethylene (TCE), tetrachloroethylene (PCE) and 1,1,-trichloroethane (TCA).
- A remediation project at an IBM facility in Dayton, Ohio. Pump-and-treat technologies were used to remove 1,1,1-trichloroethane (TCA) and tetrachloroethylene (PCE) from the aquifer.

Case 1 — Groundwater Remediation at the United Chrome Superfund Site

The United Chrome Products Site is a former industrial hard-chrome electroplating shop located in Corvallis, Oregon. Leaking plating tanks and the discharge of rinse water into a disposal pit during the shop's operation between 1956 and 1985 caused the contamination of soil and groundwater underlying the facility. Soil contamination greater than 60,000 mg/kg chromium, and groundwater contamination exceeding 19,000 mg/L chromium were measured adjacent to the plating tanks. The US EPA placed the site on the National Priorities List in 1984. In 1985, US EPA began remediation activities that have continued to the present time. These include the construction of two infiltration basins to flush contaminated soils, a 23-well groundwater extraction network in low permeability soils, an injection and groundwater extraction network in a deep gravel aquifer, and on-site treatment of concentrated chromium wastewaters (McPhillips et al. 1991). Table 9.1 shows the subsurface and contamination conditions at the site.

Table 9.1
United Chrome Site Subsurface and Contaminant Conditions

Geologic Unit	Description	Contamination	Cleanup Goal
Upper zone	5.5 m (18 ft) of coarse to fine silt.	High concentration of chromium (III) in soil, low solubility in groundwater. High concentration of chromium (VI) in soil and in groundwater (as high as 19,000 mg/L).	10 mg/L chromium
Upper aquitard	0.6 to 3 m (2 to 10 ft) thick of stiff, dark, grey clay.	High concentration of chromium (III) in aquitard soil.	
Deep aquifer	4.6 to 7.6 m (15 to 25 ft) thick of interbedded silty sand and sandy gravel layers.	Chromium (VI) was detected as high as 8 mg/L in groundwater.	0.05 mg/L chromium
Lower aquifer	At least 12 m (40 ft) of plastic clay.		

Beginning in December 1987, the US EPA implemented a two-stage remediation plan. The first stage was directed toward cleanup of the facilities, surface water, soils, and the upper-zone groundwater with the objective of protecting the deep aquifer from further contamination. The first-stage groundwater cleanup included:

- Decontamination (high-pressure spray wash) and demolition of the United Chrome building.
- Excavation and offsite disposal of about 1,000 tonne (1,102 ton) of heavily contaminated soil (from the disposal pit and plating tank areas) and contaminated disposal debris.
- Installation of 23 groundwater extraction wells and 12 monitoring wells in the upper zone.
- Construction of two infiltration basins over the disposal pit and plating tank areas with infiltration rates averaging 28,760 L/day (7,600 gal/day) in Basin No. 1 and 11,350 L/day (3,000 gal/day) in Basin No. 2 during dry summer months. During the winter months, infiltration rates decreased by 50% or more compared to the summer months.
- Construction of an infiltration trench down the axis of the upper-zone plume with infiltration rates averaging 9,460 L/day (2,500 gal/day).
- Construction of a water treatment facility, including the installation of a chemical reduction and precipitation and clarification treatment system for chromium removal.
- Rerouting of the local drainage ditch to bypass the site.

Table 9.2 provides a summary of performance data for August 1988 through December 1990 (Stage 1).

Table 9.2
Summary of Performance Data

UNITED CHROME PRODUCTS SUPERFUND SITE
Extraction and Treatment System Summary
August 1988 through December 1990

Parameter	Total	Average Daily
Groundwater Extracted	25,360,000 L (6,700,000 gal)	43,100 L (11,400 gal)
Influent Cr(VI) Concentration Range	1,923 mg/L to 146 mg/L	
Mass of Cr(VI) Removed	11,045 kg (24,300 lb)	18.7 kg (41 lb)
Infiltration Recharge	17,800,000 L (4,700,000 gal)	30,000 L (8,000 gal)
Average Effluent Cr(VI) Concentration		1.7 mg/L (monthly)
Sludge Produced (25% solids)	172 m^3 (6,070 ft^3)	0.28 m^3 (10 ft^3)

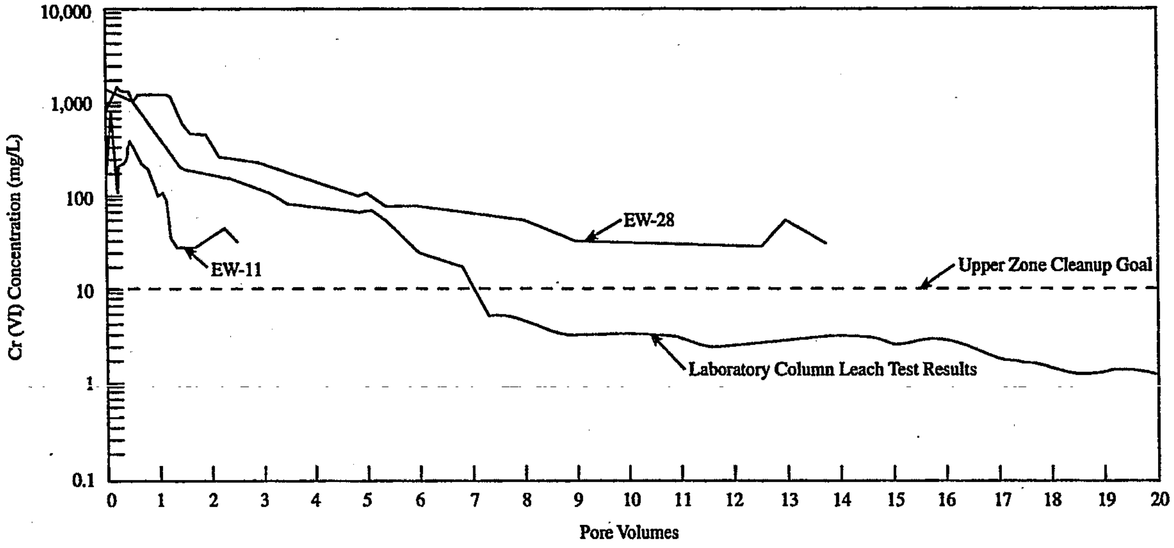
Figure 9.1 provides curves of concentration versus pore volume extraction for three different areas at the site. The two curves shown for Wells EW-11 and EW-28 (both wells in the upper zone) represent actual field conditions, whereas the third curve was generated in a laboratory column leaching test using contaminated solid collected on-site with a core sampler. The curves are generally similar in shape.

It was concluded that, "Infiltration basins have been found to be effective for delivering large amounts of flushing and recharge water to near-surface contaminated soils, whereas infiltration trenches may be more effective for delivering recharge water to deeper contaminated soils. Either structure can result in accelerated soil and groundwater cleanup in the areas around them" (McPhillips et al. 1991).

The second stage of the remedial action was directed at cleaning the deep aquifer. This work resulted in the installation of seven deep aquifer extraction wells and two irrigation wells.

Figure 9.1

Concentration vs. Pore Volume Extraction Curves



Case 2 — In Situ Surfactant Flushing of PCBs and Oils Pilot Test

A field test of the surfactant flushing method at a site contaminated with polychlorinated biphenyls (PCBs) and oils was performed by Abdul et al. in 1992.

The site was used to store unused machinery. Widespread soil contamination with PCBs and oils was confined to the fill material and was thought to be the result of leaking machinery and from contaminated fill. To contain the contaminants within the fill zone, a containment wall made of a mixture of clay and cement was installed around the site.

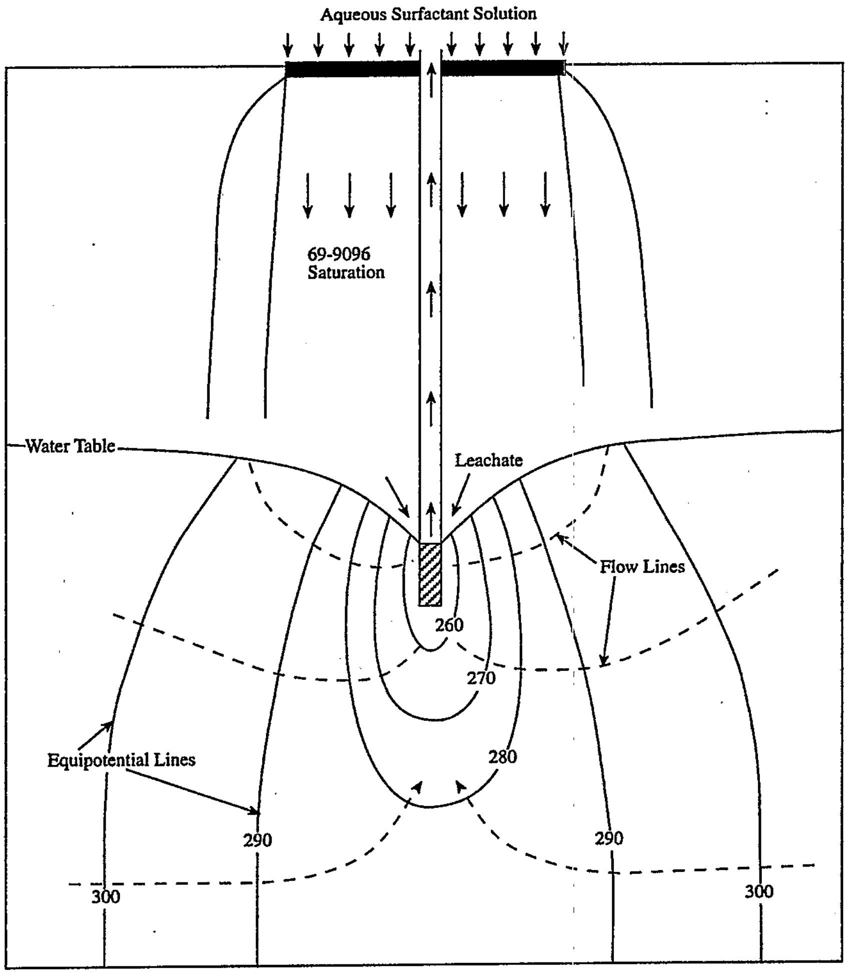
A test plot, 3.05 m (10 ft) in diameter by 1.52 m (5 ft) deep, was selected in an area of high levels of contamination. The study involved applying a surfactant solution on the test plot to wash the site material and carry the leachate down to the depressed water table, where it was collected by pumping a recovery well installed through the center of the plot. The leachate pumped to the surface was biologically treated to degrade the oils and surfactant, and the PCBs were removed from the leachate by an activated carbon system.

The upper 4.0 to 4.6 m (13 to 15 ft) of the 20,000 m^2 (5 acre) site contained fill material. The fill material resides over a layer of fine-grained alluvium, which varies in thickness from a few centimeters to several meters. Below the alluvium, an extensive layer of sandy glacial outwash extends to a depth of about 18 m (60 ft), below which is a thick layer of clay. Soil cores from the test plot indicated concentrations of up to 6,223 mg/kg PCBs and 67,000 mg/kg oils. The test plot initially contained about 15 kg (33.1 lb) of PCBs and 157 kg (346.1 lb) of oils.

Figure 9.2 shows an example of a mathematical simulation of surfactant washing of the test plot.

The surfactant washing program consisted of two phases. Phase 1 consists of a 70-day surfactant flush followed with a 30-day water flush. Phase 2 consisted of a 90-day surfactant flush and a 24-day water flush followed with laboratory soil column test. Table 9.3 presents the results of the program.

Figure 9.2
An Example of Mathematical Simulation of Surfactant Washing of the Test Plot



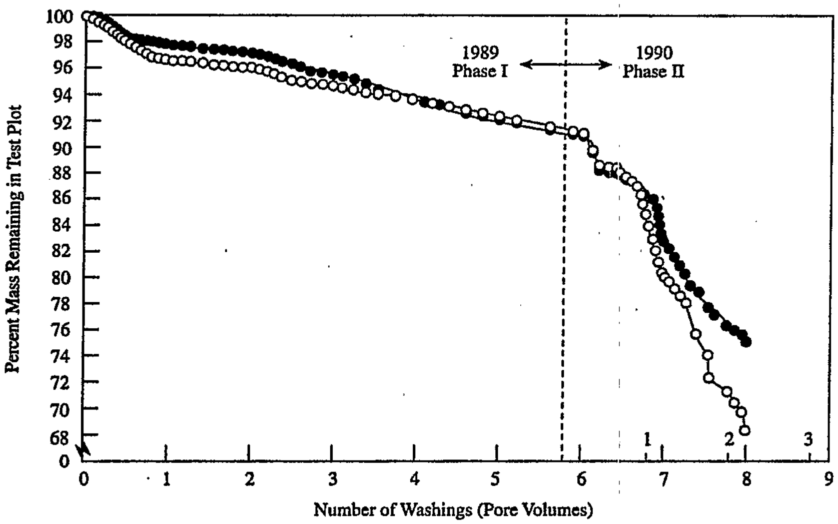
Reprinted from Abdul et al., "In Situ Surfactant Washing of Polychlorinated Biphenyls and Oils from a Contaminated Site," *Ground Water*, Volume 30, Number 2, March-April 1992, p 223, with permission of Ground Water Publishing Company.

Table 9.3
Surfactant Washing Program

	Time Elapsed	Average Surfactant Injection Rate	Average Recovery Rate	Cumulative Total Contaminant Recovered		Cumulative Number of Washings (pore volumes)	Cumulative % of Recovery	
				PCB	Oil		PCB	Oil
Phase I	70 days (July to October, 1989) plus 30 days rising with water	291 L/day (77 gal/day)	594 L/day (157 gal/day)	1.6 kg (3.5 lb)	17.0 kg (37.4 lb)	5.7	10%	10%
Phase II	90 days (June to September, 1990) plus 24 days rising with water	92 L/day (24.3 gal/day)	NA	4.1 kg (9.0 lb)	59.4 kg (130.7 lb)	8.0	25%	32%
	Laboratory soil column test	NA	NA	NA	NA	105.0	85%	90%

Figure 9.3 shows mass percent of PCBs and oils remaining in the test plot after the Phase 1 and Phase 2 flushings. Figure 9.4 provides a plot of the percent of PCBs and oil remaining in the laboratory column soil as a function of pore volume flushings.

Figure 9.3
Mass Percent of PCBs and Oils Remaining in the Test Plot After Phase I and Phase II Washings



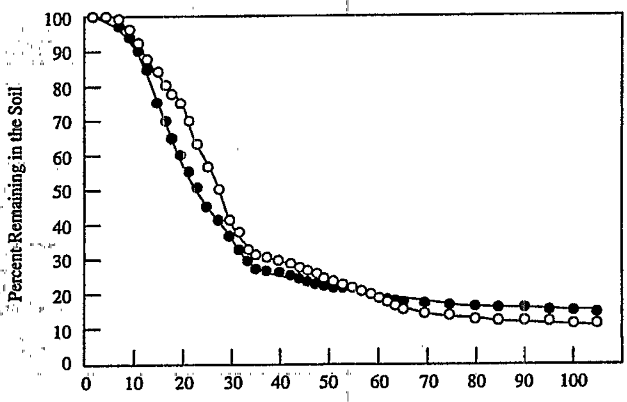
● PCB
○ Oil

Reprinted from Abdul and Ang, "Surfactant Washing of Polychlorinated Biphenyls and Oils from a Contaminated Field Site: Phase II Pilot Study," *Ground Water*, Volume 32, Number 5, September-October 1994, p 731, with permission of Ground Water Publishing Company.

It was concluded that, "the in situ surfactant washing process is a viable remediation technology for hydrophobic contaminants" (Abdul and Ang 1994).

Figure 9.4

Laboratory Column Study of Surfactant Washing of PCB-Contaminated Soil



● PCB
○ Oil

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Case 3 — Column Study of Soil Flushing of a Lead-Contaminated Sandy Loam

Several column tests were performed by Reed, Carriere, and Moore (1994) and Reed, Moore, and Cline (1995) to investigate the use of soil flushing for the remediation of a sandy loam contaminated with either lead (Pb[II]), lead sulfate ($PbSO_4$[s]), lead carbonate ($PbSO_3$[s]), or lead (Pb) and naphthalene. Lead was chosen as the study metal because of its widespread existence at Superfund sites. Over 60% of the National Priority List sites that have signed Records of Decision have heavy metal contamination.

$PbSO_4$(s)(anglesite) is a common form of lead contamination at hazardous waste sites, especially at battery crushing and recycling facilities. $PbCO_3$(s) is expected to form in soils with a high carbonate concentration. Naphthalene was used to simulate the fate of lead in the presence of a polycyclic aromatic hydrocarbon (PAH). The following extractants were investigated: Hydrochloric Acid (HCl), Nitric Acid (HNO_3), Ethylenediaminetetraacetic Acid (EDTA), acetic acid (CH_3COOH), and Calcium Chloride ($CaCl_2$). Batch soil washes and soil column flushing experiments were conducted using a sandy loam (pH = 5.5, CEC = 7.6 meq/100 g, $K_H = 2.5 \cdot 10^{-3}$ cm/sec) from Erie County, New York.

Batch soil washes were conducted using several concentrations of HCl, HNO_3, EDTA, acetic acid, and $CaCl_2$. Based on batch soil washing results, 0.1 N HCl, 0.01 M EDTA, and 1.0 M $CaCl_2$ were selected as soil flushing solutions. HCl was chosen to represent a strong acid, EDTA was chosen to represent a chelating agent, and $CaCl_2$ was chosen to represent removal using an exchange solution. Following soil contamination and placement in the column, flushing solutions were applied continuously at a constant rate for approximately 5 to 8 pore volumes. Table 9.4 summarizes the percentage recovery of lead in the column tests and the number of pore volumes required to achieve a significant amount of a final recovery (Reed, Carriere, and Moore 1994; Reed, Moore, and Cline 1995).

Table 9.4
Results of Column Leaching Tests

Flushing Solution	Pb	$PbSO_4$	$PbCO_3$	Pb-Naphthalene
Tap water	no data	0.5% (58 pv)	3% (10 pv)	10% (58 pv)
0.1 HCl	85% (5 pv)	32% (58 pv)	97% (20 pv)	78% (5 pv)
0.01 M EDTA	@ 100% (5 pv)	@ 100% (58 pv)	@ 100% (58 pv)	72% (10 pv)
1.0 M $CaCl_2$	78% (5 pv)	96% (58 pv)	14% (58 pv)	no data

Adapted from Reed, Moore, and Cline 1995

Many factors affect heavy metal retention by soils, such as soil type, cation exchange capacity, particle size, natural organic matter, pH, age of contamination, and the presence of other inorganic contaminants. This study revealed that using pump-and-treat technology alone to remove heavy metals from contaminated aquifers is a highly ineffective process. Soil flushing with proper flushing agents, in most cases, should enhance the remediation process efficiency by one order of magnitude.

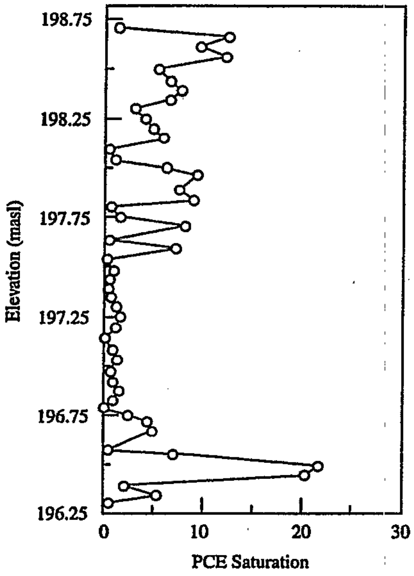
Case 4 — Surfactant-Enhanced Flushing of DNAPL Flushing Pilot Test

A field test using surfactant-enhanced, pump-and-treat remediation (soil flushing) of aquifers contaminated with dense nonaqueous-phase liquids (DNAPLs) was conducted from June 1990 to August 1991 at the Borden Canadian Forces Base near Alliston, Canada. The test was conducted in a 3 m by 3 m by 3 m (9.8 ft by 9.8 ft by 9.8 ft) cell in a shallow, clear sand aquifer. The test cell was created by driving sheet piling through 4 m (13.1 ft) of water-saturated layered sand into an underlying clay aquitard. The cell was contaminated with 231 L (61 gal) of tetrachloroethylene (PCE) using a shallow well located in the center of the test cell.

Three cores were taken from the lower portion of the test cell. There was reasonable correlation of PCE saturation with depth between the cores. The saturation distribution from a core located near the center of the test cell is shown in Figure 9.5. Preferential migration is evidenced by differences in PCE saturations with depth.

The upper 1 m (3.3 ft) of the saturated sand was excavated and replaced with a confined bentonite layer prior to remediation. A line of five injection wells was installed on one side of the test cell. A line of five withdrawal wells was installed on the opposite side of the cell. The injection and withdrawal wells penetrated the entire depth of the sand aquifer. An aqueous surfactant solution was circulated through the test cell using this system of injection and pumping wells and the injected PCE recovered (Fountain et al. 1995; Freeze et al. 1995). The remediation process involved (1) direct pumping of free-phase PCE, (2) water flooding to remove free-phase and

Figure 9.5
Measured PCE Saturation at the Location Near the Center of the Test Cell Prior to Surfactant Flooding



○ Measured

Base of diagram is bottom of test cell

Reprinted with permission from Freeze et al., *Surfactant-Enhanced Subsurface Remediation Emerging Technologies*, ACS Symposium Series 594, David A. Sabatini, Robert C. Knox, and Jeffrey H. Harwell (eds.), p 194. Copyright 1995 American Chemical Society.

dissolved PCE, and (3) surfactant flushing to solubilize additional residual PCE. Table 9.5 summarizes the results of these tests.

The results of the field test suggest that use of surfactants in soil flushing processes can effectively remove a large portion of DNAPLs in contaminated aquifers. However, at Borden, the location of the DNAPL zone was known, as was its contaminant, and was well confined in a homogenous environment. At most hazardous waste sites, subsurface conditions are highly heterogeneous. Detailed site characterization and laboratory study are required to design an effective soil flushing program tailored to the site's specific conditions.

Table 9.5
Summary of Presurfactant and Surfactant Soil Flushing Results

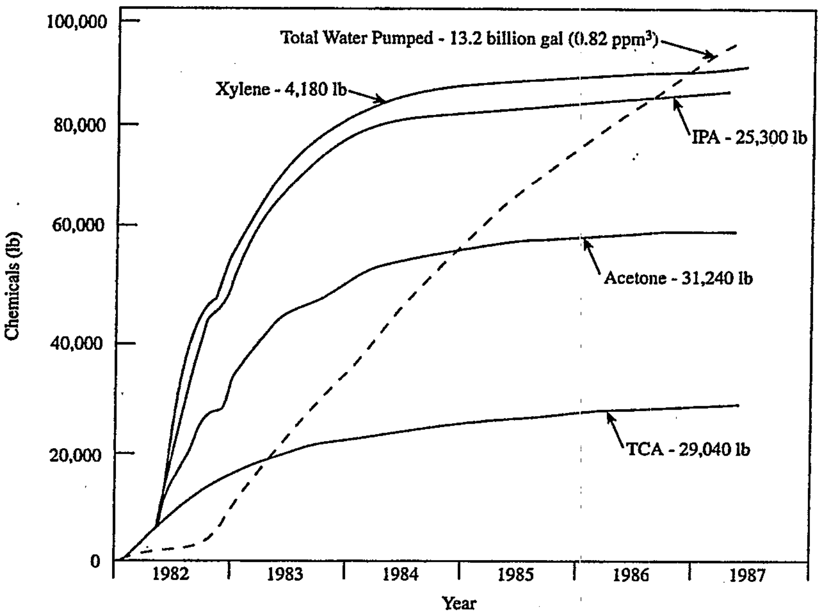
	PCE Recovered (L)	PCE Recovered (gal)	Number of Pore Volumes	% of Recovery of Remaining PCE
Presurfactant Flushing				
Excavation	52	13.7	no data	no data
Free-Phase Pumping	47	12.4	no data	26%
Water Flooding	12	3.2	6.2	7%
Surfactant Flushing				
(Remaining 120 L of PCE)	62	16.4	14.4	52%

Case 5 — Fairchild Semiconductor Company Remediation Program

An example of conventional pump-and-treat technology limitations is provided by the experience of cleaning up the site at Fairchild Semiconductor Corporation in San Jose, California (US EPA 1989). An extensive pump-and-treat system extracted 40,800 kg (89,760 lb) of organic contaminants in 5.1 years of operation at an average pumping rate of about 18,000 L/min (4,750 gal/min)(see Figure 9.6). The combination of pump-and-treat technology supplemented by a properly-positioned hydrologic barrier brought this situation under control in a relatively short time.

The actual costs of the Fairchild project were not available. For illustration purposes only, the cost was estimated using US EPA average cost for cleaning up a Superfund site of $27 million. The capital costs were assumed to be $17.55 million and the operational costs $9.45 million (NRC 1994). If only pump-and-treat technology had been used and the pumping rate had been constant throughout the process, reaching 99.9% recovery would take in excess of 200 pore volumes of treatment at a rate of about 1.6 pore volumes per year for about 127 years (see Figure 9.7).

Figure 9.6
Fairchild Site Cleanup

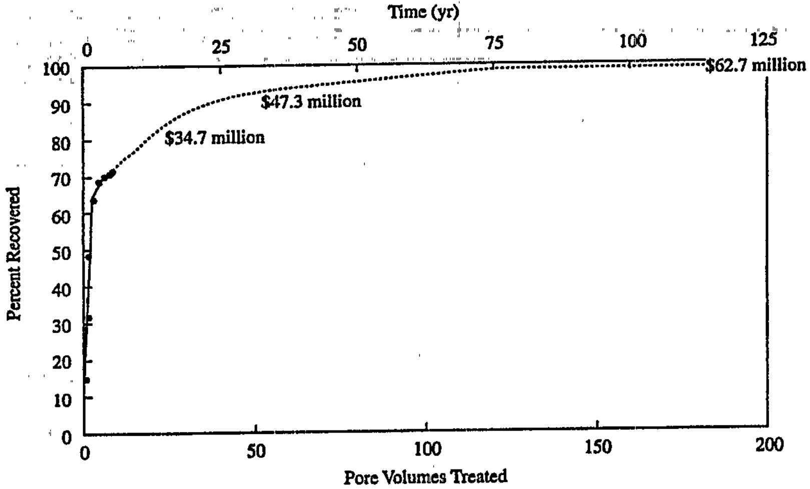


The total contaminants extracted for all wells from 1982 through 1987 was 40,800 kg (89,760 lb).

Case 6 — The Savannah River Plant Hazardous Waste Management Remediation Project

The Savannah River Plant Hazardous Waste Management Facility (HWMF) remediation project illustrates the potential benefit of applying enhanced recovery techniques. The Savannah River Plant was part of a system of weapons plants that conducted research and manufactured products necessary for the maintenance of nuclear weapons. Solvents used in the manufacturing process, namely, 1,1,2-trichloroethylene (TCE),

Figure 9.7
Hypothetical Projection of a Pump-and-Treat Case to Emulate Cleanup of a Superfund Site



DNAPLs assumed initially in place: 56,700 kg (125,000 lb)
Time to reach 99.9% recovery: 127 yr, 202 pore volumes
Remaining after 99.9% recovery: 0.011 ppm

tetrachloroethylene (PCE), and 1,1,1-trichloroethane (TCA), were released to the site's HWMF from 1952 through 1982 (US EPA 1992).

The discovery of contamination underneath the plant's HWMF in June 1981 led to a geologic and hydrologic investigation to define the scope and range of contaminants at the facility. The site assessment involved approximately 250 monitoring wells over a broad area.

The site is underlain by a wedge of unconsolidated to semi-consolidated sediment. The formations of interest beneath the plant, in order of increasing depth, are the Barnwell group, with an average thickness of 17 m (57 ft), mostly vadose; the McBean formation, with an average thickness of 9 m (30 ft), mostly saturated; and the Congaree formation, with an average thickness of 18 m (60 ft), saturated. The Ellenton formation, consisting of approximately 62% silt and clay, serves as an effective lower impermeable boundary. The groundwater level was approximately 18 to 36 m (60 to 120 ft) below the land surface within the Barnwell group and the McBean formation.

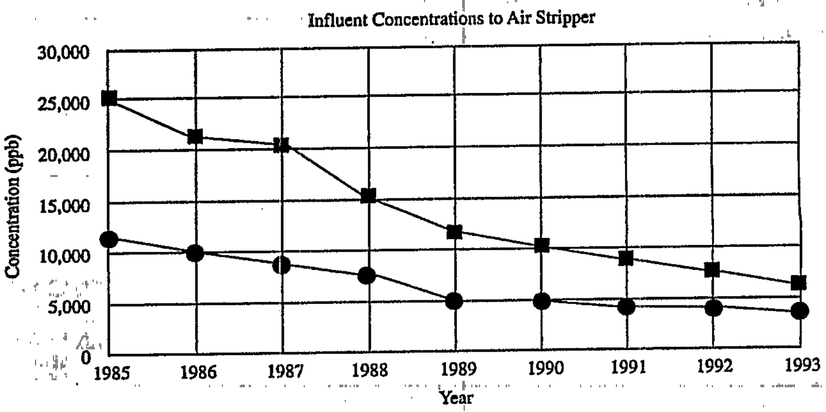
The various permeable and impermeable layers were contaminated with an estimated 211,045 kg (464,300 lb) of organic degreasing solvents, including TCE (approximately 75% of the total contamination), PCE, and TCA.

A pump-and-treat remediation program, consisting of pumping from 11 recovery wells, was implemented in 1985 to extract contaminants from the groundwater beneath the facility over a period of 30 years (US EPA 1992). From mid-1985 to December 1990, the average pumping rate from the recovery system was approximately 1,427 L/min (377 gal/min). The average pumping rate was increased to 1,813 L/min (479 gal/min) in 1993. The TCE concentration, measured in the air-stripping facility influent, was reduced from 25,000 μg/L to approximately 6,000 μg/L, while the PCE concentration decreased from 12,000 μg/L to approximately 4,000 μg/L (see Figure 9.8) by this pumping.

With the anticipated average pumping rate of 2,082 L/min (550 gal/min) for a total of 1,094 billion L (289 million gal) per year, the projected total fluid volume pumped from the aquifer in 30 years would be about 32.9 billion L (8.7 billion gal).

In the pump-and-treat process, the total volume pumped in relation to the number of pore volumes is a key parameter in estimating the time required to complete the remediation. At the Savannah River site, it was estimated that one pore volume contained approximately 55.6 billion L (14.7 billion gal) of water, assuming a dimension of 4.86 million m^2 (1,200 acres) and saturated thickness of 48 m (150 ft) and a porosity of 25%. Accordingly, it was calculated that after 30 years of continuous pumping, at an average rate of 1.09 billion L/yr (289 million gal/yr), less than one pore volume of water would be withdrawn and treated from the contaminated formation. It would, therefore, require approximately 50 years just to pump out one pore volume of water. The pore volume pumped per year is only 2% of the total pore volume (NRC 1994). Given the low pumping rates, the distance between wells, and the potential for detection of contamination outside the expected zone of capture, it was concluded that it is unlikely that contaminant concentrations would be reduced to below health-based levels in a 30-year period (DOE 1989).

Figure 9.8
Time-Concentrated Plot of TCE and PCE in the Air-Stripper Influent at the Savannah River Plant Site



■ TCE
● PCE

The NRC (1994) stated that for effective contaminant removal that "the volume of water that must be extracted will generally be larger than the volume of contaminated water." In a conventional in situ sodium carbonate/bicarbonate mining process, removal of 10 to 20 pore volumes are required to restore the aquifer to previous mining levels. A range of 10 to 20 required pore volumes suggests a 500 to 1,000 year remediation time (NRC 1994). The number of pore volumes required depends greatly on sorption/desorption phenomena and aquifer heterogeneity. Sorption/desorption phenomena retard the flow of contaminants and prolong the remediation time. Therefore, if these assumptions are correct, it may take several centuries to clean up the Savannah River Plant HWMF site.

Some options to speed up the remediation program include:

- redesign and increase the flow capability of the air stripper;
- redesign the wellfield so the pumping rate could be significantly increased;

- re-inject the treated water back to the aquifer. This would conserve the resource and increase the pumping capacity of the wells;
- apply the enhanced oil recovery technology, adding chemical recovery processes (e.g., surfactants) into the recovery system to increase the rate of contaminant removal and reduce the number of pore volumes required; or
- remediate vadose zone NAPLs to control percolation of contaminants to the water table.

Despite the fact that enhanced recovery methods offer significant promise, they have not been used at the Savannah River site.

Case 7 — IBM Dayton, Ohio, Facility Remediation Program

The International Business Machine Corporation's (IBM's) Dayton, Ohio facility produced punch cards for computer input and inked ribbons for printers until 1985. In December 1977, a contaminated plume of organic solvents was discovered in the groundwater system. The principal contaminants of concern were 1,1,1-trichloroethane (TCA) and tetrachloroethylene (PCE). In 1978, IBM started a remediation program by operating a system of groundwater extraction wells.

Two interconnected aquifers were involved in the groundwater remediation program. The water table in the shallow, unconfined aquifer is generally 9 to 14 m (30 to 45 ft) below the ground surface, with a saturated thickness of approximately 6 to 9 m (20 to 30 ft). The lower, semiconfined aquifer is approximately 18 m (60 ft) thick and is bounded from below by an impermeable shale.

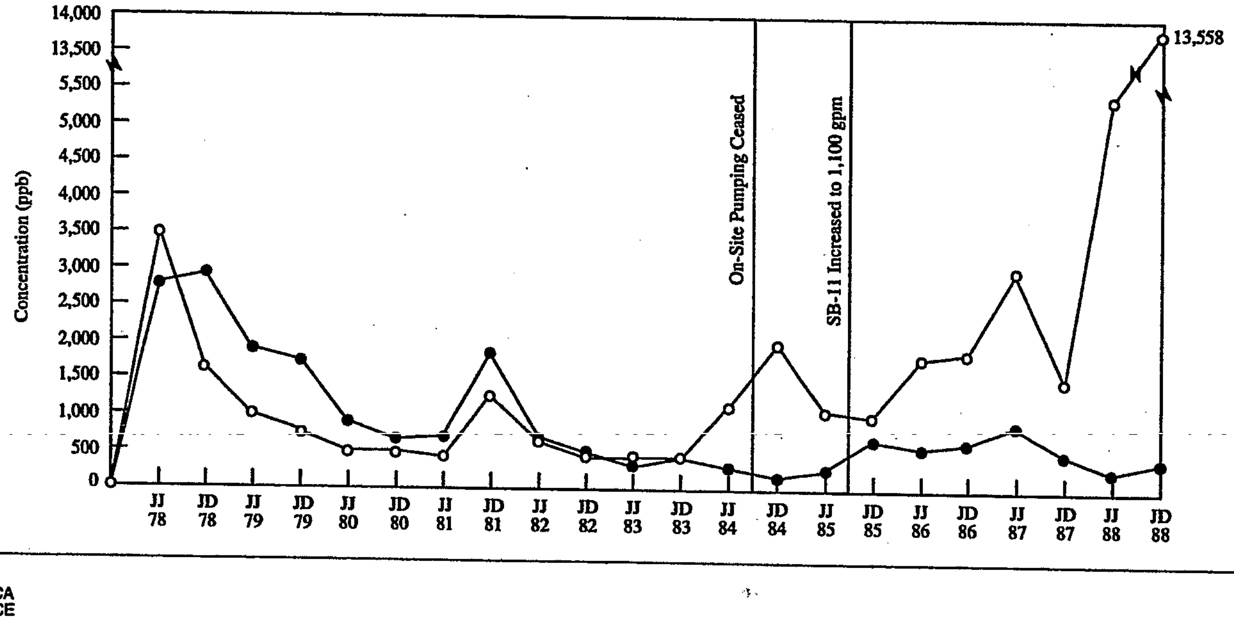
The suspected source of the contamination was near well GW-32. During the well extraction program in 1982, nine injection wells were added to inject treated water to the shallow aquifer in order to accelerate the flushing process.

In 1984, IBM's consultants concluded that the groundwater extraction system that operated between 1978 and 1984 had been successful in reducing the contaminant concentrations in the shallow aquifer (see Figures 9.9 and 9.10). The extraction system was subsequently terminated. However, continuous monitoring indicated that the concentration of TCA and PCE in the immediate source area had risen sharply (see Figures 9.9 and 9.10). The reappearance of higher concentrations has been attributed to the presence of DNAPLs in both the upper and lower aquifers. IBM's consultants have concluded that this residual source of contaminants cannot effectively be removed by groundwater extraction. IBM decided to resume extraction at lower pumping rates with the objective of plume containment.

Examination of this case indicates two options that could be considered to speed up the remediation process:

- re-inject the treated water back to the shallow, unconfined aquifer using horizontal injection wells and, thus, remediate vadose zone NAPLs to control percolation of contaminants to the water table; and
- add surfactant in the injection/extraction system to significantly increase solubilities of TCA and PCE and, thus, enhance the rate of contaminant removed, especially DNAPLs.

Figure 9.9
History of TCA and PCE Variations in Extraction Well GW32 (Six Month Average Concentrations) at IBM-Dayton Site



Source: DOE 1989

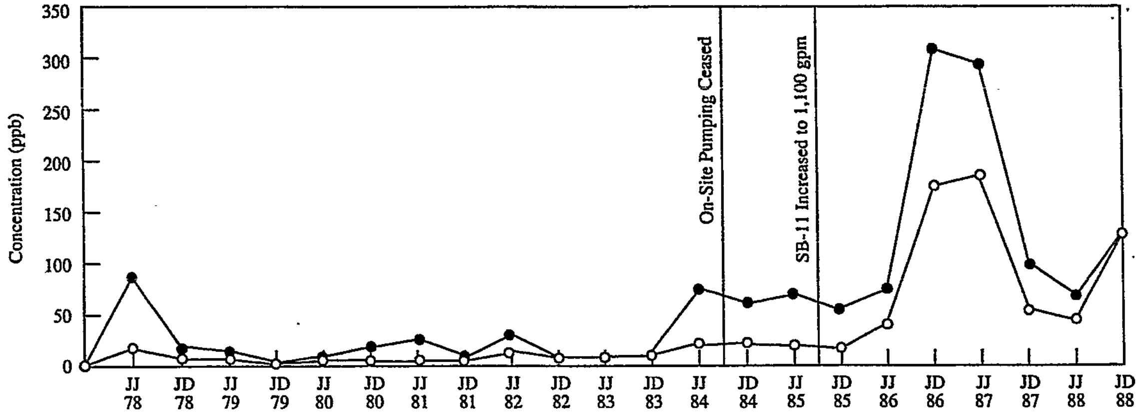


Figure 9.10
History of TCA and PCE Variations in Extraction Well GW25 (Six Month Average Concentrations) at IBM-Dayton Site

● TCA
○ PCE

Source: DOE 1989

SOLVENT/CHEMICAL EXTRACTION

10

APPLICATION CONCEPTS

10.1 Scientific Principles

Solvent/chemical extraction (SCE) is an ex-situ separation and concentration process in which a nonaqueous liquid reagent is used to remove organic and/or inorganic contaminants from wastes, soils, sediments, sludges, or water. The process is based on well-documented chemical equilibrium separation techniques used in many industries, such as oil extraction from soy beans, supercritical decaffeination of coffee, and separation of copper from leaching fluids.

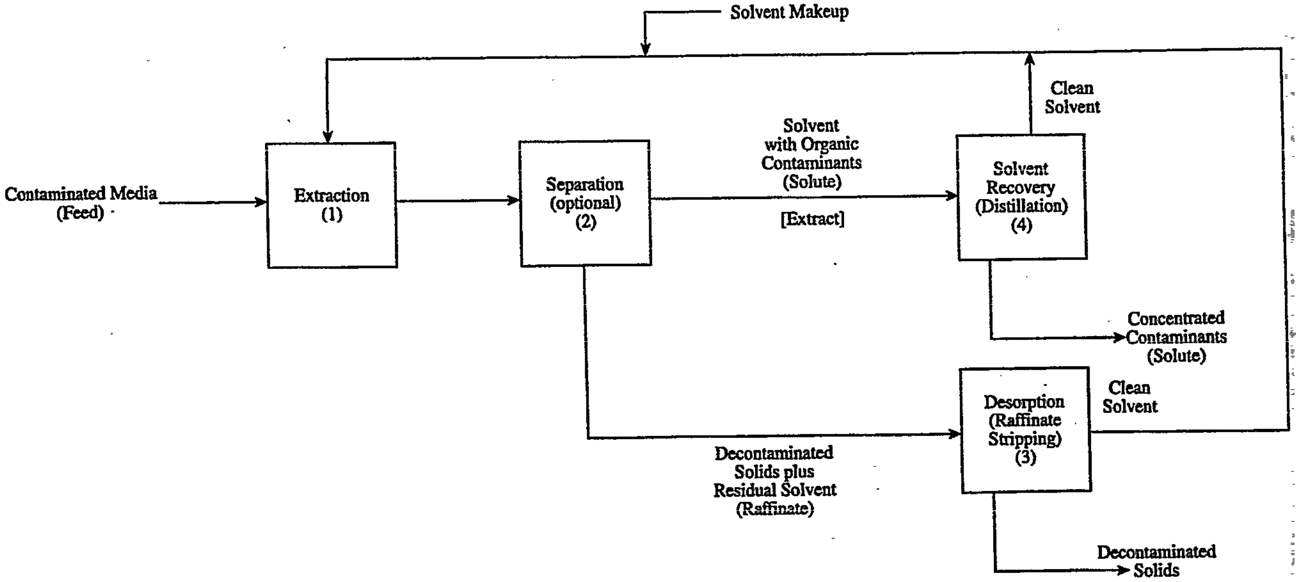
SCE is differentiated from the soil washing technology described in previous chapters in that soil washing involves the use of water, dilute aqueous solutions of detergents, or chelating agents to remove contaminants through desorption, abrasion, and/or physical separation. Whereas, SCE relies on the action of concentrated *nonaqueous* chemical agents.

SCE typically produces a clean fraction and a concentrated contaminated fraction, which requires further treatment to recover, destroy, or immobilize the contaminants. The process may concentrate contaminants by a factor as high as 10,000:1 (US EPA 1993); thereby significantly reducing the volume of material requiring further treatment or producing a concentrated stream for materials recovery. SCE effects the preferential separation of one or more constituents from one phase into a second phase. In classical chemical engineering terms, SCE is the term applied to the transfer that occurs between two liquid phases, or between a solid and a liquid phase.

As shown in Figure 10.1, in a conventional liquid-liquid contacting system, the solution to be treated is called the feed, the material to be extracted is called the solute, and the liquid selected to separate the solute from the

Figure 10.1

General Schematic of a Standard Solvent Extraction Process



Source: US EPA 1994

balance of the feed is called the solvent. The solvent-rich, solute-laden product is called the extract, and the residual of the feed stream (from which solute has been removed), is called the raffinate. The solute concentrations in two contacting liquid phases, corresponding to equal chemical or thermodynamic potentials, define the equilibrium state. The ratio of these concentrations is the *equilibrium distribution coefficient.* This is a measure of the best separation or solute removal that can be effected. Where liquid-liquid miscibility is poor (i.e., the solubility of each liquid in the other is less than 1,000 mg/L or 0.1% by weight) or merely partial, contaminant transfer is a function of relative solubilities and the equilibrium distribution coefficient. For transfer between two liquid phases, the phases can be immiscible or partially miscible. Maximum separation of contaminants is effected under the following conditions:

- the solute is much more soluble in the solvent phase;
- the solvent phase is completely immiscible with the feed; and
- the solvent has a substantially different specific gravity from that of the feed.

In liquid-liquid solvent extraction processes, the extraction operation can have one or more contact stages. A contact stage consists of three steps: (1) combining the feed and solvent in a mixer or contactor, (2) allowing the mixture to approach equilibrium, and (3) settling the mixture to separate the extract and raffinate phases. Several such stages can be combined in process trains. Partially-purified feed can repeatedly be brought into contact with fresh solvent, thereby reaching equilibrium states at successively lower solute concentrations. This design is referred to as *cross-current extraction* as shown in Figure 10.2. Alternatively, stages that approach equilibrium can be arranged in a *counter-current* flow mode whereby the final feed-side residue (effluent) stage approaches equilibrium with solute-lean solvent. Counter-current extraction is illustrated in Figure 10.3.

When a substrate is transferred from a solid to a liquid phase, the action is called leaching. SCE is the controlled leaching of contaminants from soils, sediments, and solid wastes through use of organic solvents or nonaqueous liquids. Common examples of leaching are the recovery of a metal (solute) from metal ore (substrate) by treatment with strong acid and loss of fertilizer from crop land by runoff and percolation of incident rainfall.

Figure 10.2
Cross-Current Extraction

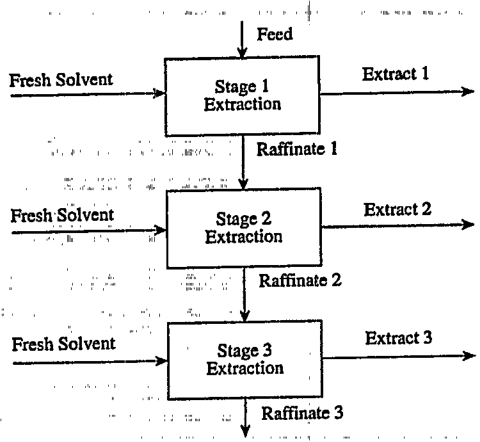
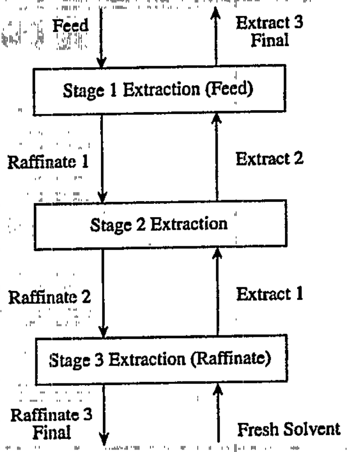


Figure 10.3
Counter-Current Extraction



SCE processes used for soil and sediment cleanup typically employ a solvent that extracts both water and organics into the liquid phase. Subsequent steps involve separating the liquid phase from the solids, separating the water and organic phases, and, finally, separating the contaminants from the solvent. As such, the extraction of the contaminant from a solid phase involves only the equilibrium of the contaminant with the solvent. Where the solute is bound to a solid substrate, solubility of the solute in the solvent is balanced by low-energy sorptive binding, high-energy chemisorption, or incorporation in the solid matrix. The chemical potential of the solute in the solid phase is a function of solute-solid interactions: weak van der Waals-induced dipole forces versus strong hydrogen, covalent, and electrostatic bonds. The stronger the interactive binding, the poorer the equilibrium distribution coefficient.

The capacity of a solvent to separate a solute from a weakly- or partially-soluble liquid or solid is its *selectivity* and is determined by the following equation:

$$\text{Selectivity} = \frac{(\text{Mass Fraction X in E}) / (\text{Mass Fraction A in E})}{(\text{Mass Fraction X in R}) / (\text{Mass Fraction A in R})} \tag{10.1}$$

where: A = primary feed stream constituent;
E = solvent-rich phase;
R = residual phase (raffinate) at equilibrium; and
X = solute.

Selectivity must exceed unity; if it is unity, no separation is possible. If "A" is water, as it is in oily wastewater, secondary sludge, sediment, or wet soil, selectivity may determine whether the extraction technology is applicable.

Most SCE processes employ solvents at near-ambient pressures and temperatures during extraction. Typical solvents used individually or in combination are amines, alkanes, alcohols, ketones, and chlorinated hydrocarbons.

Solvent extraction can occur under three processing approaches. The most common approach employs two phases in contact at ambient pressure and temperature in which the solute is exchanged between a solid or liquid substrate and a liquid solvent (at standard pressure and temperature). High pressure and moderately-elevated temperatures can be used to create efficient, dense solvents or supercritical fluids from substances that are gases at moderate conditions (near-critical fluids). In some instances, temperatures can be increased selectively to enhance solute transfer to a solvent phase (critical solution temperature).

In the near-critical fluid/liquefied gas approach, butane, isobutane, propane, carbon dioxide, or other gases liquefied under pressure at or near ambient temperature are used during extraction. These processes take advantage of the special properties of gases when they are near their critical temperature and pressure (thermodynamic critical point). At this point, the liquid and vapor phases of the solvent, in equilibrium, become identical, forming a single phase. A fluid near its critical point exhibits the viscosity and diffusivity of a gas, but also the solvent characteristics of a liquid. Under these conditions, the solvent can effectively penetrate the solid matrix and mobilize organic contaminants.

Finally, critical solution temperature SCE methods use solvents in which solubility can be varied over the process operating temperature range. These processes use liquid-liquid extraction at two temperatures. At the lower operating temperatures, the fluids are miscible. At the upper operating temperatures, the two fluids form separate phases. In these processes, solvent recovery often consists of numerous unit operations.

10.1.1 Development of Solvent/Chemical Extraction

Solvent extraction and leaching processes have been in existence for many decades, but only recently have they been adapted for remediation purposes. Within approximately the past 20 years, several technology vendors have developed and offered processes targeted at remediation activities. Many advanced no further than operation of a pilot plant or a prototype. As of the date of this publication, fewer than a half-dozen vendors offer commercially proven processes, and only one firm appears to have developed a financially-successful remediation business. Two firms offer similar technologies for non-remediation activities.

Three systems (CF Systems, RCC's B.E.S.T., and TERRA KLEEN) have been demonstrated under the US EPA Superfund Innovative Technology Evaluation (SITE) demonstration program and are fully documented. Results of test programs and evaluations have been mixed. In a number of cases, the systems have met or exceeded test objectives, while in other cases they have not. Therefore, for most applications, treatability testing is required to determine site-specific design parameters. Based on results of treatability testing or similar applications, suppliers are offering systems for a wide variety of applications.

10.1.2 Fundamental Process Concepts

The fundamental operating concepts, especially those employed in the extraction step(s), vary widely depending on the characteristics of the solvent employed. Four SCE processes are described in this section — Amine Solvent, Supercritical Fluid/Liquefied Gas, Drying/Extraction, and Conventional processes. However, all SCE processes use an organic or nonaqueous solvent to remove organic contaminants from soil, sediment, or sludge. Further, SCE processes are designed to operate in either a batch or continuous mode, but not both, and all employ relatively similar unit operations, as depicted in Figure 10.1. SCE generally includes the following operations:

- feed preparation,
- extraction,
- solids and solvent separation, and
- solvent recovery.

Contaminated soils, sludges, or sediments are excavated and enter the feed preparation system, where they may be screened, crushed, dewatered, and/or slurried depending on the particular SCE process being employed. Chemical conditioning, such as pH adjustment, may be necessary to ensure successful extraction.

The prepared feedstock is then transferred to the extraction vessel where it is mixed with the extraction solvent(s). Extraction is carried out in either batch or continuous mode in a single vessel or a series of vessels. Selection of the extraction solvent(s), the solvent-to-solids ratio, the extraction contact time, and the number of extraction stages depend upon the specific contaminant and nature of the feed. These parameters are typically determined during treatability studies. Important solvent characteristics include relative solubility of the solute, immiscibility with the feed, specific gravity, toxicity, flammability, physical properties, chemical reactivity, ease of recovery for recycling, and cost.

Feed and solvent streams can enter a continuous contact system in parallel-flow or counterflow configurations. In the counterflow arrangement, relatively clean solvent contacts solute-lean raffinate, while feed contacts solute-rich extract. This permits both end-state pairs to approach equilibrium. The effluent streams in a parallel-flow configuration can also be caused to approach equilibrium through use of multiple extraction stages. In both cases, the solvent is selected to maximize the solute distribution coefficient.

Following extraction, the decontaminated solids are separated from the contaminant-loaded extraction solvent(s). This may be effected in the extraction vessels or separately through gravity separation, filtration, centrifugation, pressure reduction, or distillation. Residual solids are normally subjected to multiple washes in order to achieve cleanup goals. The separated solids may retain some solvent, which is removed through distillation or desorption, or by an additional extraction step.

The contaminant-laden solvent, along with solvent vapors removed during desorption or raffinate stripping of the decontaminated solids are transferred to a solvent recovery system. Solvent is recovered through distillation, steam stripping, pressure reduction, or phase separation. Typically, the recovered solvent is recycled back to the beginning of the SCE process, and the concentrated contaminants are removed for further treatment. The extract containing the concentrated contaminants generally requires further treatment before disposal or recovery.

10.1.2.1 Amine Solvent Process

One vendor has developed a process in which the unique miscibility properties of certain amine solvents are applied to separate sediments, sludges, or organic-contaminated solids into their organic, water, and solids fractions (Robbins 1990; Tose 1987; Weimer 1989). Organic contaminants in the sludge or soil, such as polychlorinated bipenyls (PCBs), polynuclear aromatic hydrocarbons (PAHs), pesticides, herbicides, and chlorinated hydrocarbon solvents, end up in the organic fraction after separation. The physical properties of amine solvents can be used to overcome solvent extraction difficulties (i.e., emulsion formation) typically encountered when handling samples with high water content. The key to the success of amine extraction is the property of inverse miscibility. When using triethylamine as a solvent, at temperatures below about 27°C (80°F) the solvent is miscible with water (i.e., solvents and water are each soluble in the other). Above this temperature, the solvent and water are only partially miscible. This physical property can be exploited by using cold (i.e., chilled below 27°C [80°F]) solvent to simultaneously solvate organics and water.

This principle works by mixing the feed with solvent to create a fluid phase. The fluid phase contains amine and aqueous phases that are partially soluble in each other. This solution solvates the contaminants that were present in the feed. Unlike other solvent extraction systems where extraction efficiencies are hindered by emulsions that partially occlude the solute, amine solvents can achieve intimate contact with solutes at nearly ambient temperatures and pressures. Therefore, the process can treat feed mixtures with high water content without loss of extraction efficiency.

Once extraction of the feedstock is complete, the solid portion of the feedstock is removed from the solvent by gravity settling and/or centrifugation. The solvent/water/oil mixture is removed from the solids and subjected to additional processing. The solids are dried to remove residual solvent.

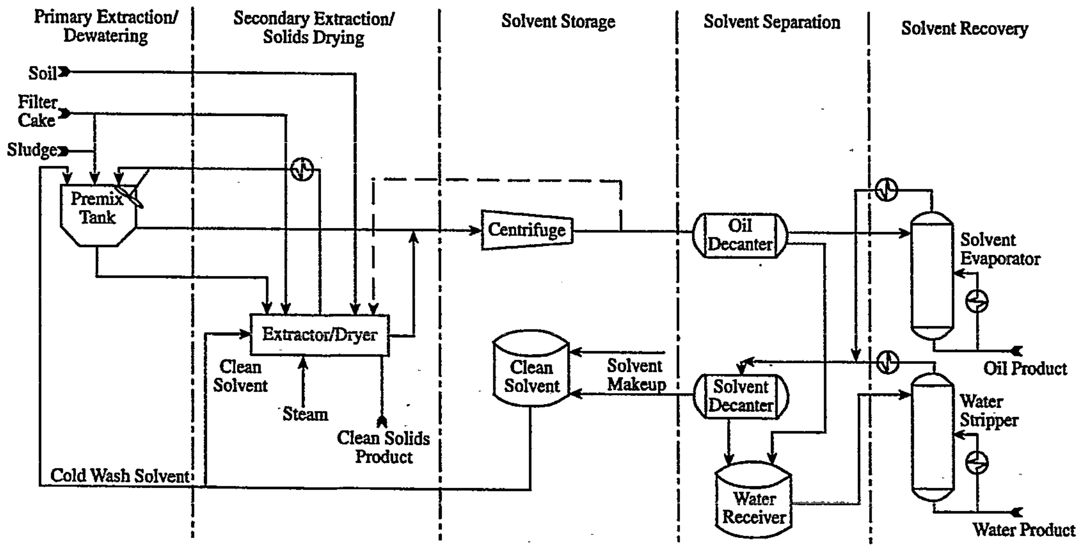
Processing the solvent/water/contaminant mixture begins with separating it into its components. The solvent and water are removed from the mixture by evaporation and condensation. The resulting solvent/water mixture is then in the temperature range (27°C to 80°C [80°F to 176°F]) where the solvent and water are only partially miscible. With the specific gravity of the solvent at 0.72 as compared to water at 1.0, the solvent and water are easily separated by decantation. The traces of residual solvent that remain in the water (about 2% by weight) are removed by steam stripping.

After the solvent/water has been removed from the contaminant, the contaminant fraction can be destroyed. An added benefit is the simultaneous extraction of other organic compounds that may be present in the feed, leaving the residual solids free of contaminants that may contain other regulated constituents such as PAHs.

A process-flow schematic for a mobile amine solvent extraction unit designed to extract PCBs, PAHs, volatile organic compounds (VOCs), and pesticides from excavated sludges, soils, and sediments is presented in Figure 10.4. Four basic operations are involved — extraction, solvent recovery and contaminant polishing, solids drying, and water stripping. A description of the major process units follow.

Extraction/Dryer. The extractor/dryer vessel is used for extraction, solids settling, solids/liquid separation, and solids drying. The extractor/dryer is equipped with horizontally aligned mixing blades and is surrounded by a steam jacket. The vessel is also equipped with direct injection ports through

Figure 10.4
Generalized Diagram of the RCC B.E.S.T.® Solvent Extraction Process



Source: US EPA 1993

which steam is injected into the jacket to provide heat during extraction, solids drying, and residual solvent removal.

Decant Tank. Following each extraction stage conducted in the extractor/dryer vessel, the liquid fraction is decanted and directed to a decant tank (not shown). This vessel serves as an equalizing tank to enable a uniform feed rate to the centrifuge and the solvent recovery system.

Centrifuge. Liquid and fine particulate stored in the decant tank are continuously fed to the centrifuge which removes any particulates that have been carried from the extractor/dryer during the decant process. The centrifuge cake is directed to the solids tank (not shown) and the liquid, or centrate, is directed to the solvent evaporator.

Solids Tank. The centrifuge cake is stored in a solids tank and reslurried with clean solvent, The reslurried fines are then directed back to the extractor/dryer prior to processing the next batch of material.

Solvent Evaporator. The solvent evaporator is used for solvent recovery and contaminant concentration. The solvent/water azeotrope formed during heating is evaporated from the concentrated contaminants. All vapors that leave the solvent evaporator are condensed and transferred to the solvent decanter. The concentrated organic contaminants are removed from the system for disposal and dechlorination.

Solvent Decanter. The solvent decanter is a vessel used to receive and separate the condensed solvent/water mixture from the solvent evaporator, extractor/dryer overhead, and water stripper overhead. The solvent decanter is maintained above the solvent/water miscibility temperature, allowing separation of the solvent and water phases. The solvent phase contains approximately 2% water by weight, and the water phase contains about 2% solvent. The solvent phase is directed to the clean solvent tank for reuse in subsequent extractions. The water phase is directed to the water receiver.

Clean Solvent Tank. The clean solvent tank stores the clean, recovered solvent. Solvent from the clean solvent tank is transferred to the extractor/dryer vessel to conduct subsequent extractions.

Water Receiver. After solvent and water have been separated by gravity in the solvent decanter, the water phase, which contains about 2% solvent, is directed to the water receiver. The water receiver stores all contact water used in the process and provides feed for the water stripper.

Water Stripper. The water stripper is used to remove residual solvent and other volatile compounds from the water recovered by the process. The water stripping column is a simple packed column, requiring few equilibrium stages. Distilled water is recovered as the bottoms product and the overhead solvent vapor is condensed and directed to the solvent decanter. Typical solvent residuals in the effluent water stream are less than 2 mg/L.

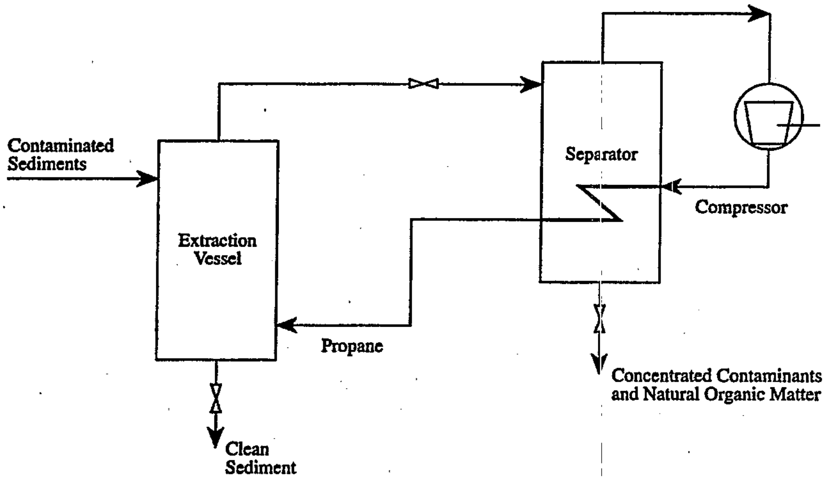
Vent System. An atmospheric vent discharge from the process is used to eliminate noncondensable gases from the various condenser systems to prevent reduction of heat transfer efficiency. Normally, this vent gas consists primarily of nitrogen purge gas with traces of oxygen and other atmospheric gases. Most of the solvent vapors present are condensed by the refrigerated vent condenser. However, to ensure that all organic vapors, including the solvent, are recovered, a vent scrubber and an activated carbon adsorption system are installed on the vent system outlet. The carbon adsorption system consists of two activated carbon beds connected in series. The primary (upstream) carbon bed outlet is monitored for organic vapors, and a secondary carbon canister (downstream) is installed in case breakthrough of the primary canister occurs. The carbon adsorption system ensures that there is no release of organic vapors from the process.

10.1.2.2 Supercritical Fluid/Liquefied Gas Processes

Other vendors specialize in the development and application of supercritical fluid and liquefied gas extraction processes for chemical production and hazardous waste treatment (Meckes et al. 1997). These processes use liquefied gases as extracting solvents to separate organic contaminants from wastewater, sludge, and contaminated soil. Target contaminants include hydrocarbons (benzene, toluene, xylene, and other constituents of gasoline), oil and grease, partially-oxidized hydrocarbons (phenols, alcohols, fatty acids, acetone, etc.), and chlorinated species (PCBs and dichloroethane). Carbon dioxide (CO_2) is generally used for aqueous solutions; propane is often selected for sediments, sludges, and soils. In selecting the solvent, the solubility of CO_2 in water and the effects on pH and soluble inorganic salt content must be considered. Propane is a volatile, flammable hydrocarbon that can constitute a fire and explosion hazard in the event of system malfunction.

Figure 10.5 is a simplified diagram of a one-stage solvent extraction process employing liquefied propane. Contaminated sediments are fed top

Figure 10.5
Process Diagram — Supercritical Fluid/Liquefied Gas Process



Source: US EPA 1990a; Donnelly et al. 1995 (modified)

down into a high-pressure contactor. Compressed liquefied propane at 20°C (70°F) passes upward, counter to the solids, and dissolves organic matter. Clean sediment (raffinate) is removed from the contactor. A solution of organic contaminants in propane is passed to a separator via a pressure reducing valve. Propane is vaporized, recompressed, and recycled to the contactor as fresh solvent. Contaminants and natural organic matter are removed from the separation vessel and recovered for disposal or reuse.

The process has seven basic operating steps. Initially, slurried sludge is fed to a stirred-tank extractor (raw sludge may require pretreatment to eliminate oversized material or to modify chemical characteristics, such as pH). Propane is compressed to operating pressure, condensed, and fed to the extraction vessel to dissolve oil in the sludge feedstock. A mixed stream is taken from the contactor to a decanter in which gravity separation of the heavier water and solids fraction and the lighter propane and oil fraction occurs. Water and treated solids are removed from the decanter; the solids are dewatered and the final filter cake is removed to a landfills.

Propane and oil pass to a solvent recovery still system which includes a distillation tower. The distillation tower operates at a reduced pressure. The reboiler is heated with recompressed propane vapor. If the process is being employed to treat petroleum refinery waste streams, the recovered oil collected as still bottoms can be recycled to the refinery, and the propane is recycled as fresh solvent.

The one-step mixer/settler system shown in Figure 10.5 is actually operated as a multiple-stage process. The number of stages must be suitable to achieve Best Demonstrated Available Technology (BDAT) standards for hazardous petroleum refinery wastes (K048-K052) prescribed by the US EPA (Office of the Federal Register 1996). The number of stages required (typically two to five) is dependent on the feed matrix and type and level of contaminants present. The treated oil and solids raffinate stream from the commercial unit is claimed to conform to BDAT standards for 16 specific volatile and semivolatile organic compounds.

The same concept can be applied with supercritical carbon dioxide or liquefied light hydrocarbon gas mixtures as the solvent. These modified processes have been evaluated at bench- and pilot-scales (Meckes et al. 1997).

10.1.2.3 Drying/Extraction Process

A unique process employing SCE has been developed by another vendor. The process separates mixtures into solids, oil, and water while extracting organics using a carrier oil or solvent (US EPA 1992a). In instances where heavy metals are complexed by organics, some metals may also be removed from the solids (US EPA 1990b). Treatment effectiveness can be increased by adding evaporation and extraction stages.

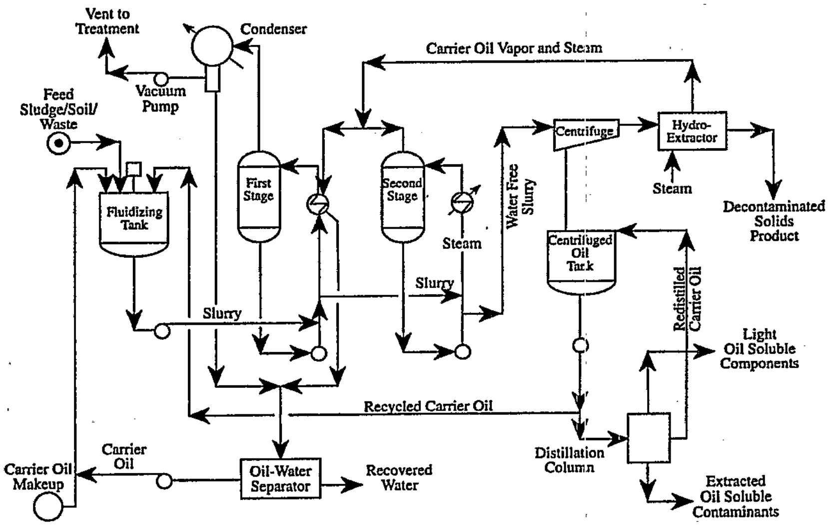
The process has been variously described as extraction (Trowbridge, Holcombe, and Kollitides 1991), drying (Lau 1991), steam stripping (*Hazardous Waste Consultant* 1991), and evaporation. It has been characterized by the US EPA both as a "solvent extraction process" (US EPA 1991a) and "other physical treatment" (US EPA 1991c). Because the main treatment steps involve solvent extraction and water evaporation stages, the process is addressed in this monograph. It should be noted that the carrier solvent may be used in the very first stage or it may be mixed with the waste in later evaporation and extraction stages after some evaporation has already occurred (US EPA 1992a). As well as serving as a medium for the extraction of organic contaminants, the solvent aids in maintaining the waste in a slurry state as water is evaporated. The process consists of seven steps as shown in Figure 10.6 and described in the following text.

Pretreatment. (not shown) Debris is separated from the feed, and if necessary, the feed particles are ground to sizes less than 6 mm (0.25 in.).

Feed Slurrying (Fluidizing). The feed material is slurried in a fluidizing tank with a carrier oil or solvent to extract indigenous oils and soluble organics. In general, the solvent-to-feed waste solids ratio varies from 5:1 to 10:1 by weight. The exact solvent to be used depends on the site, but a hydrocarbon-based solvent with a boiling point around 150°C (300°F), typically, alcohols or food-grade mineral oils, is used for hydrocarbon- or organically-contaminated solids (US EPA 1992c). The product of this stage is a slurry mixture.

Figure 10.6

Process Schematic — Dryer/Extraction Process



Source: Donnelly et al. 1995

Evaporation and Solvent Extraction Stages. The water in the slurry is evaporated. In general, two to four multi-effect Evaporators are used in commercial systems to evaporate the water (US EPA 1992c). Alternatively, mechanical vapor recompression may be used (Holcombe and Kollitides 1991). For example, the evaporative stages can employ successive boiling chambers, each operating at progressively lower pressures (Environment Today 1991). This allows succeeding chambers to use less energy to vaporize the water. Removal of the water aids in breaking emulsions, thereby increasing organic extraction. At the same time, steam generated in the evaporation system removes water and volatile compounds from the waste-solvent slurry (*Environment Today* 1991; *Hazardous Waste Consultant* 1991). The heat also destroys microorganisms. The products of these stages consist of vapors and a water-free slurry of solids in the carrier solvent.

Condensation and Oil and Water Separation (Vapor Treatment). The vapors from the evaporation step are condensed. The water, carrier oil, and solvent condensate are then sent to an oil-water separator (decanter). The decanting separates any carrier oil and solvent and water-immiscible solvents from the water.

The recovered water contains some residual solvent and low-boiling point water-soluble compounds. However, the water is generally relatively clean and virtually free of solids and can usually be treated with standard wastewater treatment technologies. Any recovered carrier oil can be recycled to the fluidizing tank. The vent gases can be treated for residual organics by granular activated carbon (US EPA 1992a).

Centrifuging (Water-Free Slurry Treatment). The majority of the carrier oil and solvent is separated from the feed solids by centrifuging. The solids may then be reslurried with clean (recirculated) solvent for additional extractions or directed to desolventization. The concentrate (from each extraction) generally consists of the carrier solvent (with extracted indigenous oil and organics) and approximately 1% fine solids. The centrifuge cake generally consists of 50% solids and 50% solvent with extracted organics.

Desolventization of Solids (Treatment of Centrifuge Cake). The solvent is removed from the solids by heating (evaporation) and stripping by counter-current contacting of the solids with gas (US EPA 1992a). Earlier descriptions referred to this as a "hydroextraction" or "vacuum hydroextraction" step (Holcombe and Kollitides 1991) that heated the centrifuge cake under vacuum and utilized steam to contact the solids (US EPA 1991a).

More recent studies have used nitrogen gas to strip the solids (US EPA 1992e). The resulting offgas is then scrubbed to remove carrier oil/solvent and recirculated. The vent gases can be treated for residual organics by granular activated carbon (US EPA 1992a). Most of the heavy indigenous oils in the centrifuge cake will remain with the solids in the centrifuge cake, rather than evaporate (US EPA 1992c).

Distillation of Carrier Oil/Solvent (Treatment of Concentrate). The used carrier solvent is distilled to recover the carrier oil and solvent and separate the indigenous oils and organics. Products of this step consist of a recovered solvent (substantially free of contaminants), which may be reused, and concentrated streams of light and heavy organics, which may be incinerated or reclaimed.

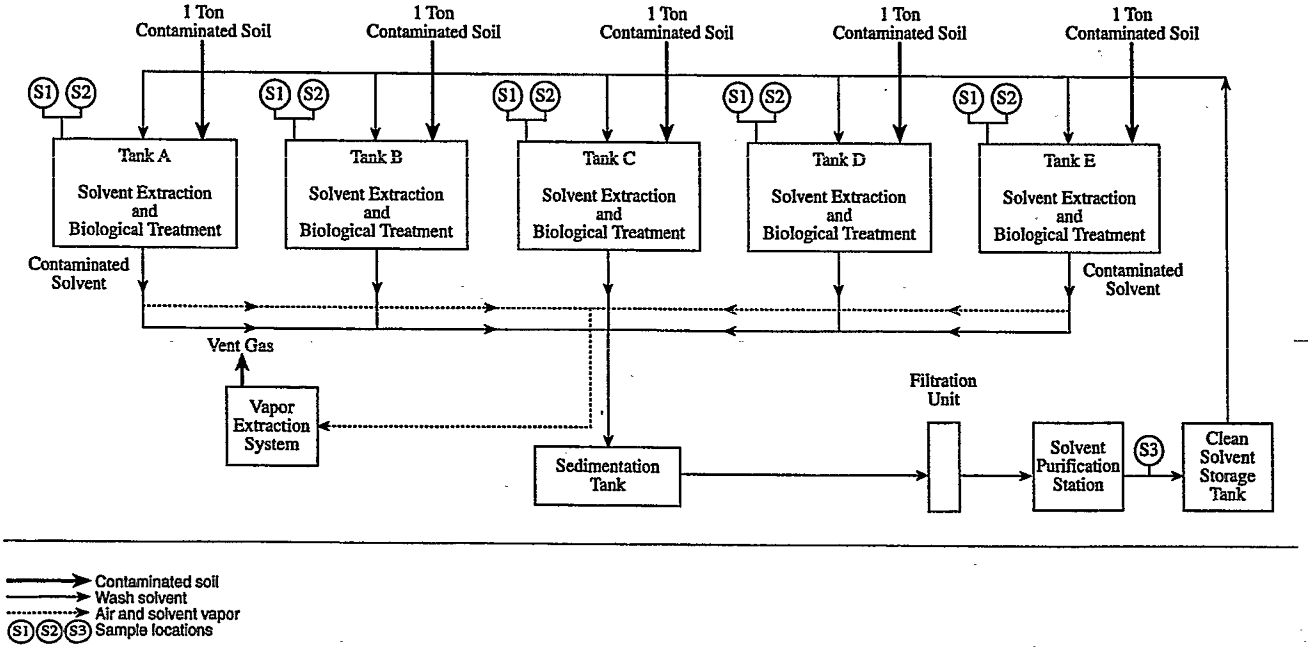
10.1.2.4 Solvent Leaching Process

Another vendor offers a process that is similar to the "generic" version described at the beginning of this section. It employs up to 14 organic solvents in treating contaminated solids. The solvents to be used in extracting organic contaminants from a particular waste stream are determined through a series of bench-scale treatability tests. The solvent is selected based upon the solubility characteristics of the contaminant(s) and its phase separation characteristics with respect to the solid matrix (Cash 1991).

As shown in Figure 10.7, contaminated soils are loaded directly into extraction vessels by a front end loader or by a conveyor system. The vessels are covered, and clean solvent at ambient temperature and pressure is pumped into each one. Organic contaminants in the solids are mobilized by the solvent without the aid of a mixing device. Contaminated solvent then flows into a sedimentation tank (clarifier) where settleable solids are separated by gravity from the solvent. Clarified solvent is pumped through a microfilter which removes fines, and then through a proprietary solvent purification unit which concentrates the organic contaminants. Clean solvent, discharged from the purification unit, is stored in a holding tank for reuse. This sequence of treatment steps, known as an extraction cycle, is repeated until contaminant concentrations of the solids within the extraction vessels are reduced to a desired level. At this point, the extraction vessels, and all solvent carrying lines are drained, and the suction side of a centrifugal blower is connected to each vessel's solvent discharge line. Much of the solvent retained within a vessel volatilizes as air is rapidly drawn through it

Figure 10.7

Process Schematic — Solvent Leaching Process



Source: Meckes, Engle, and Kosco 1996

by the blower. Vapors discharged by the blower are passed through a condenser where spent solvent is recovered as a liquid which is then filtered and processed through the purification unit. This recovered solvent is returned to the solvent storage tank for reuse.

Some solvent remains associated with the treated solids following vapor extraction. Further reduction of this residual solvent is effected through biodegradation. This is accomplished by adding a mixture of water, nutrients, and microorganisms to the soil in each extraction vessel. Biodegradation of the solvent is permitted to continue until residual solvent concentrations have been reduced to acceptable levels for land disposal (several days).

Treated solids typically are removed from the vessels by a front end loader and returned to the site. Contaminants concentrated by the solvent purification process are removed and disposed off-site in accordance with applicable regulations. Purified solvent may be used for treatment of solids at other waste sites.

10.1.3 Soil Characterization

SCE differs from soil washing in that performance is not as sensitive to the particle-size distribution of the soil or sludge being treated. Certain types of soil washing processes are not effective when the feed is predominantly clay or silt. In general, this is not the case for SCE because contaminants are mobilized using a solvent system, whereas for soil washing, some systems require separation of large particles from smaller particles. Nevertheless, characterization of the feed is important to assess process feasibility.

As with most ex-situ remediation technologies, objects greater than a certain size are usually removed to facilitate transport though the process equipment. Clumps of soil or sludge are broken up to minimize mass transfer resistance. One process calls for removal of particles greater than 6 mm (0.25 in.)(Meckes et al. 1997).

Most SCE processes employ a filtration step to separate, at least in part, the solvent from the treated feed. Because a high percentage of clay or silt could hinder this step, it is important to know the particle-size distribution of the feed.

Some solvents tend to form emulsions with certain feeds. Therefore, tests to identify this tendency are sometimes included in initial characterization of a feedstock.

Water content of the feed is important for some processes and in any event must be measured to determine a material balance. Most processes are limited to a well-delineated range of feed solids/moisture content. This may necessitate a dewatering and drying stage in some processes and a slurrying stage in others.

The pH of the feed should also be measured as some processes have limits for this parameter.

10.1.4 Contaminant Occurrence

For all practical purposes, organic compounds, as opposed to heavy metals and cyanide, are the only contaminants for which SCE processes are effective. The range of organic contaminants that can be treated is discussed in Section 10.2. Potential feeds must be characterized to determine the total spectrum of contaminants to be treated. This will, in turn, determine whether SCE will be an effective treatment approach and whether it can be employed for a total solution or must be used in combination with other treatment technologies, such as chemical oxidation or stabilization.

10.1.5 Treatability Study Considerations

Treatability studies are principally modeled after the US EPA's interim guidance document, *Guide for Conducting Treatability Studies Under CERCLA, Solvent Extraction* (US EPA 1992b). The conditions for use of the guide and the approach to be taken in using treatability testing to evaluate an SCE remedy are the same as those described for soil washing (refer to Section 3.2.2.3). It is extremely important to work with technology vendors when conducting treatability studies.

As with soil washing, a well-planned and carefully executed treatability study is a critical element of a successful SCE remediation project. Such studies are carried out at either the bench- and/or pilot-scale. They are used to verify the applicability of SCE for the particular remediation under consideration. They also provide data to determine the number of extraction stages to be employed, to identify pretreatment and posttreatment requirements, to estimate full-scale maximum batch sizes, processing times, throughput rates, and, hence, treatment costs and other aspects of the process design or configuration. Some vendors have developed mathematical models for their processes, and the input parameters for such models are obtained from treatability studies.

The primary focus of a treatability study, especially at the bench-scale, is usually the extraction step. Other operations, such as solvent evaporation, water stripping, and solid/liquid separations, can be selected or designed from first principles. However, pilot-scale studies often include studies of these ancillary operations.

10.2 Potential Applications

SCE has been shown to be effective in removing semivolatile organic contaminants from numerous substrates. Other possible applications under study and development use SCE for the removal of VOCs and metals. This section discusses appropriate applications and limitations of the technology.

10.2.1 Matrix Types

Contaminated soils, sludges, and river and harbor sediments have each been successfully treated using SCE processes. Specific characteristics of a given matrix, such as particle size, moisture content, and total organic content, affect the extraction process. River and harbor sediments, sludges, and soils with a high fines (>30%) and moisture content (>30%) can be effectively treated by SCE processes; however, it may be more cost-effective to reduce the contribution of fines with size separation equipment and/or drying the solids prior to extraction. Alternatively, a critical solution temperature (CST) or hydrophylic solvent can be used during the first extraction cycle to dewater solids. Solids with high total organic content (>10%) require more extraction cycles to meet a given cleanup goal than solids with low total organic content (<10%).

10.2.2 Contaminants and Mixtures

Contaminants at hazardous waste sites may be from a single source, such as a spill, or they may comprise a mixture of contaminants as is the case with many uncontrolled dump sites. SCE systems are effective in removing many of these contaminants and contaminant mixtures from solids.

Table 10.1 shows the effectiveness of SCE on general contaminant groups for soil, sludges, and sediments. Note that some claims have been made regarding reduction of metals using specific solvents; however, such claims have not been substantiated in the field.

10.2.3 Site Types

SCE has been successfully used to treat wastes from the following types of sites:

- river and harbor sediment sites (Tose 1987; Meckes et al. 1992; US EPA 1990a);
- refinery waste sites (CF Systems Brochure 1992);
- chemical plants (US EPA 1994a);
- wood treating sites (US EPA 1994a);
- pesticide sites (Meckes, Engle, and Kosco 1996);
- PCB spill sites (Meckes et al. 1997); and
- hazardous waste dump sites (Meckes et al. 1997; Meckes, Engle, and Kosco 1996; Meckes et al. 1992).

10.3 Treatment Trains

SCE systems are normally comprised of a group of unit processes, within a series of unit processes, which are commonly referred to as a treatment train. With respect to SCE, these other unit processes may provide pretreatment of the feed waste or posttreatment of the solids, wastewater, process gases, or concentrated extract. The need for these unit processes is dictated by site-specific considerations, such as quantity and contaminant level of oversize material, extent of contamination of wastewater following SCE, type and concentration of contaminants in the solids, and concentration of volatile emissions.

Table 10.1
Effectiveness of Solvent Extraction on General Contaminant Groups for Soil, Sludges, and Sediments

Contaminant Groups	Effectiveness		
	Soil	Sludge	Sediments
Organic			
Halogenated Volatiles	▲	▲	▲
Halogenated Semivolatiles	■	■	■
Nonhalogenated Volatiles	■	■	▲
Nonhalogenated Semivolatiles	■	■	■
PCBs	■	■	■
Pesticides	■	▲	▲
Dioxins/Furans	▲	▲	▲
Organic Cyanides	▲	▲	▲
Organic Corrosives	▲	▲	▲
Inorganic			
Volatile Metals	□	□	□
Nonvolatile Metals	□	□	□
Asbestos	□	□	□
Radioactive Materials	□	□	□
Inorganic Corrosives	□	□	□
Inorganic Cyanides	□	□	□
Reactive			
Oxidizers	□	□	□
Reducers	□	□	□

■ Demonstrated Effectiveness: Successful treatability test at some scale completed.
▲ Potential Effectiveness: Expert opinion that technology will work.
□ No Expected Effectiveness: Expert opinion that technology will not work.

Source: US EPA 1994

Pretreatment typically consists of screening and/or crushing operations to reduce the size of particles entering the extractor. Some vendors recommended a maximum particle size of approximately 0.6-1.3 cm (0.25-0.5 in.) in diameter (Meckes et al. 1992).

The need for wastewater treatment is normally determined based on site restrictions. Direct discharge to a collection system for a publicly-owned treatment works (POTW) is preferred. If this is not available, on-site treatment consisting of filtration and/or carbon adsorption or more advanced treatments may be required.

Similarly, control of gaseous emissions from distillation or evaporation equipment may be required depending on site-specific requirements. Activated carbon can be effective in removing solvent vapors from such emissions.

Solids discharged from an SCE system may not be free of contaminants of concern. Most currently-available SCE systems are designed to remove organic contaminants from solids. However, mixed wastestreams may also have high levels of hazardous metals. Such metals may be removed via soil washing. Alternatively, the solids may be mixed with appropriate agents for stabilization.

The concentrated extract is typically removed and treated off-site by incineration or dechlorination. However, on-site incineration could be included as part of a treatment train if not cost-prohibitive. Also, in the case of chlorinated hydrocarbons, it may be possible to treat extracts on-site with dechlorination technologies such as base-catalyzed dechlorination.

11

DESIGN DEVELOPMENT

11.1 Remediation Goals

For solvent/chemical extraction (SCE), the goal of a remediation project is typically removal of one or more organic contaminants from a sludge, soil, or wastewater. Removal of other types of contaminants (for example, removal of metals by adding metal chelating agents to the solvent) has rarely been practiced on a commercial-scale.

11.1.1 Proven Performance

SCE processes have been selected by the US EPA for some Superfund sites contaminated with organics such as polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), and pentachlorophenol. The SCE processes discussed herein were developed to treat a wide range of organic contaminants in several different matrices. See Table 11.1 for a summary of the types of contaminants removed in bench-, pilot-, or demonstration-scale testing. Development of these processes has typically proceeded from a design addressing a particular problem (for example, PCBs in sediments) to a more general design capable of treating a wide range of contaminants and matrices.

One vendor, employing an amine solvent-based process, has reported results for treatability tests on soils, sludges, and sediments contaminated with PCBs, PAHs, pesticides, and other semivolatile and volatile organic contaminants (US EPA 1992c). The results show that the highest removal efficiencies were achieved in treating solids that had high initial concentrations of organic contaminants. However, in many cases, the treated solids retained a significant amount of the initial contaminant. For example, tests of three harbor sediment samples contaminated with PCBs in concentrations of >20,000 mg/kg resulted in removal efficiencies of >99.8% after three extraction stages, but residual PCB concentrations in the solids ranged from 27 to 720 mg/kg. Therefore, treatability tests should be conducted before selecting SCE for site remediation. On the other hand, treatment of two sediment samples with initial PCB concentrations of 427 and 425 mg/kg resulted in removal efficiencies for both samples of 99.6% and residual PCB concentrations in the solids of 1.6 and 1.8 mg/kg or an average of 1.7 mg/kg.

Table 11.1
Potential Applications of Commercial Solvent/Chemical Extraction Processes

Contaminant Type	Matrices Tested
PCBs	Soils (sands, loams, clays)
PAHs	Sediments
VOCs	Sludges
Semi-VOCs	Slurries
Pesticides	Wastewaters Drilling cuttings Petroleum-listed wastes
Pentachlorophenols	K044 - K052 wastes*
BTX	
Dioxins	
Diesel fuel	
Petroleum Hydrocarbons	

*RCRA waste codes:

Water Treatment Sludges	K044
Dissolved Air Flotation (DAF) Float	K048
Slop Oil Emulsion Solids	K049
Heat Exchanger Bundles Cleaning Sludge	K050
American Petroleum Institute (API) Separator Sludge	K051
Tank Bottoms (leaded)	K052

Source: Donnelly et al. 1995 and Office of the Federal Register 1996

Supercritical fluid or liquefied gas SCE technology is used to remove organic contaminants, such as hydrocarbons and oil and grease, from wastewaters, sludges, sediments, and soils. Carbon dioxide is generally used for aqueous solutions, such as process water and wastewater. Light hydrocarbons are recommended for sludges, sediments, and soils. Supercritical technology can be applied to a large variety of organic contaminants, including carbon tetrachloride, chloroform, benzene, naphthalene, gasoline, vinyl acetate, furfural, organic acids, dichloroethane, oil and grease, xylene, toluene, methyl acetate, acetone, alcohols, phenols, aliphatic and aromatic hydrocarbons, and PCBs.

One vendor reports that its drying/SCE process can be used to remove oil-soluble organics from soils, sludges, and other wastes as well as to dry aqueous mixtures (NETAC 1991). As noted in a US EPA Superfund Innovative Technology Evaluation (SITE) program report (US EPA 1992a), the process can be used to treat wastes contaminated with organics, especially wastes with high water content. The developer claims a new approach for remediating soils, petroleum K-wastes, spent drilling muds, and hazardous sludges containing petroleum-based contaminants, such as fuel oils, PCBs, and polynuclear aromatics (US EPA 1992a). Success is also reported for removal of dioxins (US EPA 1991b; US EPA 1989).

Other vendors have reported success on the bench-, pilot- or full-scale for removal of pentachlorophenol from activated carbon.

Case histories of the applications of SCE systems are provided in Chapter 13.

11.1.2 Reliability

Like soil washing, the reliability of an SCE project in attaining the required treatment standards is dependent upon the relevance and accuracy of the information on which the system is designed and the experience of the contractor in operating the system and responding to changing conditions. Although soil washing has been used extensively in Europe, only a handful of commercial SCE remediation projects have been carried out. Most of these projects have been conducted in the United States and some are described in Chapter 13.

In general, SCE has only recently been applied in the remediation of contaminated soils; therefore, few data on commercial plant operations are available to evaluate long-term reliability. Most data are from bench-scale, pilot-scale, or demonstration systems. SITE demonstration reports (US EPA 1990a; US EPA 1992a) have identified some operating problems, including foaming of the extraction fluids, gumming-up of process lines, and intermittent sticking of solids to process equipment. Corrective actions have been identified that presumably will solve such problems in full-scale applications. Amine solvent extraction is reported to be free of these types of problems.

Although treatability tests at the bench-scale have shown that SCE is applicable to a wide range of contaminants, they have also shown that process parameters must be optimized for each application. In commercial applications, SCE processes must be able to handle the expected variations in feed properties found at a given site. Until more data from commercial applications become available, extensive site-specific treatability testing should be considered when applying this technology.

11.1.3 Acceptance by Regulators

SCE has been accepted to a limited extent by the US EPA. As of November 1996, SCE had been selected as the technology of choice at five sites. These sites are: United Creosoting, Texas; Arrowhead Refinery Co., Minnesota; Arctic Surplus, Alaska; Carolina Transformer, North Carolina; and Idaho National Engineering Laboratory, Idaho (US EPA 1996). SCE is promoted by the US EPA's Technology Innovation Office as an available innovative remediation process.

Although there have been few SCE applications to date, the potential exists for additional use of the technology based on the following factors:

- several SCE processes are under, or have completed, evaluation in the SITE demonstration program, which provides independent verification of the efficiency, operability, and cost of the processes;
- commercial SCE processes are already being used to treat petroleum refinery and other waste streams, allowing determination of long-term costs and system reliability;
- SCE processes do not require extensive pretreatment of the feed (other than size reduction) and can tolerate a wide range of soil moisture content (from about 5% to 90% moisture); and
- SCE processes are cost-competitive with other ex-situ technologies used to treat organic-contaminated soils, sludges, and sediments.

Use of SCE for treatment of contaminated soils, sludges, sediments, and wastewaters is a new application of a widely-used and well-understood technology. SCE is used in varied industries such as food, pharmaceutical, fine chemicals, mining, and minerals processing. The unit operations involved are also simple and well understood.

SCE has demonstrated a number of advantages in its industrial applications. It is expected that these advantages will also apply to its use in treating soils, sludges, sediments, and wastewaters. These advantages include:

- demonstrated high removal efficiencies and low residual values for a wide range of organic contaminants (PCBs, PAHs, petroleum hydrocarbons, pesticides, and dioxins);
- demonstrated high concentration factors (up to 10,000:1), resulting in greatly-reduced volumes of material requiring additional treatment; and
- concentrated contaminant streams that can potentially be recycled, especially when petroleum hydrocarbons are the soil contaminant.

Although the unit operations are well proven in other applications, their use for soil cleanup is still in its infancy. Most of the processes discussed in this monograph have few full-scale commercial applications. SCE is a developing treatment technology requiring site-specific application testing and evaluation.

11.1.4 Acceptance by the Public

To date, the public has not objected to the use of SCE for remediation projects, and the advantages of the technology appear to be recognized. However, in some cases, the use of high odor and/or flammable solvents is a potential problem. The long-term success of these processes depends in part on the ability of the operators to minimize these potential detrimental effects.

11.2 Design Basis

11.2.1 Required Design Information

This section describes the basic information needed to apply SCE technology with regard to soil physical characteristics, contaminant type and concentration, approaches to treatment, site conditions, treatment standards, and schedule.

11.2.1.1 Soil Physical Characteristics

SCE requires excavation of solids or the transfer of pumpable solids to the point of treatment. Solids produced from such activities are of varying sizes. Knowledge of the size of the particles to be treated is needed to maximize extraction and solid/liquid separation efficiencies. Oversize material (approximately >5 cm [2 in.] in diameter) is defined as debris and should be removed prior to treatment via the use of bar or vibratory screens. Alternatively, such material may be crushed or reduced in size using hammer or pug mills, as appropriate. Size reduction facilitates particle/solvent contact which increases removal efficiency and reduces the number of extraction cycles needed to achieve a remediation goal.

Moisture content can affect extraction efficiency for some SCE technologies. The degree to which the soil moisture content is a factor in treatment is directly related to the choice of extraction solvents. Critical Solution Temperature (CST) and hydrophillic solvents may be used to dewater solids during the initial extraction stage. When this option is used, provision must be made for separation of the solvent/water mixture prior to solvent reuse. This is commonly accomplished using evaporators, distillation columns, or gravity decanters. Alternatively, the soil may be dried prior to extraction. Drying may be accomplished through the use of drying beds or by mechanical drying equipment, e.g., vacuum extraction or thermal treatment. When drying is used, the appropriateness of VOC emission controls must be determined. Another alternative is to use hydrophobic solvents at temperatures above the boiling point of water to dewater the solids by volatilization. Volatilization requires an additional process to collect and dispose of the water vapor.

11.2.1.2 Contaminant Type and Concentration

The specific type of contaminant and its concentration can affect the performance of an SCE system. For example, an SCE system is capable of removing VOCs from solids; however, other technologies, such as soil vapor extraction or thermal desorption, may be equally effective and less expensive. On the other hand, SCE systems can be effective in removing both SVOCs and VOCs, whereas a soil vapor extraction system would be unable to remove the SVOC fraction. To date, SCE systems have been successfully used for removal of SVOCs, PCBs, PAHs, pesticides, and oil and grease. No limit has been identified regarding initial contaminant concentration. However, it has been shown that the higher the initial contaminant concentration, the higher the final contaminant concentration. SCE system operators can compensate for this by increasing the number of extraction cycles, but there does appear to be a point at which the use of additional extraction cycles is no longer effective. Consequently, bench-scale treatability studies are recommended to determine if solvent extraction can meet specified remediation goals.

11.2.1.3 Approaches to Treatment

Hazardous waste sites are not homogeneous; highly contaminated areas, which are referred to as "hot spots," often exist. Contaminant concentrations in hot spots are frequently used to specify the upper limits for selection of remedial technologies. However, excavation, combined with size separation, tends to redistribute the contaminant load, lowering contaminant concentrations prior to treatment. Consequently, several approaches may be used prior to implementation of SCE. The first approach is to determine if SCE can achieve remediation goals based on results of treatability tests conducted on hot spot soils. The second approach is to determine if excavation and disposal of hot spots is more economical than SCE treatment, reserving such treatment for the remainder of the site solids. The third approach is to determine if use of a size separation process could effectively be used to limit the volume of contaminated soil requiring treatment.

11.2.1.4 Site Conditions

Site conditions must allow for operation and maintenance of excavation and screening equipment and dewatering and/or drying of the feed. In addition, the site should have adequate area for the infrastructure necessary to support the extraction and solvent recovery plant and for holding treated solids.

The site conditions that must be considered relative to the treatment plant itself include location of the site, layout of the plant and materials staging area, subsoil conditions at the location of the plant operating pad, location and specifications of electrical power, location and quality of process and fire protection water, location of clean solvent storage, and weather conditions that may be expected during remediation.

11.2.1.5 Treatment Standards

Treatment standards for contaminants of concern are often determined by conducting a site-specific risk assessment. In some cases, the risk assessment may not yet be completed or is being negotiated with regulators. In such cases, it is best to base SCE designs on the most stringent potential standard. Furthermore, solvents used for extraction are not completely removed from the treated solids. Therefore, it is important that treatment standards be established for any residual solvent.

11.2.1.6 Schedule

The schedule under which the work must be performed will establish a reasonable range of the system throughput rate and thus the size of the equipment. Project completion dates will be most important and will determine the shift conditions under which the plant must operate. SCE systems are flexible in that they are easy to start up and shut down.

11.2.2 Data Collection

Contaminant concentrations in soils, sludges, or sediments are important for designing an effective SCE system. Such information is usually collected as part of a site investigation and/or a remedial investigation.

However, such investigations rarely include determinations of particle size, moisture content, and total organic content (measured as oil and grease), all of which are useful in designing an effective SCE system. This information should be gathered as part of a treatability study.

11.2.2.1 Treatability Studies

Typically, SCE treatability studies are bench-scale. A minimum of two representative samples of the solids to be treated should be collected. One sample should represent solids with the highest contaminant concentration that the SCE unit will be required to treat. The other should represent the contaminant concentration that the SCE system would most often encounter during processing. These samples should be analyzed for particle size, moisture content, oil and grease, and contaminants of concern.

There is no one specific protocol for conducting SCE treatability studies. Such studies are often conducted by vendors of SCE technologies to determine if the vendor's process will effectively treat site wastes. Consequently, data collected under these vendor-specific test conditions may be of little benefit when considering other SCE technologies. At a minimum, type of solvent, solvent-to-solids ratio, temperature, pressure, and number of extraction cycles required to meet remediation goals must be determined. The ability to separate solvent from solids, and solvent from contaminants should also be ascertained. Results from these studies should be used to specify process sequences, unit process sizes, operating parameters, and to develop implementation cost estimates. A generic approach to conducting SCE treatability studies is provided in the US EPA document, *Guide for Conducting Treatability Studies Under CERCLA Solvent Extraction* (US EPA 1992b).

11.2.2.2 Pilot Studies

A successful treatability study indicates that SCE can achieve cleanup criteria. Bench-scale treatability studies conducted by technology vendors may yield sufficient information to pursue immediate implementation. However, in some cases, it is reasonable to conduct a pilot test in the field using all unit operations that are intended for full-scale operation. Pilot studies are used to confirm treatment effectiveness and to identify potential implementation or process problems that may not be evident during bench-scale testing.

Pilot-scale studies for SCE systems vary, and the protocol for such studies is established on a site-specific basis. SCE processes have been piloted in a number of cases with no more than 45 kg (100 lb) of solids per batch with a minimum of three batch runs. Other SCE processes have been pilot tested using several tons of solids. Such studies seldom require more than a month of actual field work after securing the appropriate permits and preparing the site. Results from the pilot test should be used to verify the selection of process sequences, unit process sizes, and operating parameters and to better estimate full-scale costs.

11.3 Design and Equipment Selection

SCE is based on unit operations from the chemical process and hydrometallurgical industries. Accordingly, much of the equipment is standard and "off-the-shelf." However, complete systems cannot be purchased and must, therefore, be designed and assembled by remediation companies. Designs vary widely from vendor to vendor, and different process configurations (and solvents) are sometimes employed for different projects by an individual vendor.

Design procedures are essentially the same as for soil washing and include the following (in order of implementation):

- sizing of equipment based on the desired throughput rate,
- development of mass and energy balances,
- development of a process-flow diagram, and
- development of piping and instrumentation diagrams.

Many, if not all, of the design documents listed above must be included in the application for an operating permit or permit equivalent.

11.4 Process Modification

An ideal matrix for application of SCE would be a dry sandy soil contaminated with <10,000 mg/kg SVOC. Contaminant concentrations above this level require numerous extraction cycles to achieve stringent cleanup goals. As the number of needed extraction cycles increases, so does the cost of treatment. Consequently, excavation and removal of contaminant hot spots for off-site disposal, or homogenization with site solids of low initial contaminant concentration should be considered prior to initiation of remedial activities.

Solids with high moisture contents (>30%) can be adequately treated by many SCE systems. However, dilution of hydrophillic solvents by the moisture, or the additional energy input (due to increased mixing requirements or thermal energy required to volatilize the moisture) to systems employing hydrophobic solvents will result in reduced removal efficiencies, and/or the need for additional extraction cycles to meet a specific cleanup goal. The use of drying beds, mechanical, and/or thermal driers should be considered as potential process modifications for high moisture content solids.

SCE processes are a collection of unit processes that are sized to work in concert. Many commercially-available systems operate as batch processes with the extraction vessel(s) serving as the single solids handling device during processing. Such designs minimize problems often encountered during solids handling and allow the use of common centrifugal or positive displacement pumps for the movement of solvent streams during processing. A comprehensive treatability study, as discussed in Section 11.2.2.1, can alert the remedial design professional to potential problems that may be encountered in the field.

The effectiveness of certain solvents in mobilizing organic contaminants can be pH dependent. For example, certain organic amine solvents remain in an ionized form at neutral pH. This limits the ability of the solvent to mobilize organic contaminants. At elevated pHs (>10 s.u.) these solvents are in an un-ionized form which increases their ability to mobilize organic contaminants. Consequently, addition of caustic just prior to initiating extraction is needed to maximize the effectiveness of such solvents.

The use of hydrophillic solvents to remove organic contaminants also results in removal of any water in the matrix. The treated solids are, therefore, dry. Removal of such solids from process equipment without the addition of moisture can produce fugitive dust emissions which may collect on process equipment or present a safety hazard. Such problems can be reduced or eliminated by adding water or steam to the treated solids just prior to discharge.

11.4.1 Soil Matrix Characteristics

SCE can be used to remove VOCs from most solids, but separation of VOCs from solvents may prove difficult. As noted earlier, solvents typically recovered by employing evaporation or distillation systems. SCE solvents have relatively low boiling points, which minimizes energy requirements and results in excellent separation of the solvent and high-boiling point organic contaminants. However, many VOCs have boiling points at or near those of many SCE solvents that may be used. Consequently, the VOCs must be separated from extraction solvents using fractional distillation techniques. Well-designed treatability tests should be used to determine if fractional distillation or some other method of solvent recovery may be required.

11.4.2 Physical Conditions

Staging of untreated solids, screening equipment, process equipment, treated solids, solvent storage, and fire protection equipment must be planned well in advance of mobilization. Additionally, the planning should account for the proximity of such operations to existing superstructures, utilities, and sensitive populations. This will ensure that operations are conducted in an orderly and timely fashion.

11.5 Pretreatment Processes

11.5.1 Debris and Vegetation

Pretreatment requirements vary depending on the individual site. However, initial feed preparation is generally the same and consists of removal of trees, stumps, and other vegetative matter. The soil must be excavated, and debris and boulders must be either removed or size-reduced. High-pressure water sprays are sometimes employed to clean the debris and boulders before disposal.

11.5.2 Feed Preparation

Feed preparation is also process-dependent. Typical operations include the use of shredders and screens to obtain feed with maximum particle sizes ranging from about 6 mm (0.25 in.) to about 7.6 cm (3 in.). Note that the mechanical agitation employed by most processes will result in additional size reduction.

In some cases, water is added to produce a pumpable slurry. For one process, water is removed from the feedstock via mechanical dewatering and/or evaporation.

Another process employs premixing of the feed with the solvent as a pretreatment step when contaminant concentrations are high (>3,000 mg/L)(Cash 1992). Premixing effects intimate contact between the solids particles and the solvent, thereby reducing the overall time required for extraction.

11.6 Posttreatment Processes

SCE processes produce treated solids, water and air emissions, and concentrated contaminant extract. Samples of treated solids must be analyzed to determine if the contaminants of concern have been sufficiently removed to meet cleanup criteria. If they do not, provisions must be made for re-treatment or off-site disposal.

Water generated from solvent recovery processes must also be tested for contaminants of concern prior to disposal in a Publicly Owned Treatment Works (POTW). Alternatively, wastewater treatment processes may need to be designed for eliminating contaminants of concern prior to discharge.

Air emissions are minimal from SCE processes. Most emissions are from process vents used to ensure that excessive pressure will not build up within the system. Such vents should be routed to a condenser and/or activated carbon filters prior to being discharged to the atmosphere.

Contaminant extract is the product of the solvent recovery or purification system. All solvent-extractable materials are concentrated in this fraction. Therefore, this material is normally disposed by off-site incineration. Other options include dehalogenation of halogenated wastes and disposal in a permitted landfill. If the concentrate is not considered a hazardous waste, it may be recycled.

11.7 Telemetry, Process Control, and Data Acquisition

The information provided on telemetry, process control, and data acquisition in the previous soil washing (Section 3.7) also applies to SCE. A specific process control system used by one SCE technology vendor is described below.

This instrumentation control system provides automatic control of the system and minimizes the requirements for operator attention. All control functions operate in a fail-safe mode, going to a fail-safe and re-startable mode upon loss of power. Redundant measurement functions are provided where needed to ensure safe operation. Additional controls provide equipment protection, indicate operating parameters, and initiate alarms in case of abnormal conditions or malfunctions.

Indicators, controllers, and associated equipment are displayed on and controlled from a display and keyboard at the operator interface located near the solvent extraction system. This equipment permits an operator to supervise operation of the entire system, determine the location and type of any malfunction, and initiate corrective action. Based on final design review with the client, the local control panel may require installation in a pressurized control cubicle to meet electrical codes.

The overall control system consists of several programmable logic controllers (PLCs), connected to a CRT and an operator's keyboard, which serves as the operator's interface. A local panel associated with the field equipment (extractor) requiring local operator attention is linked to the central operator display on the control panel to provide the operator information on field activities. The PLCs are programmed for all discrete and analog control with software running on an IBM-compatible computer. The display panel is programmed as the main computer interface with a supplemental IBM-compatible keyboard. A data highway connection to the main control room is provided. Alarms and process summaries are logged and printed in the main control room.

Two PLC systems are incorporated into the control design. One PLC (with redundant backup) is dedicated to control and operation of the extractor/dryer sequence. Complete isolation of all control logic for the extractor sequence from other plant control functions ensures safe operation of this critical process equipment. The final control logic established for the extractors is permanently burned into read-only-memory, and on-line logic changes are impossible. The other PLC controls the remainder of the processing equipment and the main operator control interface in the control room. A noninterruptible power supply is provided for the PLC and operator interface equipment to permit monitoring and orderly shutdown of the facility upon loss of electrical power. Communication between equipment skids and the main control PLC system is via fiber optic cable to ensure the highest possible protection from electrical noise and to prevent erratic control system operation.

All control valves are pneumatically actuated with a spring-return fail-safe. The combination of pneumatically-operated valves (with several minutes of air supply) and battery backup for the control system allows the system to shut down the process equipment in an orderly fashion if power failure occurs.

Electronic transmitters signal the control room operator with continuous information concerning process parameters, such as temperature and flow. Local-only indication of process variables are generally limited to pump discharge pressures, seal water flow, and similar variables that are typically of interest to the field operator.

11.8 Safety Requirements

There are numerous safety and health issues that must be addressed prior to implementation of remedial activities at hazardous waste sites. In addition to safety requirements applicable to typical waste site activities and operation of process equipment (see Section 3.8), two other issues must be addressed when considering use of SCE processes: (1) working with flammable and thereby potentially hazardous solvents and (2) handling concentrated organic wastes.

All SCE processes use flammable organic extraction fluids that present potential fire and explosion hazards. The flammability of these extraction fluids varies. Low-molecular-weight hydrocarbons under pressure present the greatest potential risk of explosion. However, numerous other extraction fluids are volatile or are considered *highly* volatile with the potential to produce explosive vapors. To minimize these risks, all solvent process tanks must be grounded, and nonsparking pumps and motors (typically pneumatic) must be used in and around process equipment. Additionally, Chapter 5 of the National Fire Protection Association (NFPA) standard requires that a restricted access zone must extend from the extraction plant to a 15-m (50-ft) radius around the extraction plant, and a control zone must extend from the 15-m (50-ft) line to a radius of 30 m (100 ft)(NFPA 1990). This requirement may make it difficult to site an SCE system at some locations.

Still bottoms from solvent recycle/recovery systems yield highly-concentrated waste streams. These wastes include all solvent-soluble substances that have boiling points greater than the extraction solvent. Consequently, the contaminant(s) of concern will be present along with numerous other organic compounds. This waste stream remains in a relatively mobile state as it is removed from the process. Due to the concentrated nature of the waste, individuals who handle this material should wear double layers of chemical-resistant personal protective equipment for splash protection. Furthermore, secondary containment of vessels holding extract is recommended.

11.9 Specifications Development

The specifications development considerations presented and discussed in Section 3.9 for soil washing, including the benefits of "simultaneous engineering" also apply to SCE.

11.10 Cost Data

Cost estimates for application of SCE treatment systems at hazardous waste sites vary widely due to site-specific considerations. Some of these considerations are related to the material to be treated, such as total quantity, contaminant concentrations, total extractable organic content, moisture content, and particle-size distribution. Other factors are related to physical constraints associated with the site, such as availability of an area for setup of process equipment, materials staging, and utilities; fire protection; and accessibility. Each of these variables can affect overall project costs. For example, the cost per unit volume treated decreases with an increase in the total volume of material to be treated. This is due primarily to fixed-cost items, such as mobilization, site preparation, regulatory compliance requirements, and demobilization, associated with process operations. These costs are incurred regardless of the volume of waste to be treated at a given site. An economic model developed by the US EPA's SITE program (Evans 1990) categorizes operating costs for SCE remediation technologies into the following 12 elements:

- site preparation,
- permitting and regulatory requirements,
- startup,
- equipment,
- labor,
- consumables and supplies,
- utilities,
- effluent treatment and disposal,
- residual and waste shipping and handling,
- analytical services,
- maintenance and modifications, and
- demobilization.

Based on this model and estimates solicited from technology vendors, SCE unit costs range from \$110 to \$576/tonne (\$100 to \$523/ton)(see Table 11.2). The values presented in Table 11.2 are estimates and can vary substantially for the above listed reasons. The quoted unit costs include the cost of disposal and destruction or treatment of all residue, analyses associated with system operations (except for the Carver-Greenfield process), and mobilization and demobilization.

Table 11.2
Cost Comparison

Process	Quoted Costs \$/tonne (\$/ton)*	Wet vs. Dry Pricing Basis	Site Preparation Included	Quantity tonne (ton)	Disposal/ Destruction of Residues	Analytical	Mob/ Demob**	Profit Included
B.E.S.T.	165 (150)	Wet	No	> 18,000 (> 20,000)	Yes	Varies	Yes	Yes
CF Systems	110-550 (100-500)	Wet	Yes	> 57,000 (> 63,000)	Yes	Yes	Yes	Unknown
Carver-Greenfield	129-576 (117-523)	Wet	Yes	21,000 (23,000)	Yes	No	Yes	Yes
TKRG***	187-330 (170-300)	Wet	Yes	675 (750)	Yes	Varies	Yes	Yes

*Costs are estimates only and are expected to be site-specific.
**Mob = mobilization, demob = demobilization
***Terra-Kleen Response Group, Inc.

Source: Donnelly et al. 1995 (modified); US EPA 1997

The US EPA has published detailed cost estimates for the CF Systems process (US EPA 1990a) and the Carver-Greenfield process (US EPA 1992d). These estimates include technology-specific costs and a breakdown of site-specific costs. In estimating costs for the CF Systems process, the US EPA postulated the following scenarios:

- a base case treating 800,000 tonne (880,000 ton) of sediments contaminated with PCBs in concentrations of 580 mg/L at 450 tonne/day (500 ton/day) over a 11.3-year period;

- a hot-spot case treating 57,000 tonne (63,000 ton) of sediments contaminated with PCBs in concentrations of 10,000 mg/L at 90 tonne/day (100 ton/day) over a 1-year period; and
- analytical costs of $500/day in both of the above cases.

The estimated cost for the base case was $163 ± 20% per tonne ($148 ± 20% per ton) of raw feed, including excavation and pre- and posttreatment costs, but excluding final contaminant destruction costs. Excavation and pre- and posttreatment costs were estimated to be 41% of the total costs.

The estimated cost for the hot-spot case was $492, -30% + 50%, per tonne ($447, -30% + 50%, per ton) of raw feed. Excavation and pre- and posttreatment costs were estimated to be 32% of the total costs (US EPA 1990b).

US EPA also estimated the cost for the Carver-Greenfield process assuming treatment of 21,000 tonne (23,000 ton) of drilling mud contaminated with petroleum wastes. The total cost estimate was $576/wet tonne ($523/wet ton), with $243/tonne ($221/ton) allocated to technology costs. Site costs were estimated to be $333/tonne ($302/ton), including $264/tonne ($240/ton) for incineration of contaminated residuals. The estimate excluded regulatory, permitting, and analytical costs because of their variability. Also excluded were effluent treatment and disposal costs. Rather than assume a cost for incineration, the vendor assumed that the process would separate indigenous oil, which would be sold to a refinery for $26/tonne ($24/ton), resulting in an overall cost of $285/tonne ($259/ton)(US EPA 1992e).

11.11 Design Validation

The design validation concepts presented and discussed in Section 3.11 for soil washing also apply to SCE.

11.12 Regulatory Permits

As noted in Section 3.12 regarding permitting of soil washing applications, a complete review of pertinent environmental regulations must be conducted early in the remediation process, and appropriate federal, state, and local permits must be secured prior to initiating site work. Processes and process residuals unique to SCE systems must be addressed during the permit process. These include use of flammable solvents, volatile emissions, and handling of concentrated waste streams.

11.13 Performance Measures

SCE is a separation technology. It is employed to significantly reduce the volume of waste that must be further treated and must produce a treated residue that meets the requirements of the Record of Decision (ROD) or other performance requirements. Thus, all of the associated performance measurement considerations presented in Section 3.13 for soil washing apply to SCE.

11.14 Design Checklist

The following is a design checklist for SCE.

1. **Waste Characterization**
    - Concentrations of contaminants of concern
    - Particle-size distribution
    - Moisture content
    - Concentration of the total solvent soluble fraction
2. **Site Conditions**
    - Site access
    - Facility layout

- Excavation/staging plan
- Pad and containment requirements
- Utilities access
- Building requirements
- Support facilities (offices, decontamination facilities)
- Hot spot locations

3. **Treatment Standards**
   - Contaminants of concern
   - Cleanup goals
   - Disposition of “clean” material
4. **Treatability Study Information**
   - Soil matrix/contaminant evaluation
   - Conceptual process-flow diagram
   - Conceptual engineering
   - Cost estimate
5. **Schedule**
   - Site preparation
   - Process equipment mobilization
   - Waste processing
   - Demobilization

12

IMPLEMENTATION AND OPERATION

12.1 Implementation

The procurement and contracting considerations presented and discussed for soil washing apply equally to SCE. One SCE vendor offers to sell or lease units for its solvent-based process or to provide treatment services for a specified fee.

12.2 Start-up Procedures

Startup of a SCE system follows essentially the same procedures as those for startup of soil washing systems. These procedures include hydrostatic tests of the process tanks and plumbing followed by process runs using clean soils. At that time, a complete check of the operating equipment for leaks and system grounding is conducted. For a detailed discussion of start-up procedures refer to Section 4.2 on soil washing.

12.3 Operations Practices

The considerations presented in Section 4.3 for soil washing generally apply to SCE. However, SCE uniformly yields essentially 100% of the starting mass as cleaned product, whereas soil washing sometimes produces a contaminated fines stream containing an appreciable amount of the starting mass. Hence, the major performance indicator for SCE is meeting the treatment standard for the entire mass of feed soil or sludge.

12.4 Operations Monitoring

Operations monitoring is conducted to ensure that the process operates efficiently, consistently, and safely. The specific requirements for such monitoring are dependent upon the design of the remedial action as well as the specific SCE process employed. Section 4.4 on soil washing provides a general perspective of the types of operations monitoring that would be typical for remedial processes. The parameters to be monitored for SCE systems include:

1. **Screening**
    - Loading (mass/volume)
2. **Extraction**
    - Solvent addition (mass/volume)
    - Duration of extraction cycle
    - Mixer speed
    - pH
    - Temperature
    - Pressure
3. **Phase Separation**
    - Duration of phase separation
    - Visual inspection of separation effectiveness
    - Concentration of contaminants in the solvent
4. **Solvent Recovery System**
    - Temperature
    - Pressure
    - Condenser temperature

5. Treated Solids

- Appearance
- Concentration of contaminants

12.5 Quality Assurance and Quality Control

The Quality Assurance and Quality Controls in Section 4.5 for soil washing also apply to SCE.

13

CASE HISTORIES

This chapter presents four Solvent/Chemical Extraction (SCE) cases. Each of these cases are reprinted verbatim (other than minor edits to conform to the monograph outline) from previously published works.

In the first case, the US EPA's Superfund Innovative Technology Evaluation (SITE) Program evaluated a pilot-scale solvent extraction process developed by the Terra-Kleen Response Group (TKRG). This process uses a proprietary solvent, or mixture of solvents, to extract organic contaminants from solids. A pilot-scale evaluation was conducted at Naval Air Station North Island (NASNI), near San Diego, California, on soils which were contaminated with polychlorinated biphenyls (PCBs) and other organic substances. 4.5 tonne (5 ton) of soil with an average PCB concentration of 144 mg/kg were excavated, homogenized, and equally distributed to five extraction vessels. Eleven extraction cycles were used to produce a treated soil with an average PCB concentration of 1.71 mg/kg on a dry weight basis (98.8% removed). Oil and Grease (O&G) removal efficiencies were found to be 65.9%. This low O&G removal efficiency was attributed to solvent/solute relationships. Initial concentrations of hexachloro-dibenzofuran (HxCDF) in soils averaged 0.067 μg/kg. Following solvent extraction, no HxCDFs were detected (<0.117 μg/kg) in soil samples. A full-scale solvent extraction system was operated at a site in Stockton, California. Pesticides were extracted from 454 tonne (500 ton) of contaminated soil using 19 extractors, each 15.3 m^3 (20 yd^3) in volume. Three extraction cycles produced solids with ≤0.093 mg/kg residual pesticide (<99% removed). These results demonstrate that the TKRG's solvent extraction process is effective in removing organic contaminants from soils.

The case was developed by Mark C. Meckes, Scott W. Engle, and Bill Kosco, and reprinted with permission from the *Journal of the Air and Waste Management Association*, Volume 46, Number 10, October 1996.

In the second case, the US EPA, through its Superfund Technical Assistance Response Team (START) and Superfund Innovative Technology Evaluation (SITE) Programs, completed a treatability study to determine the effectiveness of solvent extraction in separating polychlorinated biphenyls (PCBs) from soil collected at the Springfield Township Dump (STD) Superfund Site near Davisburg, Michigan.

The study consisted of a total of six runs, in which 45.4 kg (100 lb) of dried soil was processed for each run. Based on preliminary analytical results, three 20-minute extraction cycles were chosen as the most economical way to achieve the project objectives. Therefore, this three-extraction cycle condition was repeated twice to acquire data for three runs operated at the same condition. The other three runs consisted of two, four, and five 20-minute extraction cycles.

The results of the study indicated that on average approximately 98% removal of PCBs was achieved for the test runs using three extraction cycles. The four- and five-extraction cycle runs were the most effective in reducing the concentration of PCBs in soil, to concentrations of 1.8 and 2.2 mg/kg, respectively. This indicated that the number of extraction cycles required for attaining the lowest concentrations of PCBs in product solids was greater than three but less than or equal to five since there was no discernible improvement in PCB removal from four to five extraction cycles. However, results from oil and grease analysis suggest that higher removal efficiencies may be possible with additional extraction cycles.

Analysis of the filtered process water collected from all six runs indicated that PCBs were detected only in the filtrate from the two-cycle run [1.9 micrograms per liter [µg/L)]. PCBs were not detected (<1.0 µg/L) in the filtrate collected from the other five runs.

This STD case was developed by Joseph Tillman, Lauren Drees, and Eric Saylor as a part of US EPA's START and SITE programs in Cincinnati, Ohio to announce key findings of a solvent extraction treatability study that is fully documented in a separate report of the same title.

The third case describes the patented Biotherm Process, a combination of dehydration and solvent extraction treatment technologies. This has wide applicability for separating hydrocarbon solvent-soluble hazardous organic contaminants (indigenous oil) from sludges, soils and industrial wastes. As a result of this treatment, the products from a Biotherm Process facility are:

(1) Clean, dry solids which meet U.S. Environmental Protection Agency (US EPA) Resource Conservation and Recovery Act (RCRA) Best Demonstrated Available Technology (BDAT) and/or Toxicity Characteristic Leaching Procedure (TCLP)[40 CFR, Part 261] regulations for hydrocarbons (typically less than 0.2% [by weight]) and are suitable for disposal in non-hazardous landfills;

(2) Water which is virtually free of solids, indigenous oil, and solvent and is treatable in an industrial or Publicly Owned Treatment Works (POTW) wastewater treatment facility;

(3) Extracted indigenous oil containing contaminants which may be recycled/reused for credit or disposed of at less cost than the original waste feed.

A successful demonstration of the Biotherm Process on spent oily drilling fluids was part of the US EPA Superfund Innovative Technology Evaluation (SITE) Program. In this paper the use of the Biotherm Process for economic treatment and minimization of hazardous refinery wastes is described, the SITE program results are reviewed, and the Biotherm Process technology extension to treatment of other wastes is presented.

The Biotherm Process case was developed by Theodore D. Trowbridge and Thomas C. Holcombe.

The fourth case is an evaluation of Resources Conservation Company's (RCC) Basic Extractive Sludge Treatment (B.E.S.T.®) pilot plant. This evaluation was conducted between July 1 and July 22, 1992, during a demonstration by the U.S. Environmental Protection Agency (US EPA), under the Superfund Innovative Technology Evaluation (SITE) Program. The demonstration evaluation was conducted in Gary, Indiana; the material treated was contaminated river bottom sediments collected from two locations within the Grand Calumet River (GCR). The organic contaminants of concern were PCBs and PAHs.

This demonstration was part of a cooperative effort. In addition to the US EPA SITE Program, other agencies included US EPA's Great Lakes National Program Office (GLNPO); the U.S. Army Corps of Engineers (COE), Chicago District; and US EPA Region V. The GLNPO Assessment and Remediation of Contaminated Sediments Program through the COE, in cooperation with US EPA Region V, arranged for the developer's services and the location where the demonstration was conducted.

GLNPO leads the efforts to carry out the provisions of Section 118 of the Clean Water Act (CWA). Under Section 118(c)(3) of the CWA, GLNPO is responsible for undertaking a five year study and demonstration program of methods for the assessment and remediation of contaminated sediments. One of the areas of concern for priority consideration is the GCR. The COE (Chicago District) has authorization (Rivers and Harbors Act of 1910) to maintain harbor channels by periodic dredging. This includes the federal channel at Indiana Harbor downstream of the GCR. However, US EPA has designated the bottom sediments at various locations as moderately polluted, heavily polluted or toxic. As a result, materials to be dredged from the Indiana Harbor and Canal are not suitable for open-water disposal in Lake Michigan. At the present time, an environmentally acceptable disposal facility for dredged materials from Indiana Harbor does not exist. Consequently, dredging to maintain adequate navigation depths has not been conducted at this harbor since 1972.

Case 1 — Site Demonstration of Terra-Kleen Response Group's Mobile Solvent Extraction Process

In 1986 the US EPA Office of Solid Waste and Emergency Response and the Office of Research and Development established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up uncontrolled hazardous waste sites across the country. The SITE Program is composed of four major elements: the Demonstration Program, the Emerging Technologies Program, the Measurement and Monitoring Technologies Program, and the Technology Transfer Program (US EPA 1994b). The Demonstration Program is designed to provide engineering and cost data for selected technologies by evaluating their ability to treat wastes from Superfund sites.

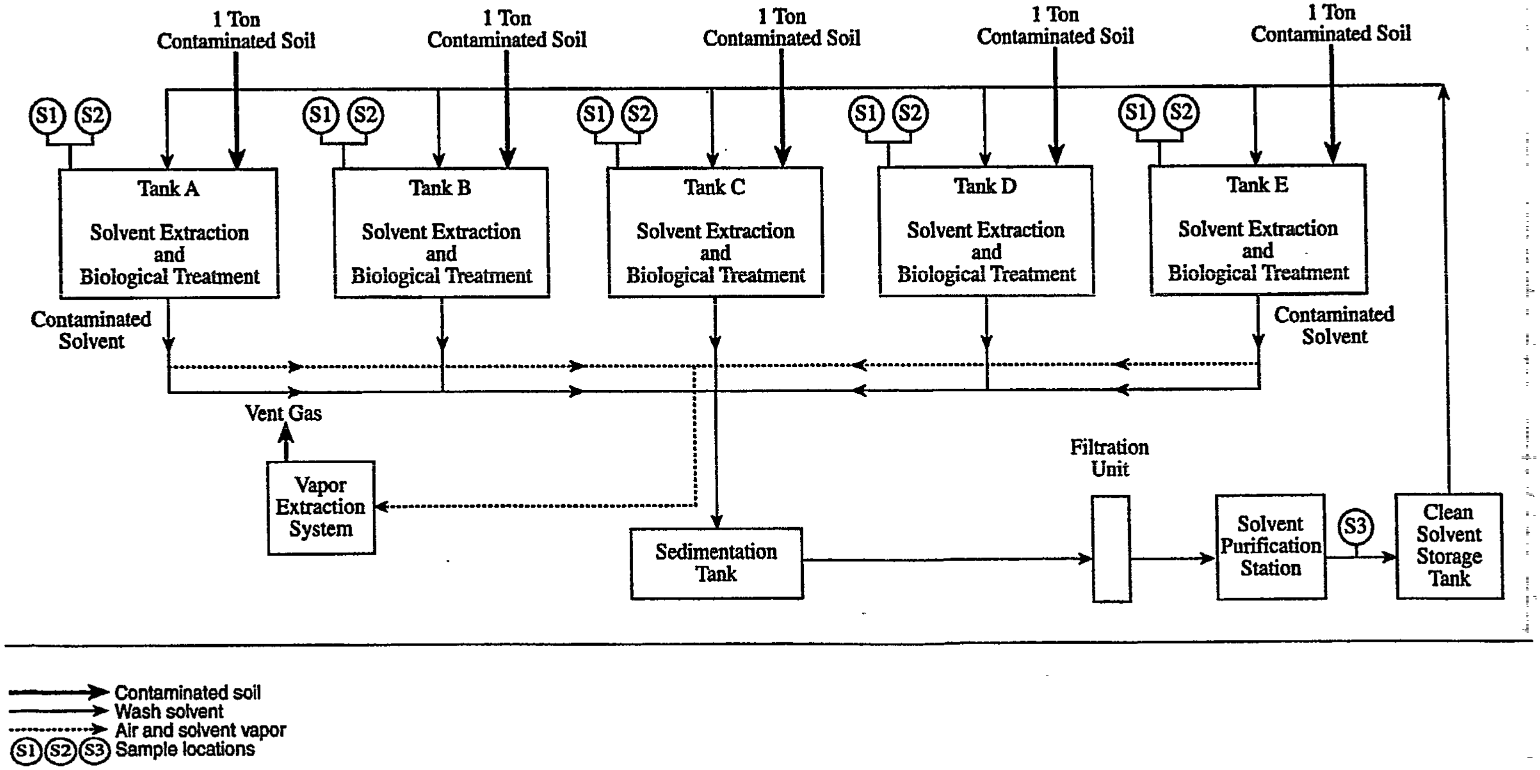
The Terra-Kleen Response Group (TKRG) requested that US EPA's Site Program evaluate their mobile solvent extraction technology, and was selected for evaluation under the Demonstration Program. This technology is a batch process system which uses organic solvents to separate contaminants from soils, sediments, and sludges. Organic contaminants are concentrated during processing, thus reducing the volume of hazardous wastes for final disposal. Therefore, this technology is nondestructive.

TKRG's solvent extraction process is transportable and can be configured to treat both small and large quantities of solids. System components are often available from local suppliers throughout the United States. This availability of system components reduces setup time and can reduce the amount of down time associated with equipment replacement.

The process is designed to use up to 14 different organic solvents or blends of solvents to extract organic contaminants from solids. The identity of these solvents is proprietary; however, none of the solvents used is listed as a hazardous waste according to the U.S. Code of Federal Regulations (1994).

A schematic diagram of the TKRG's solvent extraction system is shown in Figure 13.1. Processing begins following excavation of contaminated solids, which are loaded into extraction vessels. The vessels are covered, and clean solvent at ambient temperature and pressure is pumped into each one. Organic contaminants in the solids are mobilized by the solvent without the aid of a mixing device. Contaminated solvent then flows into a clarifier, where heavy solids are separated from the solvent by gravity. Clarified solvent is pumped through a microfilter, which removes fines, and then through a proprietary solvent purification unit that concentrates the organic contaminants. Clean solvent, discharged from the purification unit, is stored in a holding tank for reuse. This sequence of treatment steps, known as an extraction cycle, is repeated until contaminant concentrations of the solids within the extraction vessels are reduced to a desired level. At this point, the extraction vessels and all solvent carrying lines are drained, and the suction side of a centrifugal blower is connected to each vessel's solvent discharge line. Much of the solvent retained within a vessel volatilizes as air is rapidly drawn through it by the blower. Vapors discharged by the blower are passed through a condenser, where spent solvent is recovered as a liquid that is then filtered and processed through the purification unit. This recovered solvent is returned to the solvent storage tank for reuse.

Figure 13.1
Simplified Process Schematic — Terra-Kleen Solvent Extraction Process



Some solvent remains associated with the treated solids following vapor extraction. Further reduction of this residual solvent is effected through biodegradation. This is accomplished by adding a mixture of water, nutrients, and microorganisms to the soil in each extraction vessel. The vessels are allowed to stand until residual solvent concentrations have been reduced to acceptable levels for land disposal (several days).

Treated solids typically are removed from the vessels by a front-end loader and returned to the site. Contaminants concentrated by the solvent purification process are removed and disposed of off-site in accordance with applicable regulations. Purified solvent may be used for treatment of solids at other waste sites.

The SITE Demonstration of this technology was conducted during May 1994 in cooperation with the Naval Environmental Leadership Program (NELP) at Naval Air Station North Island (NASNI) near San Diego, California. TKRG was contracted by NASNI to treat 4.5 tonne (5 ton) of soil contaminated with polychlorinated biphenyls (PCBs). The performance of the TKRG's solvent extraction process was evaluated under the direction of the SITE project manager in accordance with a mutually agreed-upon quality assurance project plan. This project was considered a pilot-scale demonstration of the capabilities of the TKRG's solvent extraction process. The primary objective of this demonstration was to determine if the process could achieve a soil cleanup level of <2.0 mg/kg total PCB.

Experimental Methods

NASNI environmental managers used existing site to identify an area on base where soils were contaminated with >100 mg/kg PCB. A backhoe was used to excavate 4.5 tonne (5 ton) of PCB-contaminated soil from the area. This soil was then homogenized, using the front-end loader of the backhoe for mixing. Five extraction vessels (designated A through E) were filled with approximately one ton of homogenized soil, and were weighed to determine the total mass of soil to be treated. A sampling grid was laid out across the top of each vessel, and a core sampler was used to collect seven samples from each vessel. The seven samples were composited by vessel such that a composite sample represented the contents of an individual vessel. These samples were analyzed for soil moisture content (ASTM 1992) and particle-size distribution (ASTM 1990) in accordance with American Society for Testing and Materials (ASTM) methods. PCBs, volatile organic compounds

(VOCs), semivolatile organic compounds (SVOCs), and oil and grease (O&G) were analyzed in accordance with US EPA's test methods for evaluation of solid wastes (US EPA 1992g).

Following sample collection, approximately 380 L (100.4 gal) of clean solvent were added to each extraction vessel to cover the soil. After approximately 30 minutes, a drain valve was opened, and the solvent was permitted to drain by gravity into a clarifier. The total elapsed time for this fill, stand, and drain regime was approximately four to six hours and defines a single extraction cycle. Samples of the extraction solvent were periodically collected from the drain lines leading to the clarifier. Results from PCB analysis of these samples were used to determine if additional extraction cycles were required to meet the predetermined soil cleanup goal (<2.0 mg/kg PCB). The clarified solvent was pumped through a 5 micron bag filter and then through TKRG's proprietary solvent purification station. Samples of the purified solvent were collected periodically and analyzed for PCBs to determine if the purification system was effectively removing contaminants from the solvent. Purified solvent was pumped into a storage tank and held there until it was reused for subsequent extraction cycles.

When the solvent in all of the extraction vessels had finished draining, the valves to the drain lines were closed, and a second extraction cycle was initiated. The extraction cycles were continued until the measured concentration of PCBs in the drained solvent was <2.0 mg/L. Vapor extraction was then employed to further recover solvent from the solids. The suction side of a centrifugal blower was connected to the drain lines of each extraction vessel and was operated continuously for three days. Following this treatment, biological degradation of the remaining solvent was encouraged by spraying a mixture of water, nutrients, and microorganisms onto the contents of each extraction vessel, and seven core samples of the solids were collected, composited, and analyzed for contaminants as described above.

Results

The characteristics of the soils obtained from each extraction vessel prior to treatment are shown in Table 13.1. The untreated soil was a dry sand with an average moisture content of 0.83%; 93.6% of the solids was retained on a 0.075 mm screen. Polynuclear aromatic hydrocarbons (PAHs), hexachlorodibenzofurans (HxCDFs), and pentachloro dibenzofurans (PeCDFs) were identified, but only at low concentrations (total PAHs <3.4

Table 13.1
Physical and Chemical Characteristics of Untreated Soils

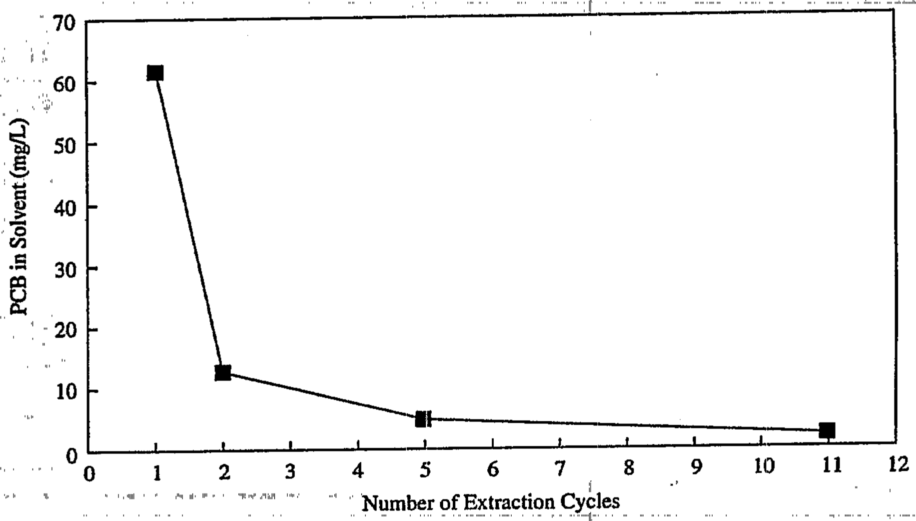
Analyte	Extraction Vessel A	B	C	D	E	Mean	SD[1]
Particle Size (% > 0.075 mm)	92.7	93.4	93.4	93.5	95.0	93.6	0.85
Moisture Content (%)	0.79	0.79	0.79	0.80	0.99	0.83	0.09
Total PAHs[2] (mg/kg*)	2.10	2.23	3.38	1.55	1.94	2.24	0.69
Total HxCDF[3] (mg/kg*)	0.659	0.629	0.647	0.848	0.704	0.697	0.089
Total PeCDF[4] (mg/kg*)	< 0.409	0.144	< 0.343	0.162	0.218	< 0.255	–
Total PCB[5] (mg/kg*)	130	140	134	147	170	144	15.7
Oil and Grease (mg/kg*)	747	720	707	767	860	760	60.5

[1] Standard Deviation
[2] Polynuclear Aromatic Hydrocarbons
[3] Hexachlorodibenzofuran
[4] Pentachlorodibenzofuran
[5] Polychlorinated biphenyl
*Dry weight

mg/kg; total HxCDFs <0.85 μg/kg; total PeCDFs <0.7 mg/kg in the untreated soils. Other analyses showed the average O&G concentration to be 760 mg/kg and the average total PCB concentration to be 144 mg/kg. The only PCB mixture identified matched Aroclor 1260 chromatographs.

Eleven extraction cycles were completed over seven days for each of the five 1 tonne (1 ton) batches of contaminated soil. Solvent discharged from one of the five extractors (A) was sampled and analyzed for PCBs after the first, second, fifth, and eleventh extraction cycles. Results from these analyses are shown in Figure 13.2. To limit the number of analyses, no attempt was made to sample solvent discharged from the other four extractors. The highest concentration of PCBs in the discharge solvent (61 mg/L) was observed following the first extraction cycle. This was expected, since a high initial concentration gradient existed between the solvent-soluble soil contaminants and the clean solvent. After completion of the first extraction cycle, the solvent-soluble contaminant concentrations in the soil were reduced to a level below the initial contaminant concentration, thus reducing the concentration gradient between the remaining solvent-soluble

Figure 13.2
Effect of Extraction Cycle on the Concentration of PCBs in Discharge Solvent



Discharge solvent from extractor A only

contaminants and the solvent during the next extraction cycle. Evidence of this is seen as the reduced solvent PCB concentration (14 mg/L) following the second extraction cycle. This same phenomenon is believed to be responsible for the observed reduction in solvent PCB concentrations following the fifth (4.4 mg/L) and eleventh (1.9 mg/L) extraction cycles.

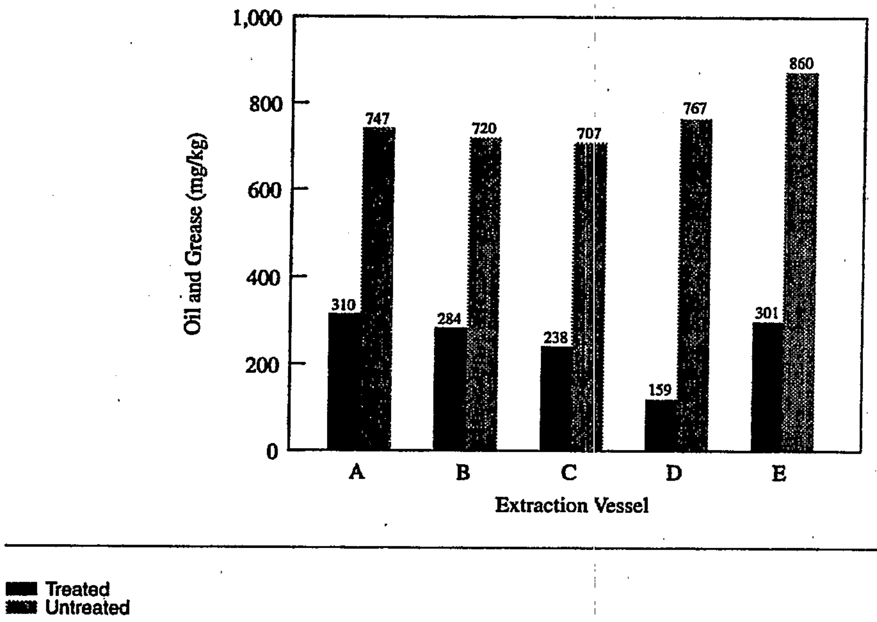
After vacuum extraction was completed, the covers were removed from the extraction vessels and a proprietary mixture of water, microorganisms, and nutrients was sprayed over the exposed soil surfaces. Soil samples were collected daily and analyzed for residual solvent. After two weeks, soil samples were again collected from each vessel. These samples were analyzed for organic contaminants and residual solvent.

Oil and Grease Removal

The ability of the TKRG's solvent extraction process to remove organic contaminants from site soils was determined by comparing concentrations of a given analyte before and after treatment. Measured concentrations of

O&G, PAHs, PCB, and, HxCDF in untreated soils were above method detection limits. Only the O&G and PCB concentrations in the treated soils were found to exceed the method detection limits for these analytes. Figure 13.3 graphically compares the concentrations of O&G in soils before and after treatment. The average concentration of O&G in the treated solids from all five extractors was 258 mg/kg, yielding an average removal efficiency of 65.9%. However, some variation in individual extractor performance is evident. For example, removal efficiencies O&G ranged from a low of 58.5% for extraction Tank A, to a high of 79.3% for extraction Tank D. Some of the observed variation can be attributed to sampling and analytical activities.

Figure 13.3
Oil and Grease Concentrations in Soil Before and After Extraction



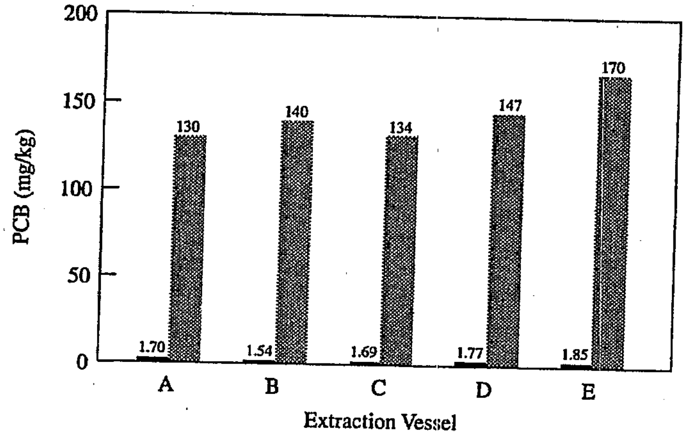
Data variability is common to monitoring activities, regardless of the matrix or technology under observation. To determine if the observed variation in O&G results was reasonable, the treated soil O&G concentrations from each extraction were compared to the average O&G concentrations from all five extractors, plus or minus two standard deviations (258 ± 124 mg/kg). Results from this comparison show that all treated soil O&G concentrations were within two standard deviations of the average value. This indicates that the observed variation between extraction tanks in product O&G concentrations was within control standards for this investigation. Regardless, the O&G concentration of the product solids from all extraction tanks was shown to be ≤310 mg/kg.

An earlier study (Meckes et al. 1993) using an alternate solvent extraction process at an Indiana waste site described an average O&G removal efficiency of 98.2% following treatment of one contaminated sediment sample. Sediment treated by that system had much higher initial O&G concentrations (mean = 7,580 mg/kg) than did the untreated soils used for this investigation (mean = 760 mg/kg). The average O&G concentration following treatment of sediments at the Indiana test site was found to be 140 mg/kg. This is less than half of the average O&G concentration observed in soil samples following treatment by the TKRG's process, and likely reflects the difference in the makeup of the O&G fractions between waste sites. No direct comparison was made between the two solvent extraction systems on split samples from a single source of contaminated solids. Therefore, based upon the above results, it is impossible to determine if one of the two systems could more effectively extract O&G from a given source of contaminated solids.

PCB Removal

PCB removal was consistently high with an average removal efficiency of 98.8%; concentrations of PCBs in treated soils averaged 1.71 mg/kg. Analytical results of the treated soil samples from all five extractors confirmed that the treatment objective — to produce soils with a total PCB concentration of <2.0 mg/kg — was achieved (Figure 13.4). Furthermore, it was determined that the average PCB concentration in the treated soil (1.71 mg/kg) was significantly less than 2.0 mg/kg (significance level $\alpha = 0.05$). The observed range of PCB concentrations (1.85 to 1.54 mg/kg) shows that little variation existed between the treated soil samples obtained from individual extraction vessels. As was noted above, some of the observed variation can be attributed to sampling and analytical activities.

Figure 13.4
PCB Concentrations in Soil Before and After Extraction



■ Treated
▨ Untreated

To determine if the observed variation in PCB results was reasonable, the PCB concentrations for the treated soil from each extractor were compared to the average PCB concentration for all five extractors, plus or minus two standard deviations (1.71 ± 0.22 mg/kg). Results from this comparison show that all treated-soil PCB concentrations were within two standard deviations of the average value. This indicates that the observed variation between extraction tanks in product PCB concentrations was within control standards for this investigation, and confirms the effectiveness of the process in consistently meeting the specified soil cleanup goal.

HxCDF Removal

Concentrations of HxCDFs in untreated soil samples were all below 1.0 µg/kg, with an average concentration of 0.697 µg/kg (Table 13.1). Concentrations of HxCDF in treated soils were all below method detection limits for this analyte (<0.117 µg/kg). A removal efficiency for HxCDF was estimated to be >83%, based upon the average concentration of HxCDF in the untreated soils, and on the method detection limit for this analyte in the solvent-treated soils.

Solvent Removal from Treated Soils

Solvent concentrations in treated solids ranged from 46.9 to 36.0 g/kg prior to vacuum extraction, with a mean concentration 40.5 g/kg. Vacuum extraction quickly reduced the residual solvent concentration, as shown in Figure 13.5. The greatest reduction of residual solvent (39.3%, taken as the mean of the five extractors) was observed following the first day of vapor extraction. Removal of solvent following the first day of treatment was not remarkable, yielding only an additional 9% over two days of treatment for an overall mean removal efficiency of 48.3%. To comply with the terms of an operating permit issued by local officials, no additional vapor extraction was attempted. Full-scale operation of the TKRG's solvent extraction system involves operating the vapor extraction system until residual solvent concentrations are below 10 g/kg.

Following vapor extraction, the covers were removed from the extraction vessels, and a proprietary mixture of nutrients and microorganisms was sprayed over the solids. Figure 13.6 shows the effect of biological treatment on the residual solvent, as a mean value of four extractors. Residual solvent concentrations of the solids in extractor A were not used for this analysis, because those solids were manually mixed with a shovel on a periodic basis during this phase of the evaluation. No mixing of solids was attempted in the remaining four extractors. Biological treatment appeared to reduce the concentration of residual solvent rapidly during the first four days of operation. This yielded a mean removal efficiency of 60%. On the fifth day of biological treatment, the centrifugal blower was used to supply air to the extraction vessels for a brief period of time. Following this operation, the mean concentration of solvent in soils (20.8 g/kg) was found to exceed the mean concentration prior to initiating biological treatment (13.2 g/kg). It was discovered that some solvent had not been completely drained from the base of the extraction vessels and the solvent drain lines. When the blower was used to add air to the extraction vessels through the drain lines, standing solvent was forced into the solids, thus increasing the concentration of solvent in the solids. Biological treatment proceeded for nine more days. During this period, residual solvent concentration in the soil continued to decline. The lowest mean solvent concentration in the treated soil (5.4 g/kg) was from the samples taken following twelve days of biological treatment. The mean value of the residual solvent concentration was found to increase during the thirteenth and fourteenth days of biological treatment (9.0 to 10.0 g/kg, respectively). This observed increase in residual solvent

Figure 13.5
Effect of Vapor Extraction on Residual Solvent

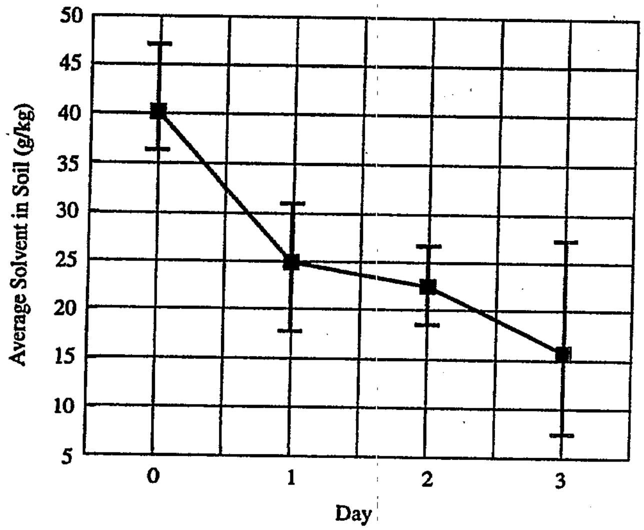
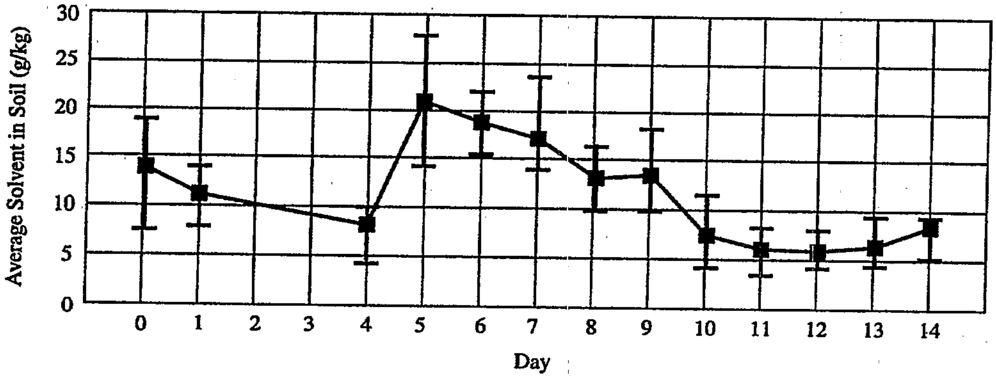


Figure 13.6
Effect of Biological Treatment on Residual Solvent



Data from extractors B through E only

concentrations could not be attributed to any operational event. Treatment was considered complete at this point; final samples were taken from each extraction vessel (as reported above), and the system was decommissioned. As part of these activities, samples of purified solvent were collected from the holding tank and were analyzed for PCBs. Results showed that the purified solvent contained no detectable concentrations of PCBs (<0.33 mg/kg). Therefore, the solvent may be reused.

Full-Scale Treatment of Pesticide-Contaminated Soil

Since completion of this evaluation, TKRG has implemented a full-scale solvent extraction system at a site in Stockton, California. This full-scale system used 19 steel roll-off containers for batch treatment of soils. Each roll-off container was filled with 15.3 m^3 (20 yd^3) of pesticide-contaminated soil and operated in a manner similar to the system described above (Figure 13.1). Therefore, 290.5 m^3 (380 yd^3) of soil were treated simultaneously within the 19 vessels. Twelve grab samples of untreated soil were collected as the solids were loaded into the first extraction vessel. These samples were composited and analyzed for pesticides (US EPA 1992g). Three extraction cycles were used to remove pesticides from the soil. Following the third extraction, all solvent was drained from the extraction vessel, and vapor extraction was initiated. A closed-loop vapor extraction system was used for the full-scale system. Air was drawn through the solids via a centrifugal blower and passed through a refrigerated condenser. The condensate was recovered and treated through the solvent purification system. Air discharged from the condenser passed through a heat exchanger and was fed to an intake manifold at the top of the covered extraction vessel. Following this treatment, 12 grab samples of the treated soil were obtained, composited, and analyzed for pesticides (US EPA 1992g). Results from these analyses are shown in Table 13.2.

The full-scale system effectively removed DDT, DDD, and DDE from the Stockton soils. Pesticide concentrations in treated soils were ≤0.093 mg/kg, with removal efficiencies exceeding 99% for each analyte.

Conclusions

These results show that the TKRG's solvent extraction process is effective in removing PCBs, O&G, HxCDF, and certain pesticides from dry sandy soils. Results from the pilot operation at NANSI showed that the

Table 13.2
Pesticide Concentrations and Removal Efficiencies

Analyte	Source of Soil		
	Before Extraction (mg/kg)	After Extraction (mg/kg)	Removal Efficiency (%)
DDT	80.5	0.093	99.9
DDD	12.2	0.024	99.8
DDE	1.5	0.009	99.4

DDT Dichlorodiphenyltrichloroethane
DDD Dichlorodiphenyldichloroethylene
DDE Dichlorodiphenyldichloroethane

effectiveness of the process could be monitored by measuring contaminant concentrations in samples of solvent discharged from the extraction vessels. Furthermore, this work showed that the solvent purification system was effective in removing PCBs from the extraction solvent. The pilot-scale work also demonstrated that solvent removal from treated soils by vapor extraction and biological treatment was possible. Further reduction of residual solvent concentrations in solids is deemed to be likely with additional vacuum extraction (>3 days) and biological treatment. The vapor extraction system was modified in the full-scale system to include a heat exchanger. The effectiveness of this modification was not evaluated; however, it permits operation of the vapor recovery system as a closed-loop system, thereby eliminating a potential source of air emissions.

The effectiveness of the process in removing O&G was limited. This is most likely due to solvent/solute relationships. The makeup of the O&G fraction can vary depending on its source(s). The average removal efficiency of PCBs was found to be high (98.8%) during this evaluation, while the O&G removal efficiencies averaged 65.9%. Results from a previous study using an alternative solvent extraction system had average PCB and O&G removal efficiencies of 99.2% and 98.2%, respectively. This suggests that O&G removal efficiency may be used as an indicator of overall solvent extraction process effectiveness, but that it is of limited use for determining the effectiveness of the process in removing specific organic contaminants.

Acknowledgments

The authors which to thank all of the individuals who assisted in the evaluation of this technology. Specifically, we recognize Alan Cash of the Terra-Kleen Response Group, and Andy Harrison and Arnold Bernardo of Naval Air Station North Island for their efforts in seeing this work through to completion.

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Case 2 — Removal of PCBs from Contaminated Soil Using the CF Systems® Solvent Extraction Process: A Treatability Study

US EPA conducted a treatability study on soil collected from the Springfield Township Dump (STD) Superfund Site. The approximately 4-acre site is located near the town of Davisburg, Michigan (Figure 13.7). Between 1966 and 1968 the STD was used for the disposal of drummed and liquid industrial waste. Primary contaminants in the soil (a fine-to-coarse-grained sand) include: arsenic, lead, and barium; volatile organic compounds (VOCs); and semivolatile organic compounds (SVOCs), which include PCBs and the pesticide dieldrin.

On-site incineration had been specified in the Record of Decision for remediating the soil at the site, but negative public opinion toward incineration has led to the consideration of treatment alternatives. Based upon preliminary bench-scale testing on soil samples taken from the site, the CF Systems® (CFS) solvent extraction process was believed to be such an alternative. Therefore, a treatability study was conducted to determine whether the technology would be effective in treating soils at the STD to the desired cleanup standard.

Approximately 525.3 kg (1,158 lb) of soil was obtained directly from PCB hot zones at the STD Site and then screened on-site to remove oversize material (>1/2 in. diameter), which was approximately 76.2 kg (168 lb)(14.5%). Of the approximately 453.6 kg (1,000 lb) of material screened to <1/2 in. diameter, CFS used approximately 68 kg (150 lb) to conduct a series of bench-scale tests in order to establish basic operating conditions for the treatability study. The remaining volume was shipped to Hazen Research, Inc. in Golden, Colorado, which is the home base for CFSs Mobile Demonstration Unit (MDU).

The treatability study was conducted using CFSs pilot-scale MDU on a batch-mode. Liquified propane was the solvent chosen to extract the organic compounds from the STD soil. Figure 13.8 illustrates the basic CFS process and the sample locations.

Figure 13.7
Location of the STD Superfund Site

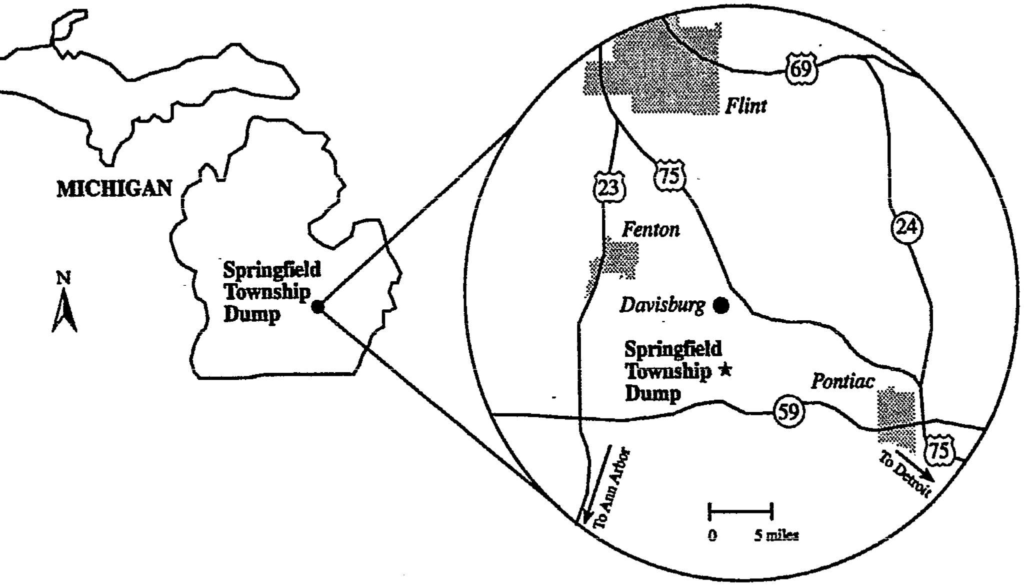
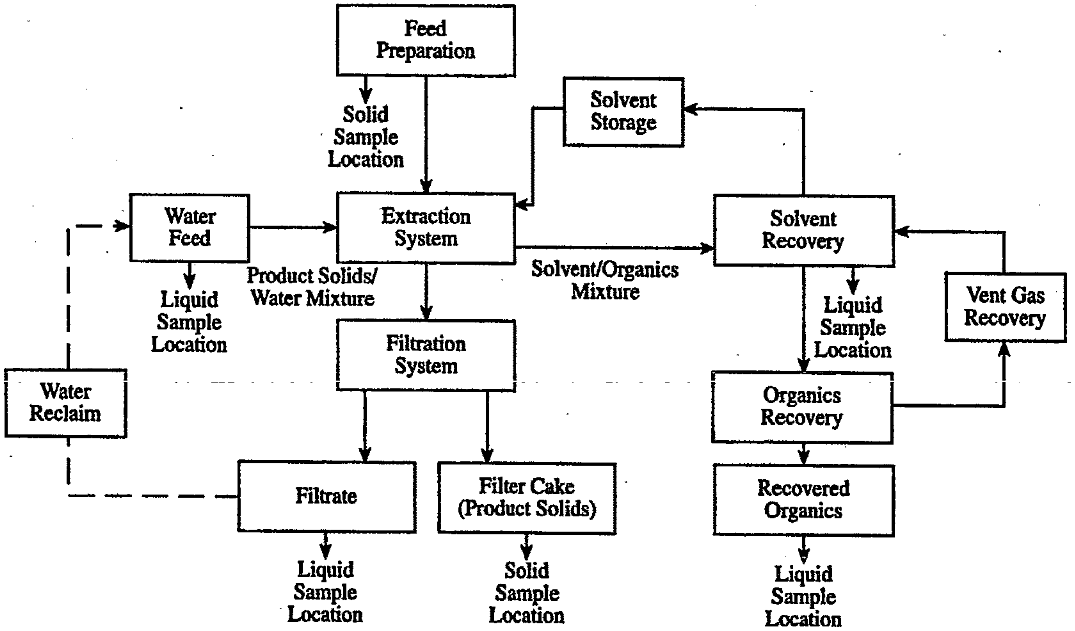


Figure 13.8
CFS® Process Diagram



— ➤ Process path used for full-scale system only

At Hazen Research Inc., the feed material was air-dried, further screened to remove oversize material (>1/4 in. diameter), and mixed to produce a homogenous test feed. Table 13.3 summarizes the results of the test soil screening for removal of oversize material.

Table 13.3
Percentage of Screened Oversized Material

Location	Starting Material (lb)	Material Screened (lb)	Oversize (%)
Springfield Township Dump	1,158	168[a]	~ 14.5
Hazen Research Inc.	~ 626	26[b]	~ 4.0
	Total % oversize ≥ 1/4 in.		~ 18.5[c]

[a] Using plastic crating having approximately 1/2-in. openings.
[b] Using an ASTM sieve having 1/4-in. openings.
[c] Oversize material could be treated following size reduction (i.e., pulverizing) during a full-scale remediation.

The contaminated soil was fed in 45.4 kg (100 lb) batches into the extractor and thoroughly mixed with approximately 68 kg (150 lb) of solvent for each cycle. Following phase separation of the solvent and contaminants from solids, the solvent/contaminant mixture passes from the extraction system to the solvent recovery system. Once in the solvent recovery system, the solvent is vaporized from the contaminant, condensed, and recycled back to the extraction system as fresh solvent. After all extraction cycles are completed, water is added to the extractor and mixed with the solids to aid in removing any residual propane. Product solids are discharged as a slurry in water and then filtered to form a filter cake.

Test Objectives and Conditions

The primary objectives for the treatability study were:

- determine the effectiveness of removing PCBs from STD soil to the remedial action standard (RAS) of <1 mg/kg; and

- determine PCB concentrations in the filtrate water to ensure proper disposal.

Secondary objectives of the treatability study included but were not limited to: verifying the absence of PCBs in the pilot-scale unit prior to testing, determining residual concentrations of dieldrin in the product solids, and determining mass balance for total materials.

The CFS pilot-scale treatability study was conducted in two phases, which included a total of five main process runs. Phase I consisted of three test runs, each consisting of a different number of extraction cycles. The first run consisted of three 20-minute extraction cycles, the second run consisted of four 20-minute extraction cycles, and the third run consisted of five 20-minute extraction cycles.

Preliminary analytical results, using hexane as the extracting agent, indicated that the primary objective of producing solids having <1.0 mg/kg PCB concentration was met for the three-cycle run. Therefore, Phase II consisted of two additional test runs using three 20-minute extraction cycles each, since this process condition was believed to be the most economically feasible in achieving the objective. It was later determined that these preliminary results underestimated the concentration of PCBs in the treated soil. A sixth run consisting of two 20-minute extraction cycles was added to test the limits of the pilot unit in treating soil to the desired levels. Table 13.4 summarizes the process conditions for all six runs.

Analytical Results

Sampling was performed in accordance with an US EPA-approved Quality Assurance Project Plan. The critical process streams sampled for each of the six runs included: feed soil; product solids (filter cake); and filtrate water. Samples of the organic extract were taken at the end of Run 6, in order to perform a mass balance on PCBs.

Table 13.5 summarizes the MDU's PCB percent removal efficiencies for each run and as averages of all six runs and the 3 triple extraction cycle runs. Oil and grease (O&G) analysis was also conducted on feed and product solids for each test run to determine propanes capability in extracting semi- and nonvolatile organic compounds in addition to PCBs. Results of the O&G analyses are summarized in Table 13.6.

Table 13.4
Process Conditions for all Test Runs

Test Phase	Run Number	Feed Loaded (lb)	Number of Extraction Cycles	Mixing Time Each Cycle (min)	Mixing Speed	Solvent/Feed Ratio (by weight each cycle)	Extraction Pressure (psi) Average/Range	Extraction Temperature (°F) Average/Range
I	1	100	3	20	Full	1.5/1	315/250-409	133/125-138
	2	100	4	20	0/Full[a]	1.5/1	261/223-308	122/106-133
	3	100	5	20	Full	1.5/1	238/182-294	117/93-150
II	4	100	3	20	Full	1.5/1	266/202-309	124/98-140
	5	100	3	20	Full	1.5/1	243/194-299	119/98-137
Added Run	6	100	2	20	Full	1.5/1	277/231-319	125/110-138

[a] During one of the four extraction cycles, the mixer was inoperable; however, a solvent flow was established by recirculating propane from the top of the extractor into the bottom.

Table 13.5
PCB Removal Efficiencies

Run Number	Number of Extraction Cycles	Soil Feed Concentration[1] (mg/kg)	Product Solids Concentration[1] (mg/kg)	% Removal
1	3	210	4.9	97.7
2	4	240	1.8	99.3
3	5	340	2.2	99.4
4	3	310[2]	4.0[2]	98.7
5	3	220	5.8	97.4
6	2	220	19.0	91.4
Average[3]		**260/250**	**6.3/4.9**	**97.6/98.0**

[1] The test method used was SW-846 3540/8080; Aroclor 1254 was the only PCB identified.
[2] Average concentration of analyses of field duplicate samples (see Table B.7).
[3] Two values are given; the first is the average of all six runs and the second is the average of the three extraction cycle runs (Runs 1, 4, and 5).

Table 13.6
Oil and Grease Removal Efficiencies

Run Number	Number of Extraction Cycles	Soil Feed Concentration[1] (mg/kg)	Product Solids Concentration[1] (mg/kg)	% Removal
1	3	4,480	112	97.5
2	4	4,560	73	98.4
3	5	5,870	< 20	> 99.6
4	3	5,460	133	97.6
5	3	5,140	93	98.2
6	2	7,060	279	96.0
Average[2]		**5,430/5,030**	**< 118/113**	**> 97.8/> 97.8**

[1] The test method used was SW-846 9071.
[2] Two values are given; the first is the average of all six runs and the second is the average of the three-extraction cycle runs (Runs 1, 4, and 5).

PCBs were not detected in the filtrate samples collected for the five main test runs (<1.0 μg/L). However, for Run 6, which involved only two extraction cycles, PCBs were detected at 1.9 μg/L. The product oil collected at the end of the entire study (3,700 g) contained a PCB concentration in excess of 11,000 mg/kg. This shows that the process was effective in concentrating the PCBs within the product oil fraction.

Dieldrin was not detected in the feed soil nor product solids; therefore removal could not be evaluated. More detail of the analyses and measurements are discussed in the Project Report.

Mass Balance

A total materials balance was conducted to account for all material loaded into the unit for each run and to ensure that the majority of the material was recovered and did not simply remain in one or more of the process components. Any material loaded into the unit or exiting the unit was examined in the total materials mass balance.

Table 13.7 summarizes the results of the total materials balance for each run and over the entire treatability study. Results indicate that approximately 98% of input material was accounted for in the product streams. The mass balance closure for PCBs was approximately 62%. The low recovery is believed to be at least partially attributable to the inability to drain all of the oil from the extract product tank and associated piping.

Quality of the Data

The data quality objectives established for this pilot-scale treatability study were based on project requirements and thus designed to ensure that the data generated during the study would be of known and acceptable quality to achieve the projects technical objectives.

There were several quality control analyses conducted to evaluate the laboratory performance. These results are discussed in detail in the full report. The critical target analyte (PCB Aroclor 1254) was spiked into both a sample of the product solids and into a sample of the product water to determine the accuracy and precision for these matrices. The results of these matrix spike/matrix spike duplicate (MS/MSD) samples (Table 13.8) show that accuracy and precision were obtained for both matrix types and that the project quality assurance (QA) goals were met.

Table 13.7
Total Materials Balance

Run Number	Input (g)			Output (g)				Recovery (%)
	Feed Soil[1]	Water	Total	Oil Extract	Slurry	F-1 Filter Solids	Total[3]	Material
1	45,400	52,600	98,000	–	71,600	485	72,090	73.6
2	45,800	80,800	126,600	–	147,400	485	147,900	117[2]
3	45,800	93,800	139,600	–	116,200	485	116,700	83.6
4	45,800	88,500	134,300	–	134,800	640	135,400	101
5	45,800	99,500	145,300	–	141,200	640	141,800	97.6
6	45,800	103,000	148,800	3,700	158,800	640	163,100	110
Total	**274,400**	**518,200**	**792,600**	**3,700**	**770,000**	**3,380**	**777,000**	**98**

[1] Runs 2-6 include the addition of 454 g of sand to fill void space in the extractor.
[2] Solids not flushed out in Run 1 exited at the end of Run 2.
[3] Totals rounded to four significant digits.

Table 13.8
PCB Aroclor 1254 Matrix Spike/Matrix Spike Duplicate (MS/MSD) Results

Sample	Spike	Sample Concentration	MS	MS % R	MSD	MDS % R[1]	RPD[2]
Product Solids	4.9 mg/kg	4.1 mg/kg	8.2 mg/kg	84	9.1 mg/kg	102	10
Filtrate	10.0 µg/L	< 1.0 µg/L	9.0 µg/L	90	7.8 µg/L	78	14

[1] The QA objective for accuracy was a recovery of 50-150%.

$$\% \text{ Recovery} = \frac{C^1 - C_o}{C_t} \bullet 100$$

where: C^1 = the measured concentration in the spiked sample;
C_o = the measured concentration in the unspiked sample; and
C_t = the known concentration of analyte added to the sample.

[2] The QA objective for precision was an RPD of ≤ 40.

$$\text{RPD} = \frac{(\text{Maximum Value} - \text{Minimum Value})}{(\text{Maximum Value} + \text{Minimum Value})/2} \bullet 100$$

Field duplicate samples of raw feed, product solids, product oil, and product water were collected and analyzed for PCBs. Field duplicates provide a measure of precision for the combined sampling and analytical processes. Table 13.9 presents these results, which show that the project relative percent difference (RPD) goal of 40 was easily met.

It should also be mentioned that PCBs were not detected in any of the laboratory method blanks, nor in a rinsate sample collected from the pilot plant prior to the study, indicating that contamination was not a problem.

Conclusions

The analytical test data indicate that the primary goal of producing solids having a <1.0 mg/kg PCB concentration was not attained by the designated test method used. Of the five main test runs, the closest PCB concentration to the RAS was 1.8 mg/kg in Run 2 product solids, which was approximately a 99.3% removal efficiency. The average PCB removal efficiency attained for the three-extraction cycle test runs was 98%.

There is not enough PCB data to indicate whether the additional fifth extraction cycle conducted during Run 3 benefited PCB removal beyond the

Table 13.9
PCB Aroclor 1254 Field Duplicate Results

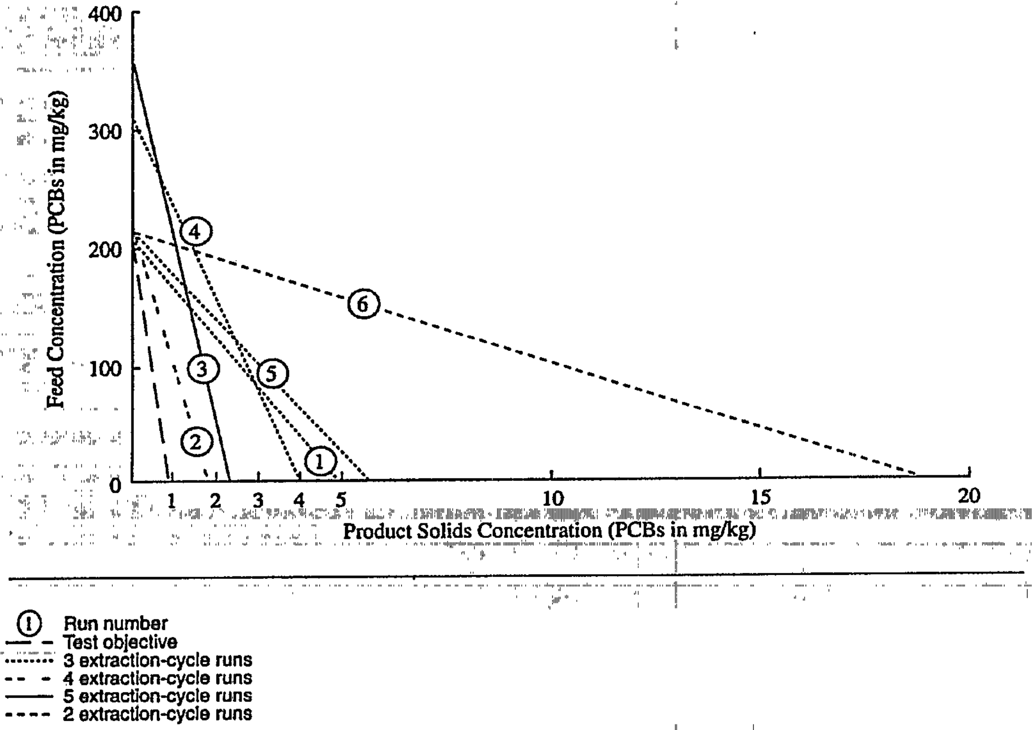
Sample Matrix	Sample Result	Result 2	RPD[1]
Feed	350 mg/kg	260 mg/kg	30
Product Solids	4.0 mg/kg	3.9 mg/kg	2.5
Product Oil	11,200 mg/kg	11,300 mg/kg	0.9
Filtrate	< 1 µg/L	< 1 µg/L	NC[2]

[1] The project objective for precision was an RPD of ≤ 40.
[2] NC = not calculated

four-extraction cycles conducted during Run 2. The two concentration values, for Run 2 (1.8 mg/kg) and Run 3 (2.2 mg/kg), are essentially equal since they are within the range of field sampling and analytical error. However the O&G analyses conducted can be used to supplement the interpretation of results, with respect to organics removal in general. As Table 13.6 indicates, when the O&G data are evaluated, the five-extraction cycles used for Run 3 appears to have performed the best for overall organics removal.

The performance of the runs relative to one another is illustrated in Figures 13.9 and 13.10. These show the removal of PCBs and O&G, respectively, for each test run as the decline in contaminant concentration from starting feed to product solids as sloped lines. Both figures show the disparity in performance between test runs for the respective parameters, which may not be as apparent when simply looking at percent removal values. Figure 13.9 clearly shows that Runs 2, 3, and 4 came closer to the test objective, assuming a feed concentration equal to the average of all runs (250 mg/kg). Their slopes essentially parallel one another. Figure 13.9 also shows that Runs 1 and 5 had an almost identical performance and that Run 6 had the poorest performance. For O&G removal, Figure 13.10 indicates that Run 3 produced the cleanest solids, while Runs 1, 2, 4, and 5 had similar performance. Again, Run 6 had the poorest performance, indicating that greater than two extraction cycles are required to achieve O&G removal efficiencies >96%. These results suggest that the extraction process

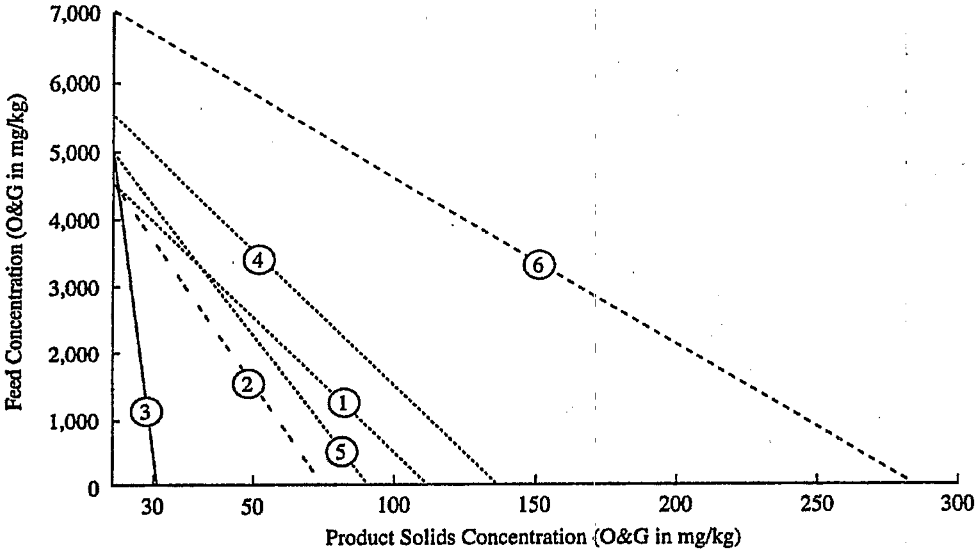
Figure 13.9
PCB Removal Trend



operating conditions could be further optimized to yield higher removal efficiencies than were identified in this study.

Another important conclusion that resulted from the study regarded the volume reduction of hazardous waste. Although the CFS solvent extraction process is not capable of destroying PCBs and other contaminants present in the STD soil (as is the case with solvent extraction technologies in general), it is a means of separating those contaminants from the soil, thereby reducing the volume of hazardous waste that must be treated. This in turn reduces the cleanup costs involved. The cumulative mass of the wet contaminated feed soil for all six runs of the treatability study was approximately 274,000 g. The mass of the oily extract sampled at the completion of Run 6 was approximately 3,700 g. Therefore, the process reduced the overall mass of the contaminated material to 1.35% of its original waste mass. The volume of the feed soil [SG=1.34 grams per milliliter (g/mL)] and oil extract (SG=0.87 g/mL) were approximately 204 and 4.3 L (53.9 and 1.1 gal), respectively. Therefore, the process reduced the overall volume of the contaminated material to 2.1% of its original waste volume. The highly concentrated oil extracted from the CFS process is either destroyed by incineration or chemical dechlorination.

Figure 13.10
Oil & Grease Removal Trend



① Run number
········ 3 extraction-cycle runs
-- - 4 extraction-cycle runs
—— 5 extraction-cycle runs
- - - - 2 extraction-cycle runs

Case 3 — Refinery Sludge Treatment and Minimization with the Biotherm Process™

In 1996 Biotherm, LLC purchased the rights to the Carver-Greenfield (C-G) Process which had been developed and licensed by Dehydro-Tech Corporation for over 30 years. The Biotherm Process, which is now offered commercially by Biotherm, LLC, is an improved version of the C-G Process. More than 80 C-G (Biotherm) Process facilities in ten countries have been built to solve waste disposal problems in a wide variety of fields. More than half of the plants were designed to dry and deoil slaughterhouse wastes (in rendering plants). The other units are used to evaporate water and extract indigenous oil from a broad spectrum of other materials, including municipal and industrial sewage sludges, wool scouring wastes, petrochemical sludges, wood-pulp wastes, pharmaceutical wastes, dairy and food products, textile wastes and animal manure.

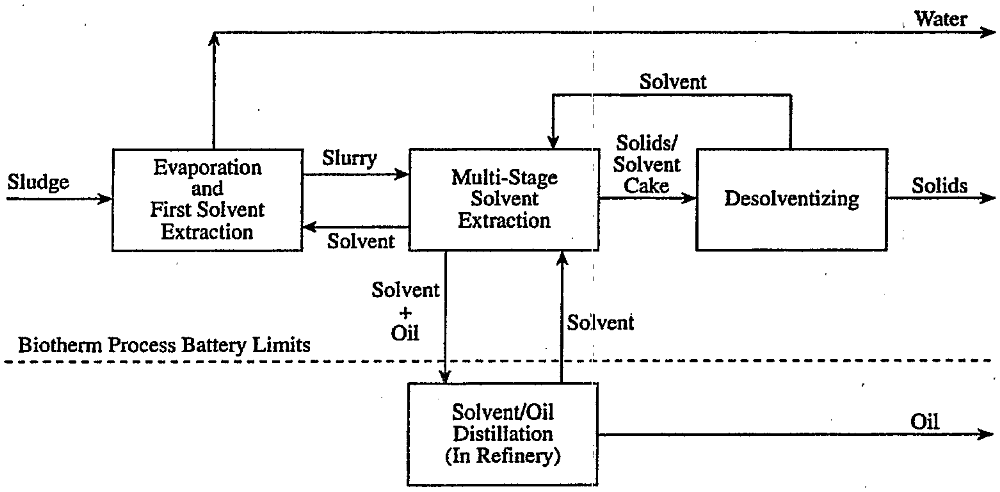
The Biotherm Process is very flexible. Although the applications cited above cover a wide range of feedstocks, the process designs for all of them are similar. Furthermore, with environmental regulations increasing the incentives for effective economic treatment of hazardous wastes, the adaptation of the Biotherm Process for improved contaminant removal and hazardous volume minimization is a natural extension of previous experience. In addition, depending upon the waste characteristics and treatment goals, the process can also be modified to operate in a resource recovery mode within a waste treatment facility.

Biotherm Process Description

As shown in Figure 13.11, when treating oil refinery K- and F-wastes (or other materials), the Biotherm Process involves mixing the waste with a solvent from the refinery at a ratio of 5-10 lb of solvent per lb of feed solids and transferring the waste/solvent slurry to an evaporator system where the water is vaporized and solvent extraction of the indigenous oil is initiated. Here, indigenous oil is considered to be the hydrocarbon portion of the process feed which contains the contaminants of concern in the hazardous waste.

In addition to extracting contaminants from the solids, the solvent "fluidizes" the solids and ensures a low slurry viscosity as the solids are dried.

Figure 13.11
Block-Flow Diagram of the Biotherm Process™ for Refinery Sludge Treatmen



The solvent also prevents scaling and fouling of the heat transfer surfaces, thereby assuring good heat transfer. By evaporating the water, problems with emulsions are avoided, even with "difficult-to-process" feeds.

Depending on the water content of the feed, a single-effect or an energy-saving multi-effect water evaporation system may be utilized under mild process conditions (<5 psig, <121°C [250°F]). Next, the dried solids/solvent slurry is fed to a multi-stage counter-current extraction unit where the solids are contacted with additional clean, recycled solvent until the desired degree of indigenous oil extraction is reached. Finally, the bulk of the solvent is separated from the solids by centrifuging. The residual solvent is removed by "hydroextraction", a desolventizing step that uses hot recycled low pressure inert gas to vaporize the solvent from the solids at relatively low temperatures (<177°C [350°F]). The product solids contain minimal percentages of water (<2%) and solvent (<1%).

The spent solvent containing extracted indigenous oil is returned to the refinery and reprocessed. Alternatively, a solvent/indigenous oil distillation unit may be included in the Biotherm Process facility to separate the solvent for reuse and recover the indigenous oil for disposal. The solvent is typically a narrow-cut refinery hydrocarbon stream with a boiling point of about 204°C (400°F). Food-grade Isopar L or other nontoxic hydrocarbons, including alcohols, are also suitable solvents depending on the application.

The combination of water evaporation with solvent extraction in the Biotherm Process results in many technical advantages:

- any emulsions initially present are broken;
- emulsion formation during processing is prevented;
- solvent extraction of contaminants is more efficient; and
- if metals contamination is a concern, the reduced volume of dry solids product may be stabilized (fixed) or otherwise treated more readily for landfill disposal.

Refinery Waste Treatment Standards

Hazardous listed wastes generated by oil refineries have been categorized by the US EPA under RCRA as follows:

- K048 — dissolved air floatation (DAF) float;
- K049 — slop oil emulsion solids;
- K050 — heat exchanger bundle cleaning sludge;
- K051 — API separator sludge;
- K052 — leaded tank bottoms;
- F037 — primary oil/water/solids separation sludge; and
- F038 — secondary (emulsified) oil/water/solids separation sludge.

Treatment standards for these wastes have been issued by the US EPA as the BDAT Standards and those for hydrocarbons from these Refinery K- and F- wastes are given in Table 13.10. There are also BDAT standards for these wastes for some metals, e.g., chromium, lead, mercury, etc. The Biotherm Process will not remove these metals from the solids. However, as noted above, overall volume reduction of the solid waste and removal of the oil and water will usually permit more economic treatment of the residual metals-containing solids via solidification (fixation) or acid leaching, etc.

By separating the individual components of a waste stream which in turn allows them to be recycled back to the refinery and incorporated in a refinery product, the Biotherm Process meets the criteria for the "closed-loop recycling exclusion" of RCRA (40 CFR 261.1[a][8]; 40 CFR 264.6[a][1]-[3]) which reduces the waste treatment permitting process.

Table 13.10
US EPA Best Demonstrated Available Technology (BDAT)
Standards for Refinery Hazardous Wastes K048-K052

Hydrocarbon Compound	BDAT Specifications (ppm)
Benzene	14
Ethylbenzene	14
Toluene	14
Xylenes	22
Naphthalene	42
Phenanthrene	34
2-Methylphenol	6.2
Anthracene	28
Benzo(a)anthracene	20
Pyrene	36
Chrysene	15
Benzo(a)pyrene	12
Phenol	3.6
4-Methylphenol	6.2
Bis(2-ethylhexyl)phthalate	7.3
Di-n-butylphthalate	3.6

Biotherm Process Treatment of Refinery K-Wastes

Tables 13.11 and 13.12 present analytical results on feeds and product solids from laboratory simulations of the Biotherm Process on API Separator Bottoms (Table 13.11) taken from an operating refinery and Lagoon Sludges (Table 13.12) accumulated from oil refineries and other waste sources (which include chlorinated hydrocarbons) over a period of many years.

Table 13.11
Biotherm Process Analytical Results After Three Laboratory Solvent Extraction Steps on API Separator Bottoms

Component	Feed	Product Solids	%Removal, Solids Basis	Comments
Water	76.5% (by weight)	0.4% (by weight)		–
Solids	3.6% (by weight)	99.4% (by weight)		–
Oil and Grease	19.9% (by weight)	0.2% (by weight)(TPH)	99+	–
Benzene	50 ppm	U	99.9+	Meets BDAT
Toluene	50 ppm	1.2 ppm	99.9+	Meets BDAT
Ethylbenzene	670 ppm	U	99.99+	Meets BDAT
Xylenes	360 ppm	U	99.99+	Meets BDAT
Naphthalene	3.5 ppm*	U	93.1	–
Fluorene	3.0 ppm*	1.1 ppm*	98.7	–
Phenanthrene	5.2 ppm*	8.4 ppm	94.2	–

*Approximate, below limits of reliable quantitation

TPH Total Petroleum Hydrocarbons (US EPA Procedure 418.1)
U Undetected, % removals based on minimum detection limits
BDAT Best Demonstrated Available Technology

In both cases, the water was evaporated from the feed sludges during the first laboratory extraction which was followed by two extractions using fresh Isopar-L solvent. This closely simulates the counter-current extraction of a commercial unit in which fresh recycle solvent is contacted with the "cleanest" solids to permit final traces of contamination to be removed. Extractions were performed at approximately 10/1 solvent to solids ratio at about 93°C (200°F). The number of extractions, the solvent to solids extraction ratio and the actual solvent used may be adjusted for the commercial operation to optimize the contaminant removal according to the specific project's overall treatment targets.

As shown in Tables 13.11 and 13.12, removal efficiencies of specific contaminant compounds based on the solids present in the sludge feed were nearly always more than 99% and in most cases signficantly higher than that when there was analytically reliable detection. In virtually all cases, the

Table 13.12
Biotherm Process Analytical Results After Three Laboratory Solvent Extraction Steps on Refinery (and Other Waste) Lagoon Sludge

Component	Feed	Product Solids	%Removal, Solids Basis	Comments
Water	34.6% (by weight)	0.5% (by weight)		–
Solids	14.6% (by weight)	99.0% (by weight)		–
TPH	28.0% (by weight)	0.5% (by weight)	99.9+	–
BDAT Compounds				
Benzene	150 ppm	2 ppm*	99.6	Meets BDAT; TCLP = U
Toluene	530 ppm	4 ppm	99.8	Meets BDAT; TCLP = 0.05
Ethylbenzene	530 ppm	U	99.9+	Meets BDAT; TCLP = U
Xylenes	1,400 ppm	1 ppm	99.9+	Meets BDAT; TCLP = U
Phenol	1,600 ppm	35 ppm	99.4	TCLP = 0.15
m,p-Cresol	240 ppm*	7 ppm*	99.2	TCLP = U
o-Cresol	200 ppm*	3 ppm*	99.7	Meets BDAT; TCLP = U
Naphthalene	2,800 ppm	1 ppm*	99.99	Meets BDAT; TCLP = U
Acenaphthene	320 ppm*	U	99.1	No BDAT; TCLP = U
Fluorene	830 ppm*	1 ppm*	99.9+	No BDAT; TCLP = U
Phenanthrene	2,700 ppm	13 ppm	99.9	Meets BDAT; TCLP = U
Di-n-butylphthalate	330 ppm*	2 ppm*	99.8	Meets BDAT; TCLP = U
Anthracene	320 ppm*	10 ppm	99.1	Meets BDAT; TCLP = U
Bis(2EH)phthalate	1,200 ppm	35 ppm	99.2	TCLP = U
Pyrene	600 ppm*	6 ppm*	99.7	Meets BDAT; TCLP = U
Benzo(a)anthracene	100 ppm*	2 ppm*	99.4	Meets BDAT; TCLP = U
Chrysene	170 ppm*	3 ppm*	99.5	Meets BDAT; TCLP = U

Table 13.12 cont.
Biotherm Process Analytical Results After Three Laboratory Solvent Extraction Steps on Refinery (and Other Waste) Lagoon Sludge

Component	Feed	Product Solids	%Removal, Solids Basis	Comments
Other Hydrocarbons				
Styrene	1,000 ppm	12 ppm	99.7	TCLP = U
2-Methylnaphthalene	5,600 ppm	1 ppm*	99.99	TCLP = U
Acenaphthylene	450 ppm*	16 ppm	99.0	TCLP = U
Dibenzofuran	100 ppm*	2 ppm*	99.5	TCLP = U
Butylbenzylphthalate	480 ppm*	4 ppm*	99.7	TCLP = U
Di-n-octylphthalate	1,100 ppm	5 ppm*	99.9	TCLP = U
Fluoranthene	330 ppm*	U	99.2	TCLP = U
Chlorohydrocarbons				
Methylene Chloride	72 ppm	U	99.9+	TCLP = 0.51
1,1,1-Trichlorethane	240 ppm	U	99.9	TCLP = U
Trichloroethene	190 ppm	U	99.9	TCLP = U
1,1,2-Trichlorethane	19 ppm*	1 ppm*	99.1	TCLP = U
Tetrachloroethene	260 ppm	U	99.9	TCLP = U
Chlorobenzene	72 ppm	U	99.8	TCLP = U
1,2-Dichlorobenzene	790 ppm*	U	99.7	TCLP = U
Hexachlorobutadiene	1,200 ppm	U	99.8	TCLP = U
Trichlorobenzene	440 ppm*	U	99.4	TCLP = U
Pentachlorophenol	4,715 ppm	18 ppm*	99.9	TCLP = U
Hexachlorobenzene	360 ppm*	U	99.2	TCLP = U

*Approximate, below limits of reliable quantitation

TPH Total Petroleum Hydrocarbons (US EPA Procedure 418.1)
U Undetected, % removals based on minimum detection limits
BDAT Best Demonstrated Available Technology
TCLP Toxicity Characteristic Leaching Procedure (40 CFR, Part 261)

BDAT standards for refinery hazardous waste hydrocarbon compounds are met. It is noted that achieving refinery hydrocarbon BDAT levels may not be the only remediation criteria for the lagoon sludge (Table 13.11) since it contains hydrocarbon and chlorinated hydrocarbons which are not included in the refinery RCRA standard.

Only the partially oxygenated aromatics m,p-cresol and bis(2-ethylhexyl)phthalate failed to meet the hydrocarbon BDAT standards (Table 13.12). There is some concern in the industry that the apparent high levels of the plasticizer bis(2-ethylhexyl)phthalate may be artifacts of sample handling procedures due to leaching of plastic utensils or clothing (gloves, etc.) containing the plasticizer prior to the analysis. This, coupled with the belief that refinery wastes would not typically contain this manufactured petrochemical product, means that the presence of bis(2-ethylhexyl)phthalate must be carefully verified in a specific feed before too much effort is expended on its removal from the waste.

To illustrate the flexibility of the Biotherm Process in a refinery waste treatment application, it is also possible to use only the water evaporation (drying) feature in certain circumstances. In this case the dried solids are not desolventized but remain with the solvent either in a centrifuge cake or a dry slurry. This Biotherm Process product is then fed to a coker (Elliot 1992), asphalt plant or other suitable refinery operation. Here the "solvent" is typically a higher boiling hydrocarbon like a fuel oil which is a component of the feed to the downstream refining unit (e.g., coker).

Biotherm Process Pilot Plant Treatment of Spent Drilling Fluids (US EPA SITE Demonsration Program)

US EPA's Superfund Innovative Technology Evaluation (SITE) program is dedicated to advancing the development, evaluation, and implementation of innovative treatment technologies applicable to hazardous wastes and waste sites. Dehydro-Tech Corporation (now Biotherm, LLC) was selected by the US EPA in 1990 to participate in the SITE program and a Biotherm Process pilot plant demonstration was conducted at the US EPA research facility in Edison, New Jersey in August 1991, using drilling fluid waste from the PAB Oil and Chemical Services (PAB Oil) Superfund Site in Abbeville, Louisiana. Drilling fluid waste, a combination of fine bentonite clay, water and oil is very similar to refinery sludges and the technical/engineering results of this demonstration can be readily extended for processing refinery and other waste streams in a commercial facility. The Applications Analysis Report (AAR) and Technology Evaluation Report (TER) written by the US EPA for the demonstration program are available from Biotherm, LLC or the US EPA (US EPA 1992a; US EPA 1992f).

The demonstration was performed in a mobile pilot plant having a processing capacity of about 45.4 kg/hr (100 lb/hr) feed (about 13.6 kg/hr [30 lb/hr] solids) installed on a 14.6 m (48 ft) trailer. In commercial units, the Biotherm Process is normally operated on a continuous basis. However, because of equipment limitations, the SITE demonstration was done batch-wise on a total of 294.8 kg (650 lb) of feed in two runs as described below:

- dehydration was done batch-wise in a single effect evaporation operation at about 121°C (250°F) and 55.9-58.4 cm (22-23 in.) Hg vacuum.
- three solvent extractions, using fresh "food-grade" Isopar-L solvent at 8.5 to 12.0 solvent/solids ratio, were done batch-wise at about 121°C (250°F) on each of the two feed quantities treated.
- demonstration of the distillation step for separation of the solvent from the indigenous oil was done on a smaller scale in the laboratory.

During the demonstration, the Biotherm Process pilot plant experienced no major operational problems. The analytical results on the feed and products for the two runs are given in Tables 13.13 and 13.14.

The final solids product was a dry powder (<0.1% water) similar to bentonite in appearance. Since residual solvent on the product solids also analyzes as Total Petroleum Hydrocarbons (TPH)[US EPA Procedure 418.1], and since the solvent is a "food-grade" hydrocarbon, a quantity called "indigenous TPH removal efficiency" (initial feed TPH minus final product TPH minus final product solvent divided by initial feed TPH) was used to describe the Biotherm Process's oil removal efficiency. The "indigenous TPH removal efficiency" of 100% indicates no harmful hydrocarbons are present on the product solids. The hydrocarbon analyses of the product solids and the percent removal efficiencies based on feed solids are given in Table 13.13. By all measures considered, hydrocarbon removal efficiencies were more than 93%.

TCLP analysis of the final solids product from both test runs indicated that metals, Volatile Organic Compounds (VOCs) and Semivolatile Organic Compounds (SVOCs) are not leached from the treated product solids above RCRA regulatory limits. The Biotherm Process does not typically extract metals although in the cases presented here, with the solids content increasing from about 50% in the feedstock to 98% in the final solids product, a proportional increase in the absolute value of the metals content in the solids and TCLP extract may be expected due to volume reduction through the process. There is no evidence, however, that actual leachability of metals is increased by the process.

Table 13.13
Biotherm Process Analytical Results After Three Pilot Plant Extraction Steps on Spent Drilling Fluids (US EPA SITE Demonstration Program)

Component	Feed	Product Solids	%Removal, Solids Basis	Comments
		Test Run 1		
Water (% by weight)	21.8	< 0.1	–	• Compositions not normalized • Total solids product passed all TCLP tests
Solids (% by weight)	52.4	96.6	–	
Solvent (% by weight)	NA	0.9	NA	
Indigenous Oil (% by weight)	17.5	1.4	95.8	
TPH (% by weight)	14.7	0.8	97.2	
Indigenous TPH (% by weight)	14.7	< 0.1	99.99+	
Phenol	< 100 ppm	< 0.7 ppm	> 99	
Phenanthrene	16 ppm	0.3 ppm	99.0	
2-Methylnaphthalene	< 26 ppm	< 0.7 ppm	> 98	
Isophorone	< 50 ppm	< 0.4 ppm	> 99	
Bis(2-EH)phthalate	< 50 ppm	0.6 ppm	> 99	
Di-n-octylphthalate	< 50 ppm	< 0.3 ppm	> 99	
		Test Run 2		
Water (% by weight)	34.8	< 0.1	–	• Compositions not normalized • Total solids product passed all TCLP tests
Solids (% by weight)	52.4	98.3	–	
Solvent (% by weight)	NA	1.0	NA	
Indigenous Oil (% by weight)	7.2	0.9	93.7	
TPH (% by weight)	8.9	0.7	96.1	
Indigenous TPH (% by weight)	8.9	< 0.1	99.99+	
Phenanthrene	8.1 ppm	< 1.7 ppm	> 90	
2-Methylnaphthalene	49 ppm	2.3 ppm	> 97	
Naphthalene	< 28 ppm	1.0 ppm	> 98	
Bis(2-EH)phthalate	< 50 ppm	1.4 ppm	> 98	
Di-n-octylphthalate	< 50 ppm	U	> 99	

TPH	Total Petroleum Hydrocarbons (US EPA Procedure 418.1)
Indigenous TPH	Total TPH less TPH contributed by residual "food-grade" solvent
U	Undetected, % removals based on minimum detection limits
SITE	Superfund Innovative Technology Evaluation program
TCLP	Toxicity Characteristic Leaching Procedure (40 CFR, Part 261)

Table 13.14
Biotherm Process Product Water Quality from Spent Drilling Fluids (US EPA SITE Demonstration Program)

	Test Run 1	Test Run 2
Solvent, (% by weight)	0.90	0.10
TPH (wppm)	1,442	333
Suspended Solids (mg/L)	82.3	70.3
BOD_5 (mg/L)	76	12.7
COD (mg/L)	1,193	394.7
pH	4.57	6.82
Metals	Trace	Trace

The average ultimate particle size analysis of 12 microns and average agglomerated particle size of 73 microns from the Biotherm Process on the PAB Oil Site material reveals that the process can treat solids having smaller particle sizes than those being handled by conventional soil washing techniques. Considered as ultimate or agglomerated particles the sizes are below or close to the 63 micron average below which the US EPA has found soil washing to be difficult (US EPA 1990c).

The centrifuge centrate of solvent containing indigenous oil was a dark liquid with a strong odor indicative of the heavy hydrocarbon (crude oil) source of the indigenous oil. Although not done in the demonstration, as part of a commercial process the centrate can be easily split by fractional distillation into its indigenous oil and solvent components allowing cost-effective recycling of the recovered solvent and disposal of the indigenous oil.

The condensed water product was a clear liquid with low suspended solids and low biological oxygen demand (BOD). Specific analyses are given in Table 13.14. The characteristics of the water product were similar to dilute municipal wastewater and complied with the Organic Chemical, Plastics, and Synthetic Fibers industrial category discharge limits with respect to metals and organics concentrations.

Biotherm Process Remediation of PCB Contaminated Soil

An additional application of the Biotherm Process is for the extraction of PCB's (and/or other trace hazardous compounds) from contaminated soils, sediments, etc. Table 13.15 presents laboratory analytical data indicating greater than 99.95% PCB removal from a soil by first concurrently drying and solvent extracting followed by two solvent extractions using S-140 solvent at ratios of 6/1 solvent to solids (Pedersen 1991). These data partially confirm previous findings that the combination of water removal and solvent extraction via the Biotherm Process is more effective for PCB removal than solvent extaction of a water-wet soil. Results of other workers shown in Table 13.16 indicate that PCB extraction is particularly difficult in the presence of water.

Table 13.15
Biotherm Process Analytical Results After Three Extraction Steps on PCB Contaminated Soil

Component	Feed	Product Solids	Comments (Removals reported on solids basis)
Water (% by weight)	4	< 0.1	–
Solids (% by weight)	68	99.0	–
Oil (% by weight)	28	0.8	99.8% Removal
Aroclor 1260 (PCB)(ppb)	2,000	< 1	99.95+% Removal

Biotherm Process Economics

Table 13.17 presents some typical comparative economics when treating a refinery K-waste (e.g., K-051 API Separator Sludge) via the Biotherm Process and illustrates the value of feed component separation and volume reduction which is achieved by the process. In this case it is assumed that 4,536 tonne/yr (5,000 ton/yr) of waste, concentrated by onstream centrifuging or belt pressing from a typical 100,000 bbl/day oil refinery is treated at the refinery site. The on-site investment for the facility is about $1.3 million and, assuming purchase of utilities and manpower from the refinery, the total processing cost is about $101/tonne ($92/ton) feed. On the basis that the water and solids products are nonhazardous and can be treated in an industrial wastewater treatment facility and nonhazardous landfill, respectively, the final treatment costs is slightly over $110/tonne ($100/ton) of feed exclusive of the credit/cost of recovered indigenous oil disposal.

Table 13.16
Effect of Water on Solvent Extraction of PCB's from Contaminated Soil

Feed Sludge	100% Solids	58% Solids/42% Water	
Solvent	Kerosene	Kerosene	Acetone
	PCB Concentration on Solids (ppm)		
Initial	36,268	36,268	33,641
After 4 Extractions	251	30,873	11

Source: Blank, Rugg, and Steiner 1989

Soil Moisture	40% Moisture	10% Moisture	Dry Soil
	PCB Concentration (ppm)		
Initial	28	28	50
After 1 Extraction	25	18	10
After 2 Extractions	25	17.5	0

Source: Massey and Darian 1989

Table 13.17 assumes a credit for recovery of the indigenous oil of $15/bbl which lowers the net operating cost of the Biotherm Process Unit to $82 to $88/tonne ($75 to $80/ton) of feed. The present alternative for hazardous K-Waste disposal as practiced by many refineries is to burn the wet sludge in a cement kiln or incinerator at a cost of $549 to $1,648/tonne ($500 to $1,500/ton). Thus, the Biotherm Process has a major economic advantage.

Table 13.17
Biotherm Process Economic Estimates — Refinery K-Wastes

Cost Component	Unit Cost	Waste Feed ($/ton)
Operating and Maintenance Costs:		
Electricity, 46 kW	$ 0.06/kWhr	4
Steam, 1.2 klb/hr	$4.50/klb	8
Cooling Water, 130 gal/min	$ 0.50/kgal	6
Operators, 1/shift	$35 k/man-yr	32
Maintenance	3% Inv/yr	8
Indigenous Oil Recovery	Estimate	3
Capital Recovery	12% Inv/yr	31
Biotherm Process Cost (including Indigenous Oil Recovery)	–	92
Disposal Costs:		
Water Disposal; 0.6 ton/feed ton, 150 gal	$15/kgal	2
Solids in Nonhazardous Landfill; 0.1 ton/feed ton	$100/ton	10
Recovered Oil Credit; 0.3 ton, 1.8 bbl	($15/bbl)	(27)
Total Processing/Recovery Costs	–	77
Disposal as Hazardous Waste in Cement Kiln/Incinerator	$500/ton	500
Savings for Biotherm Processing	–	> 400

Process/Economic Bases:

Feed:

Water	3,000 tons/yr	60% (by weight)
Solids	500	10
Indigenous Oil	<u>1,500</u>	<u>30</u>
Total	5,000 tons/yr (0.7 tons/hr)	100% (by weight)

Estimated On-site Facility Investment (1993) $1.3 million (US)

It should be noted that if, because of the presence of undesirable components, the recovered indigenous oil had to be disposed of as hazardous waste at $549/tonne ($500/ton)($165/tonne [$150/ton] of feed), the total processing/recovery costs would be about $275/tonne ($250/ton), still a savings of about $275/tonne ($250/ton) of feed. Similar reasoning would prevail if the separated solids were still hazardous and required disposal as a hazardous waste at $549/tonne ($500/ton) solids or the equivalent of only $55/tonne ($50/ton) of feed. Again, a substantial savings over disposal of the total feed as hazardous waste.

In applications where only drying is done with the use of a heavy "solvent", Biotherm Processing costs will be one half to two thirds of those when full solvent extraction and desolventizing is performed.

Table 13.18 presents Biotherm Process economics developed according to the guidelines furnished by the US EPA for the SITE demonstration for remediating 20,865 tonne (23,000 ton) of drilling fluid wastes having the properties of the PAB Oil Site materials. Although the total technology based costs of $110 to $182/tonne ($100 to $200/ton) of feed for the Biotherm Process is attractive relative to alternative processes, larger plants result in even more economical operations. It is obvious from Table 13.18 that the most important factor in the controllable operating costs is operating labor. This portion of the total cost drops at higher unit capacities because it requires about the same number of operators to run larger units.

As shown in Table 13.18, a significant Biotherm Process advantage is that it produces residuals which may be disposed of very economically. Using the economic bases furnished by the US EPA, it is assumed that the clean product solids are backfilled at their original location at $16.50/tonne ($15/ton); alternately they could be sent to a sanitary landfill at $49.50/tonne ($45/ton). As noted previously, removal of oil and water from the solids also gives a product which is more readily stabilized if remaining components such as metals require it. Recovered water is treated in a POTW at $2.00/kgal.

In Table 13.18 it is assumed that since the recovered indigenous oil was originally a product of petroleum drilling production, it may be recycled to an oil refinery at an approximate crude oil value of $20.00/bbl. As a result, there is a credit to this Biotherm Process application of over $33/tonne ($30/ton) of feed for the recovered indigenous oil. It must be noted that because it came from a Superfund site, the suggested US EPA basis (US EPA 1992a; US EPA 1992f) for disposal of recovered indigenous oil was incineration at $200 per 55 gal drum (about $1,099/tonne [$1,000/ton] oil) or approximately $264/tonne ($240/ton) of feed versus a credit of about $33/tonne ($30/ton) of feed shown in Table 13.18. While disposal as hazardous waste may be appropriate in some cases, due to regulatory constraints and/or where analyses indicate the presence of sufficient contamination to require burning, in this instance incineration seems unnecessary.

Table 13.18
Biotherm Process Economic Estimates — Spent Drilling Fluids

Basis: 23,000 ton Remediated; 31% Water, 17% Indigenous Oil, 52% Solids			
Feed Rate (ton/hr)	1.4	1.9	2.5
Years @ 70% On-Stream	2.7	2.0	1.5
Investment ($ in millions)	1.30	1.50	1.75
Technology Based Costs ($/ton feed)			
Capital Amortization	21.50	18.70	16.20
Startup/Shutdown	8.20	8.20	8.20
Labor	105.50	78.50	59.00
Solvent Makeup	8.90	8.90	8.90
Utilities	15.30	15.30	15.30
Maintenance	4.50	3.90	3.40
Total Technology Based	163.90	133.50	111.00
Site Specific Costs ($/ton feed)			
Site Prep/Excavation	54.00	40.20	30.20
Residuals Treatment			
Solids and Water	7.30	7.30	7.30
Recovered Oil Credit	(31.20)	(31.20)	(31.20)
Total Site Specific	30.10	16.30	6.30
Grand Total ($/ton feed)	**194.00**	**149.80**	**117.30**

Economic Bases (except as noted per US EPA):
Equipment Amortization: 7%/yr interest, 10 year life
Startup/Shutdown Costs : $125k startup; $63k shutdown
Labor: 1 Feed and 2 System Operators @ $40/hr, 3 shifts/day; 1 mechanic @ $40/hr, 1 shift/day; 0.5 Supervisor @ $60/hr, 1 shift/day
Solvent: 5.93 gal/ton of feed @ $1.50/gal
Utilities:
Cooling Water 8.8 kgal/ton of feed @ $0.05/kgal
Fuel (steam) 1.47 MBtu/ton of feed @ $5.00/MBtu
Electricity 28.6 kWhr/ton of feed @ $0.06/kWhr
Nitrogen 1.16 kscf/ton of feed @ $5.00/kscf
Maintenance 3% Investment/yr
Site Prep/Excavation: $75.55/hr operation
Solids Disposal: 0.48 ton/ton of feed @ $15.00/ton
Water Disposal: 72.2 gal/ton of feed @ $2.00/kgal
Indigenous Oil Credit: 1.56 bbl/ton of feed @ $20.00/bbl (per Biotherm)

Caution must be exercised in comparing the continuous operation of the refinery waste case of Table 13.17 (0.7 ton feed/hr) with the relatively short remediation period (1.5-2.7 years) of the drilling fluid case of Table 13.18 (1.4-2.5 ton feed/hr). Although the higher capacity divisor of the remediation case is an advantage, it is offset by higher labor costs since it must be more fully manned at an independent site rather than operated within a refinery complex. Capital recovery concerns must also be considered for a continuing treatment process in a refinery where a "feed" supply is assured for a number of years versus the relatively short period of operation of a remediation project where the investment capital must be recovered in less time for one project or over a few assured projects. Finally, feed compositions and product quality requirements will determine both investment and operating costs for specific projects. Sufficient economic details are given in both tables so that the reader may develop very preliminary screening economics for comparable potential projects.

No economics are presented for PCB soil remediation cases since they would be very site-specific, but it is predicted that treatment costs would be in the $110 to $182/tonne ($100 to $200/ton) of feed range like those for the drilling fluid cases. Costs of treating/destroying the concentrated PCB product stream are not included.

Conclusions

The technology flexible, commercially proven, proprietary Biotherm Process is a combination of dehydration and solvent extraction treatment technologies which has wide applicability for separating hydrocarbon solvent-soluble hazardous organic contaminants (indigenous oil) from sludges, soils and industrial wastes. Materials which may be treated include refinery K- and F- wastes which are regulated under RCRA, contaminated soils and sediments which must be remediated under Superfund, as well as other hazardous and nonhazardous solids/oil/water mixtures. As a result of this treatment, the products from a Biotherm Process facility are:

(1) Clean, dry, hydrocarbon-free solids which meet RCRA BDAT and other regulatory requirements and are suitable for disposal in nonhazardous landfills;

(2) Water which is treatable in an industrial or POTW wastewater treatment facility;

(3) Extracted indigenous oil containing contaminants which may be recycled/reused for credit or disposed of at less cost than the original waste feed.

While Biotherm Process economics are feed and product quality sensitive and site-specific, typical operating costs are usually between \$55 and \$110 per feed tonne (\$50 and \$100 per feed ton) for a refinery type waste and \$110 and \$182 per feed tonne (\$100 and \$200 per feed ton) for soil remediation; both are very competitive with other treatment techniques such as incineration which may be \$549 to \$1,648/tonne (\$500 to \$1,500/ton) for hazardous waste.

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Case 4 — Resources Conservation Company's Basic Extractive Sludge Treatment (B.E.S.T.®), Grand Calumet River, Gary, Indiana

The B.E.S.T.® Process is a patented solvent extraction system that uses triethylamine at different temperatures to separate organic contaminants from sludges, soils, and sediments. The organics are concentrated in an oil phase, thereby reducing the volume of wastes that require further treatment. Multiple extractions are conducted at predetermined process conditions and are followed by solvent recovery, oil polishing, solids drying, and water stripping.

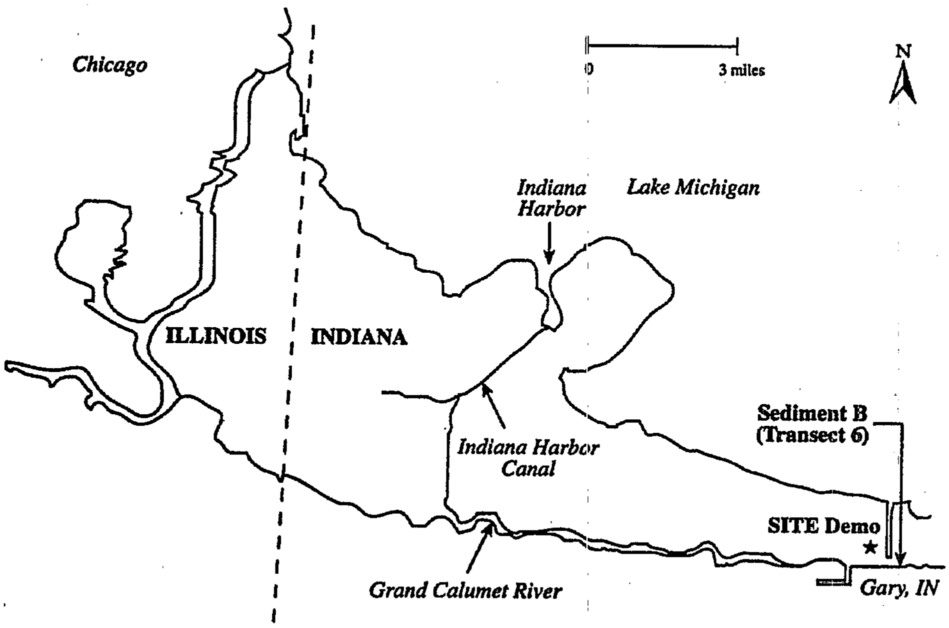
The use of triethylamine as the extracting agent distinguishes B.E.S.T.® from other solvent extraction and soil washing technologies. Triethylamine has a property known as inverse miscibility. At temperatures below 16°C (60°F), triethylamine is miscible with water; above 16°C (60°F), triethylamine is only slightly miscible with water. Therefore, at temperatures below 16°C (60°F), solids can be dewatered and organic contaminants can be extracted simultaneously. This process is referred to as a cold extraction. Following cold extractions, the extraction temperature is raised above 16°C (60°F), and any remaining organic contaminants are removed. These warm and hot extractions are usually conducted at temperatures ranging between 38 to 77°C (100 to 170°F). The organic contaminants initially present in the sludge or soil are concentrated in the oil fraction; additional treatment (e.g., incineration) is required to destroy or immobilize these contaminants.

This Summary was developed by US EPA's Risk Reduction Engineering Laboratory, Cincinnati, Ohio, to announce key findings of a SITE Program demonstration, which is fully documented in two separate reports.

The SITE Program was established in 1986 to promote the development and use of innovative technologies to remediate Superfund sites. One component of the SITE Program is the Demonstration Program, through which US EPA evaluates field or pilot-scale technologies that can be scaled up for commercial use. The main objective of the demonstration is to develop performance, engineering, and cost information for these technologies.

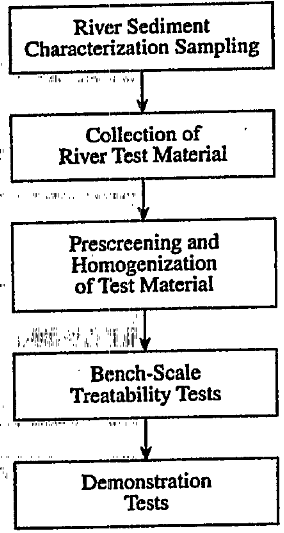
This Technology Demonstration Summary highlights the results of an evaluation of the effectiveness of the B.E.S.T.® Process to remove PAHs, PCBs, and oil and grease (O&G) from bottom sediments collected from the GCR in Gary, Indiana. Figure 13.12 shows the general locations of the demonstration test area, test sediment collection points in the GCR, and major regional features. Sample locations were chosen to obtain two different sediment types, Sediment A and Sediment B. Sediment A contained high concentrations of metals and low concentrations of organic compounds, relative to Sediment B. Sediment B, collected upstream from Sediment A, contained high concentrations or organic contaminants such as PAHs, PCBs, and O&G.

Figure 13.12
Regional Location Map



Prior to the demonstration testing, both sediment types were prescreened to separate oversize materials and were thoroughly homogenized (mixed). Separate bench-scale treatability tests were then conducted on each of the sediment types. These tests were performed by RCC to determine initial operating conditions, such as the number of extraction cycles, to be used in the demonstration. A flowchart of the experimental design used to guide the B.E.S.T.® evaluation is shown as Figure 13.13.

Figure 13.13
Experimental Design Flow Diagram



The demonstration consisted of two separate tests, one for each sediment type. Each test consisted of two phases. Phase I involved determination of the optimum process variables from the results of three runs, and Phase II consisted of two additional runs at the determined optimum conditions. Samples of the untreated sediments, product solids, product water, and product oil were collected during each of the five runs (Phases I and II). These samples were analyzed for total PAHs, PCBs, and O&G. Product solids, product water, and product oil were also analyzed for residual triethylamine solvent.

Results of the demonstration showed that the process met (or exceeded) the vendor's claims for organic contaminant removal efficiency of ≥96% for treating both of the test sediments. The analytical results for Sediment A indicated that the process removed greater than 98% of the O&G, greater than 99% of the PCBs, and 96% of the PAHs. The residual solvent in the product solids and product water generated from Sediment A was 45 mg/kg and less than 2 mg/L, respectively. A final oil product was not generated for Sediment A because of a lack of oil (less than 1%) in Sediment A feed. The analytical results for Sediment B indicated that the process removed greater than 98% of the O&G and greater than 99% of the PCBs and PAHs. The residual solvent in the product solids, product water, and product oil generated from Sediment B was 103 mg/kg, less than 1 mg/L, and 733 mg/kg, respectively.

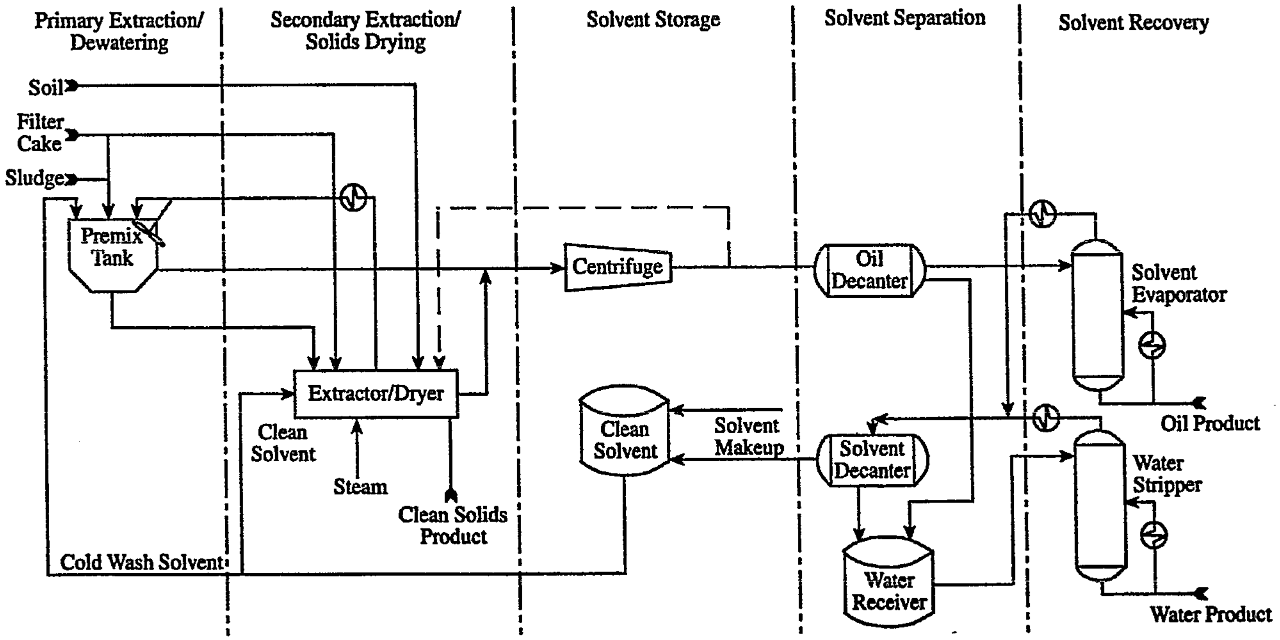
Process Description

The B.E.S.T.® pilot-scale system is designed to separate organic contaminants from soils, sludges, and sediments, thereby reducing the volume of hazardous waste that must be treated. Triethylamine is used as the extracting agent because it exhibits several beneficial characteristics. These characteristics include:

- a high vapor pressure (therefore the solvent can be easily recovered from the extract of oil, water, and solvent through simple stream stripping);
- formation of a low-boiling azeotrope with water (therefore the solvent can be recovered from the extraction to very low residual levels, typically less than 100 mg/L);
- a heat of vaporization one-seventh that of water (therefore, solvent can be recovered from the treated solids by simple heat with a very low energy input); and
- alkalinity (pH = 10)(therefore, some heavy metals can be converted to metal hydroxides, which can precipitate and exit the process with the treated solids).

The generalized B.E.S.T.® solvent extraction process is shown in Figure 13.14. Contaminated materials are initially screened to less than 1/2-in. diameter (1/8-in. for this demonstration). The screened material is added to a refrigerated Premix Tank along with a predetermined volume of 50% sodium hydroxide. The Premix Tank is sealed, purged with nitrogen, and then

Figure 13.14
Generalized Diagram of the RCC B.E.S.T.® Solvent Extraction Process



filled with chilled triethylamine solvent. The chilled mixture is agitated and allowed to settle. The resulting solution and this cold extraction consists of a mixture of solvated oil, water, and solvent. The mixture is decanted from the solids and centrifuged, and the solvent and water are separated out of the mixture by distillation.

The cold extractions are repeated as additional feed is added to the Premix Tank to accumulate enough solids to perform subsequent extraction cycles. Solids with high moisture contents may require more than one cold extraction. During this demonstration, Sediment A (containing 41% moisture) required two cold extractions.

Once a sufficient volume of moisture-free solids is accumulated, it is transferred to the steam-jacketed Extractor/Dryer. Warm triethylamine is then added to the solids. This mixture is heated, agitated, settled, and decanted. The warm and hot extractions separate the organics not removed during the initial cold extractions. Three products are derived from the total process: product solids, product water, and concentrated oil containing the organic contaminants.

The pilot plant used for this demonstration is a self-contained mobile unit that allows on-site testing to be performed at a pilot-scale. It consists of two portable skids that are mounted on a low boy trailer 2.4 m by 13.7 m (8 ft by 45 ft) on which the unit is transported. The process skid 6.1 m by 2.4 m (20 ft by 8 ft) has two levels and contains the majority of the B.E.S.T.® process equipment including the Premix Tank, the Extractor/Dryer, the Solvent Evaporator, the Centrifuge, storage tanks, pumps, and heat exchangers. The second smaller utility skid 3 m by 2.4 m (10 ft by 8 ft) contains several utility systems to support the operation of the process skid, including a refrigeration unit used to cool the solvent. Power requirements for the pilot plant are 480 V, three-phase power at 225 amp, which is accessed from a main power source (i.e., electrical drop) by an electrical distribution panel supplied by RCC. A support trailer accompanies the pilot plant, transporting ancillary equipment and providing a storage and working facility during testing.

Test Program

The primary objective of this SITE demonstration was to evaluate the effectiveness of the B.E.S.T.® solvent extraction technology on two test sediments having different contaminants or contrasting concentration levels of the same contaminants. Therefore, the sediments treated were collected at two different transect locations along the east branch of the GCR (see Figure 13.12). Sediments collected and homogenized from Transect 28 were designated Sediment A, and sediments collected and homogenized from Transect 6 were designated Sediment B. The transect locations were located approximately 3.22 km (2 mil) apart. The Sediment A (Transect 28) location was located slightly downstream of an oil-skimmed settling lagoon, which receives wastewater from primary bar plat mills and basic oxygen process (BOP) shops. Sediment B (Transect 6) was located slightly downstream from the discharge of a coke plant. Sediment A consisted of high levels of metals and low levels of organic contaminants relative to Sediment B. Sediment B was composed of high levels of organic contaminants and lower levels of metals.

Prior to the demonstration, each of the two sediment types was prescreened, thoroughly homogenized, and subjected to bench-scale treatability testing. These tests, which were conducted by RCC, provided initial operating conditions. Critical measurements were identified with the aid of sediment characterization analyses. The critical parameters selected for the demonstration tests were:

- PAHs and PCBs in all solid and liquid process streams;
- O&G in the feed material, treated solids, and water (O&G was identified as critical because oil is a process residual);
- triethylamine in the treated solids, water phase, and oil phase;
- moisture in the feed material and treated solids;
- Toxicity Characteristic Leachate Procedure (TCLP) metals in the feed material and treated solids;
- masses of feeds (including steam and caustic); and
- masses of treated residuals (solids, oil, water, and recovered solvent).

After the initial conditions and critical measurements were determined, the actual demonstration testing was initiated. A pilot-scale unit was utilized to conduct the testing, and was batch-loaded on average with approximately 77 kg (170 lb) of wet sediment/batch (test run). Two demonstration tests were conducted, one for each sediment type. Each demonstration test consisted of two phases. Phase I involved the determination of optimum process variables for each test sediment. These variables included number of extraction cycles, mixing times, and extraction temperature. Three sets of conditions, determined by RCC, were tested. Phase II consisted of two additional runs at optimum conditions determined in Phase I. This resulted in a total of three runs at optimum conditions for each sediment type. Tables 13.19 and 13.20 present the actual sequence of extraction cycles conducted during the demonstration for Sediments A and B, respectively.

Table 13.19
Extraction Sequence Used for Sediment A

Extraction Cycle	Extraction Temperature (°F) Phase I Run 1	Phase I Run 2	Phase I Run 3	Phase II Run 4	Phase II Run 5
1	cold (62)	cold (50)	cold (53)	cold (48)	cold (52)
2	warm (106)	cold (40)	cold (45)	cold (42)	cold (46)
3	warm (95)	cold (38)	warm (100)	warm (110)	warm (97)
4	warm (95)	warm (98)	hot (155)	hot (155)	hot (152)
5	warm (103)	warm (125)	hot (166)	hot (163)	hot (167)
6	hot (170)	hot (160)	hot (166)	hot (164)	hot (160)
7	–	hot (160)	hot (166)	hot (164)	hot (160)

The three optimum runs are Runs 3, 4, and 5.

Samples were collected and analyzed for each process stream specified in Table 13.21. PAHs, PCBs, and O&G were critical analyses for all media except vent gas. These contaminants were known to be in both sediment types and were the primary constituents targeted for removal using the B.E.S.T.® Process. Triethylamine was targeted for analysis in the product streams and vent gas emissions because of its potential as a process residual. Moisture content and TCLP were considered critical because of the original characteristics of the sediments (high moisture and metals contents).

Table 13.20
Extraction Sequence Used for Sediment B[a]

Extraction Cycle	Extraction Temperature (°F)				
	Phase I			Phase II	
	Run 1	Run 2	Run 3	Run 4	Run 5
1A1	cold (49)	cold (28)	cold (32)	cold (28)	cold (51)
1A2	cold (47)	cold (42)	cold (40)	cold (48)	cold (41)
1A3	NC[b]	cold (38)	cold (40)	cold (39)	cold (39)
1B1	cold (41)	cold (39)	cold (29)	cold (51)	cold (39)
1B2	cold (53)	cold (47)	cold (38)	cold (53)	cold (45)
1B3	cold (52)	cold (36)	cold (46)	cold (46)	cold (44)
2	hot (145)	hot (152)	hot (151)	hot (147)	hot (146)
3	hot (152)	hot (157)	hot (150)	hot (156)	hot (160)
4	hot (161)	hot (150)	hot (152)	hot (170)	hot (153)
5	hot (148)	hot (152)	hot (151)	hot (155)	hot (154)
6	hot (157)	hot (151)	hot (146)	hot (158).	hot (152)
7	hot (143)	–	hot (150)	–	–

The three optimum runs are Runs 2, 4, and 5.

[a] Because of the high moisture content of Sediment B, both sediment and solvent were fed to the Premix Tank. The portions of each were limited so that the temperature rise of the solvent/water phase was at an acceptable limit.

[b] NC = not conducted

Six main process streams were sampled and analyzed for each of the two tests. These process streams included untreated sediments (raw feed), product solids, product water, product oil or oil/solvent mix, recycled solvent, and vent emissions. Decant water collected from buckets holding the feed from one of the Sediment B batches was also sampled. Each lot of product triethylamine was sampled prior to use.

Results

The following data summary is derived from this SITE demonstration:

- Contaminant reductions of 96% or greater for total PAHs and greater than 99% for total PCBs were achieved from treatment of bottom sediments collected from Transect 28 (Sediment A) of the GCR. Contaminant reductions of greater than 99% for total PAHs and greater than 99% for total PCBs were achieved from treatment of bottom sediments collected from Transect 6 (Sediment B) of the GCR. Table 13.22 provides the percent removals for individual PAH compounds from test sediments, as determined from averaging the three optimum runs. Table 13.23 presents the PCB removal efficiencies from test sediments for each test run and as total optimum run averages.

- O&G removal efficiencies in excess of 98% were achieved in the treated solids generated from both sediment types, as shown in Table 13.24.
- Mass balances calculated for all materials entering and exiting the process indicated that very good mass balance closures were achieved from treatment of both test sediments. Closures of 99.3% and 99.6% were obtained for Sediments A and B, respectively.
- The products generated using the B.E.S.T.® Process were consistent with RCC's claims with regard to residual triethylamine concentrations. Average triethylamine concentrations of 103 mg/kg, less than 1 mg/L, and 733 mg/kg for solid, water, and oil product, respectively, were generated during the treatment of Sediment B (Transect 6). Solid and water products generated from the treatment of Sediment A achieved average residual triethylamine concentrations of 45 mg/kg and less than 2 mg/L, respectively. Product oil was not generated from treatment of Sediment A because Sediment A originally contained very little oil (less than 1%). A summary of RCC's claims, and actual triethylamine concentrations in the treated solids, product water, and product oil are presented in Table 13.25.

Costs

Operating and equipment capital cost estimates were developed for the proposed full-scale B.E.S.T.® system. The cost estimates were based on information provided by the vendor and on several assumptions. These assumptions were based on the experiences of this demonstration and a

Table 13.21
Summary of Analyses Conducted for the RCC B.E.S.T.® SITE Demonstration

Parameter	Untreated Sediment (Raw Feed)	Treated Sediment (Product Solids)	Water Phase (Product Water)	Decant Water (From Raw Feed)	Oil Phase (Product Oil)	Intermediate Solvent/Oil Mixture	Solvent Feed and Recycled Solvent	Vent Gas
Critical								
PAHs[a]	▲	▲	▲	▲	▲	▲	▲	
PCBs	▲	▲	▲	▲	▲	▲	▲	
Oil and Grease	▲	▲	▲	▲				
Moisture[b]	▲	▲			▲			
Triethylamine		▲	▲		▲			▲
TCLP Metals[c]	▲	▲						
Non-critical								
Total Suspended Solids			▲	▲			▲	
Proximate/Ultimate	▲	▲			▲			
Total Metals[d]	▲	▲	▲	▲				
Total Recoverable Petroleum Hydrocarbons	▲	▲	▲	▲				

Volatile Solids	▲	▲	▲	
Total Cyanide	▲	▲	▲	
Reactive Cyanide	▲	▲		
Reactive Sulfide	▲	▲		
Particle Size	▲	▲		
Total Phosphorus	▲	▲	▲	
pH	▲	▲	▲	
Total Dissolved Solids			▲	▲
Total Organic Carbon/Total Inorganic Carbon			▲	
Biochemical Oxygen Demand			▲	
Conductivity			▲	
Special Studies				
Biodegradation		▲		

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[a] Specific PAH compounds analyzed are presented in Table D.4.
[b] Moisture was critical for all samples except for the oil phase.
[c] TCLP metals include As, Ba, Cd, Cr, Pb, Hg, Se, and Ag.
[d] Total metals include Sb, As, Ba, Be, Cd, Cr, Cu, Mn, Hg, Ni, Se, Tl, Va, and Zn.

Table 13.22
PAH Removal Efficiencies

	Sediment A			Sediment B		
PAH Analyte	Feed[a]	Treated Solids[a]	% Removal[b]	Feed[a]	Treated Solids[a]	% Removal[b]
Acenaphthene	68	1.3	98.1	12,800	42	99.7
Acenaphthylene	< 16	< 0.8	–	210	6.6	96.9
Anthracene	22	1.3	94.1	2,370	16	99.3
Benzo(a)anthracene	25	0.52	97.9	1,050	4.7	99.6
Benzo(a)pyrene	24	0.34	98.6	810	4.6	99.4
Benzo(b)fluoranthene	23	0.36	98.4	857	4.1	99.5
Benzo(k)fluoranthene	17	0.22	98.7	533	3.6	99.3
Benzo(ghi)perylene	15	0.20	98.6	457	2.3	99.5
Chrysene	25	0.52	97.9	937	4.7	99.5
Dibenz(a,h)anthracene	< 18	< 0.76	–	140	< 2.9	> 97.9
Fluoranthene	76	1.4	98.2	4,280	16	99.6
Fluorene	51	1.9	96.3	7,290	35	99.5
Indeno(1,2,3-cd)pyrene	15	0.18	98.8	547	2.2	99.6
2-Methylnaphthalene	25	3.7	85.2	6,410	83	98.7
Naphthalene	< 18	5.1	–	18,700	230	98.8
Phenanthrene	92	3.6	96.1	10,800	41	99.6
Pyrene	67	1.0	98.5	2,810	12	99.6
Total PAHs	**548**	**22**	**96.0**	**70,920**	**510**	**99.3**

[a] Concentrations reported in mg/kg (dry weight basis) and are the average of the three optimum runs for each sediment (Sediment A = Runs 3, 4, and 5; Sediment B = Runs 2, 4, and 5).

[b] $\% \text{ Removals} = \frac{\text{Feed Concentration} - \text{Treated Solids Concentration}}{\text{Feed Concentration}} \cdot 100$

Table 13.23
PCB Removal Efficiencies

Parameter	Test Runs					Average[c]	Standard Deviation[c]
	R1	R2	R3	R4[a]	R5[b]		
Sediment A							
Total PCBs-Feed (mg/kg-dry weight)	7.33	6.41	8.01	11.8	16.4	10.0/12.1	4.1/4.2
Total PCBs-Treated Solids (mg/kg-dry weight)	< 0.07	0.20	0.05	0.04	0.04	0.08/0.04	0.07/0.006
Percent Removal (%)	> 99	96.9	99.4	99.7	99.8	99.2/99.7	–
Sediment B							
Total PCBs-Feed (mg/kg-dry weight)	364	316	495	462	497	427/425	82/96
Total PCBs-Treated Solids (mg/kg-dry weight)	1.5	2.1	1.2	1.8	1.4	1.6/1.8	0.35/0.35
Percent Removal (%)	99.6	99.3	99.8	99.6	99.7	99.6/99.6	–

[a] Concentrations reported for Run 4 are the average of three field replicate measurements.
[b] Concentrations reported for Run 5 are the average of samples analyzed in triplicate.
[c] Two values are given; the first pertains to all five runs and the second pertains to the three optimum runs (Sediment A = Runs 3, 4, and 5 and Sediment B = Runs 2, 4, and 5).

Table 13.24
Oil and Grease Removal Efficiencies

Parameter	Test Runs R1	R2	R3	R4[a]	R5[b]	Average[c]	Standard Deviation[c]
Sediment A							
Total Oil and Grease-Feed (mg/kg-dry weight)	9,400	7,800	7,400	6,600	6,700	7,580/6,900	1,030/436
Total Oil and Grease-Treated Solids (mg/kg-dry weight)	195	169	203	66	65	140/111	69/79
Percent Removal (%)	97.9	97.8	97.3	99.0	99.0	98.2/98.4	–
Sediment B							
Total Oil and Grease-Feed (mg/kg-dry weight)	66,400	116,000	67,300	167,000	99,100	103,000/127,000	41,600/35,300
Total Oil and Grease-Treated Solids (mg/kg-dry weight)	1,800	1,330	1,490	1,230	1,810	1,530/1,460	266/310
Percent Removal (%)	97.3	98.9	97.8	99.3	98.2	98.5/98.9	–

[a] Concentrations reported for Run 4 are the average of three field replicate measurements.

[b] Concentrations reported for Run 5 are the average of samples analyzed in triplicate.

[c] Two values are given; the first pertains to all five runs and the second pertains to the average of the three optimum runs (Sediment A = Runs 3, 4, and 5 and Sediment B = Runs 2, 4, and 5).

Table 13.25

Triethylamine Concentrations — Treated Solids, Product Water, and Oil Phases

		Test Runs[a]						Standard
Parameter	Claim	R1	R2	R3	R4[b]	R5	Average[c]	Deviation[c]
Sediment A								
Triethylamine in Treated Solids (mg/kg)	< 150	61.7	93.1	27.8	28.0	79.6	58/45	29.6/29.8
Triethylamine in Product Water (mg/L)	< 80	< 1	< 1	< 1	< 1	2.2	< 2/< 2	–
Triethylamine in Oil Phase (%)	NA	–	–	–	–	–	65.8[d]	–
Sediment B								
Triethylamine in Treated Solids (mg/kg)	< 150	106	88.7	55	130	89.3	94/103	27.4/23.7
Triethylamine in Product Water (mg/L)	< 80	< 1	1.0	< 1	< 1	< 1	< 1/< 1	NA
Triethylamine in Product Oil (mg/L)	< 1,000	–	–	–	–	–	733[d]	–

[a] Concentrations reported for each of the five test runs for each sediment are the average of laboratory triplicate analysis conducted on the sample.

[b] Concentrations reported for Run 4 are the average of three field replicate measurements, each of which are the average of laboratory triplicate analysis.

[c] Two values are given for treated solids and product water; the first pertains to all five runs and the second pertains to the three optimum runs (Sediment A = Runs 3, 4, and 5; Sediment B = Runs 2, 4, and 5).

[d] The % values reported for the Sediment A oil/solvent mixture and the Sediment B product oil are the averages of five aliquot (field replicate) measurements.

previous full-scale test conducted at a site in Georgia. Certain cost factors which were not included in the treatment cost estimate were assumed to be the responsibility of the site owner/operator. Costs associated with system mobilization, site preparation, startup, and demobilization were also excluded from the treatment cost estimate. The reasoning used in making these estimates, or omitting a particular cost category, is discussed in the Applications Analysis Report.

The pilot-scale unit used in this demonstration operated at an average feed rate of 40.8 kg (90 lb) of contaminated sediment/day. The full-scale commercial unit is projected to be capable of treating 169 tonne/day (186 ton/day)(TPD) of contaminated soil or sludge. The cost estimates are based on the remediation of contaminated soil, sludge or sediment using the proposed full-scale unit. The treatment cost is estimated to be \$123/tonne (\$112/ton) if the system is on-line 60% of the time or \$103/tonne (\$94/ton) if the system is on-line 80% of the time. Cost information is presented in the Applications Analysis Report for this demonstration.

Conclusions

The B.E.S.T.® solvent extraction process is designed to treat sludges, soils, and sediments contaminated with organic compounds. The system is capable of physically separating organic contaminants, such as PAHs, PCBs, and O&G from contaminated media and concentrating the organics for contaminant volume reduction. The prototype full-scale system is only applicable to sludges, but the proposed full-scale system will be applicable to soils and sediments as well.

The effectiveness of treatment can be illustrated from this demonstration and from previous case studies. This demonstration removed at a minimum 96% of the PAHs, greater than 99% of the PCBs, and greater than 98% of the O&G from the contaminated sediments.

A

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