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In Situ Flushing

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FOREWORD

About GWRTAC

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) is a national environmental technology transfer center that provides information on the use of innovative technologies to clean up contaminated groundwater.

Established in 1995, GWRTAC is operated by the National Environmental Technology Applications Center (NETAC) in association with the University of Pittsburgh's Environmental Engineering Program through a Cooperative Agreement with the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO). NETAC is an operating unit of the Center for Hazardous Materials Research and focuses on accelerating the development and commercial use of new environmental technologies.

About "O" Series Reports

This report is one of the GWRTAC "O" Series of reports developed by GWRTAC to provide a general overview and introduction to a ground-water remediation technology. These overview reports are intended to provide a basic orientation to the technology. They contain information gathered from a range of select, currently available sources, including project documents, reports, periodicals, Internet searches, and personal communication with involved parties. No attempts are made to independently confirm or peer review the resources used.

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ABSTRACT

This technology summary report is an overview of information collected by GWRTAC on *in situ* flushing as an *in situ* ground-water remediation technology. Information provided includes an introduction to the general principles and techniques, a discussion of the general applicability of the technology, an overview of data related to its utilization, and reported advantages and limitations of the technology. References cited, and a bibliography compiled during preparation of this report containing additional information sources, are also provided.

In situ flushing is the injection or infiltration of an aqueous solution into a zone of contaminated soil/groundwater, followed by downgradient extraction of groundwater and elutriate (flushing solution mixed with the contaminants) and aboveground treatment and discharge or re-injection. Flushing solutions include plain water sometimes augmented by surfactants, cosolvents, or other facilitators. *In situ* flushing enhances conventional pump and treat technology through increasing the efficiency of a flushing pore volume, or accelerating natural flushing action. The technology is potentially applicable to a very broad range of contaminants, and is not limiting in terms of contaminant depth or location within the hydrogeologic regime, although successful implementation is highly site-specific. This paper provides many site-specific and contaminant-specific critical success factors. Some of the more important site-related parameters include variations in hydraulic conductivity, degree of heterogeneity, and soil organic content. Some of the contaminant-related factors include solubility and octanol/water partitioning coefficient. The report discusses data which must be collected to evaluate the potential for successful implementation, and for design of an *in situ* flushing project. The site specificity of application of this technology necessitates extensive pre-design data collection and treatability studies.

Several aspects of physical constructions and operation of *in situ* flushing projects are discussed in this overview report. Limited case study and generalized cost information is also presented. Finally, technology advantages and limitations are reviewed. Advantages include the potential applicability to a broad range of contaminants and acceleration of site clean up relative to conventional pump and treat. Limitations include potential for spreading contaminants and consequent limited regulatory acceptance, site geologic setting limitations, and uncertainties involved in prediction of performance and clean up duration.

This document was prepared for distribution by the Ground-Water Remediation Technologies Analysis Center (GWRTAC). GWRTAC is operated by the National Environmental Technology Applications Center (NETAC) in association with the University of Pittsburgh's Environmental Engineering Program, under a Cooperative Agreement with the U.S. EPA's Technology Innovation Office (TIO).

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1.0 INTRODUCTION

In situ flushing is the injection or infiltration of an aqueous solution into a zone of contaminated soil/groundwater, followed by downgradient extraction of groundwater and elutriate (flushing solution mixed with the contaminants) and aboveground treatment and discharge or re-injection. Introduction of the flushing solution may occur within the vadose zone, the saturated zone, or both. *In situ* flushing differs from soil washing, which is generally used to describe the *ex situ* process of using solutions and a mechanical process to remove contaminants from soil, although some authors may refer to *in situ* soil washing synonymously with *in situ* flushing. The solutions used for *in situ* flushing may consist of surfactants, cosolvents, acids, bases, oxidants, chelants, solvents, or plain water, and serve to increase the mobility and/or solubility of the contaminants, or to increase the rate of flushing (1,2,3).

Unconventional soil flushing techniques may include waterflooding, gaseous and chemical processes, and thermal methods. These are techniques of enhanced oil recovery applied in the oil and gas industry, and are not discussed in this overview report, though references cited may provide additional information (4).

In situ flushing enhances conventional pump and treat technology by making each pore volume of groundwater cycling through the contaminated zone more efficient at contaminant removal, or increasing the natural flushing rate, thus accelerating the overall ground-water remediation process. Any variety of configurations of injection wells, horizontal wells, trenches, infiltration galleries, aboveground sprayers or leach fields, and extraction (recovery) wells, open ditches, or subsurface collection drains or trenches are used to contact the flushing solution with the contaminated zone and collect elutriate. Soil flushing may also be used in conjunction with other technologies, such as enhanced biodegradation, to achieve remediation goals (1,2,3).

Two of the most common reagents used in flushing solutions are surfactants and cosolvents or mixtures thereof. Use of surfactants and cosolvents, while included under the general class of *in situ* flushing, are not discussed in detail in this report. Details relating to the principles of surfactant and cosolvent use, as well as information regarding research projects where these reagents are being used, are included in other GWRTAC reports (3,5,6), as well as other sources (7). This overview report instead focuses on the general considerations for use of *in situ* flushing, a general overview of flushing solutions, including surfactants and cosolvents, and the physical mechanics of contacting the flushing solution with the contaminated zone. In addition, a GWRTAC “S” Series Status Report for *In Situ* Flushing is available to provide information on case studies compiled for this technology (8). Status information is thus presented only as an overview in this document.

2.0 APPLICABILITY

2.1 CONTAMINANTS

Investigators and practitioners are using *in situ* flushing to treat a variety of organic and inorganic contaminants. Organics susceptible to *in situ* flushing include:

- non-aqueous phase liquid (NAPL);
- volatile organic compounds (VOCs);
- semivolatile organic compounds (SVOCs);
- polychlorinated biphenyls (PCBs);
- halogenated pesticides;
- dioxins/furans;
- cyanides; and,
- corrosives.

Inorganics, including volatile and nonvolatile metals, corrosives, cyanides, and radioactive contaminants, may also potentially be removed via *in situ* flushing.

Removal efficiencies of contaminants will depend upon the contaminant as well as the soil type. Halogenated volatiles, nonhalogenated semivolatiles, and nonvolatile metals are among the classes of chemical compounds treated successfully by *in situ* flushing (2). Section 3.1 provides information on generally accepted values for various contaminant properties which may allow for successful application of *in situ* flushing.

2.2 SITE CONDITIONS

Thorough understanding of the nature of the hydrogeologic regime of a site is essential for potential soil flushing projects. This understanding is important to:

- assess whether *in situ* flushing is applicable, the likelihood of success, and the potential duration of the project; and,

- design the entire *in situ* flushing project, including flushing additive selection, as well as the physical injection/extraction, and hydraulic or physical containment aspects of the project.

Depth to the contaminated zone and the physical location of the contaminant within the hydrogeologic regime is not a limiting factor in itself. Contaminants present in the vadose zone, in the saturated zone of unconfined aquifers, or in confined aquifers are candidates for *in situ* flushing. Depth is a limiting factor primarily due to the economics involved with injection and extraction, as operation and maintenance will require larger amounts of energy relative to more shallow projects.

Permeability is a key physical parameter in determination of the feasibility of *in situ* soil flushing. Hydraulic conductivity, which is measured to assess permeability, will ideally be greater than 1.0×10^{-3} cm/second to allow flushing solutions to pass through the geologic matrix in a reasonable period of time. Less permeable materials, with hydraulic conductivities ranging from 10^{-5} to 10^{-3} cm/second may also be considered for *in situ* flushing. Hydraulic conductivity measurements should take vertical and lateral variability into account. Determination of hydraulic conductivity should thus be made at several different locations within the potential treatment zone, and the variation examined, rather than using average hydraulic conductivities and disregarding the variation. The number of hydraulic conductivity measurements should be consistent with the size of the potential treatment zone, and the potential for heterogeneity. It is also important to assess hydraulic conductivity in the units adjacent to the potential flushing operation for assessment of potential for natural containment, and for design of additional containment needs (2).

Containment of the flushed contaminants and spent flushing solutions is essential to successful application of *in situ* flushing. Application is thus simplified when vertical and horizontal hydraulic gradients are low and/or the treatment zone is bounded geologically by materials with relatively low hydraulic conductivity. Inversely, the presence of streams, lakes, seeps, or other ground-water discharge zones in near proximity to the treatment zone complicate application, because the presence of these systems do not facilitate hydraulic containment (9).

This technology is most effectively applied when geologic materials exhibit moderate to high hydraulic conductivity, and are also relatively homogeneous. Ideally, hydraulic conductivity contrasts in the target media will be less than an order of magnitude within the area to be treated, and the material with the lower conductivity will be surrounded by material with higher hydraulic conductivity. Nonhomogeneous conditions will cause channeling and uneven treatment. Flushing additive movement through material of lower hydraulic conductivity may occur through the slower process of diffusion rather than bulk transfer. The feasibility of *in situ* flushing depends upon the details of the distribution of primary and secondary flowpaths (2,4,9).

Types of situations which could cause heterogeneities and could preclude use, or render implementation of *in situ* flushing complex, include the following (2,4,9).

- Soil/rock containing appreciable fine-grained material, such as clay and silt. Such materials are less responsive to soil flushing, especially as a stand-alone technology.

- Large amounts of debris within the soil, as sometimes associated with waste disposal sites, may also interfere with soil flushing, as the flow of treatment agents could be obstructed or diverted.

- Soils with a high degree of preferential pathways developed from shrink/swell cycles, root intrusions, or uneven settling may hinder the contact of the flushing solution within the treatment zone.

- The presence of fractures or preferred pathways to ground-water flow, such as highly developed bedding planes, may decrease the reliability of *in situ* flushing.

Section 3.1 provides additional information on generally accepted values for various physical properties which may allow successful application of *in situ* flushing.

3.0 METHODOLOGY

Figure 1 depicts an ideal *in situ* soil flushing process, in which injection of a flushing solution into an unconfined aquifer occurs. In Figure 1, the contaminated zone shown (TCE as DNAPL and dissolved phase) is located largely within the saturated zone.

In general practice, the flushing solution is applied to/above the contaminated soil zone (within the vadose or saturated zone, or both), and percolates or migrates through the contaminated zone. In some cases, preflushing (such as with an innocuous tracer) is conducted to demonstrate that the extraction system will achieve the necessary hydraulic containment. Preflushing adjusts the salinity of the ambient ground-water system prior to application of surfactants or polymers, and minimizes the potential for adsorption of the surfactant.

Upon introduction, the flushing solution removes contaminants via:

- solubilization;
- emulsion formation; or,
- chemical reaction.

The soil flushing process accelerates one or more geochemical reactions that alter contaminant concentrations in groundwater, such as:

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

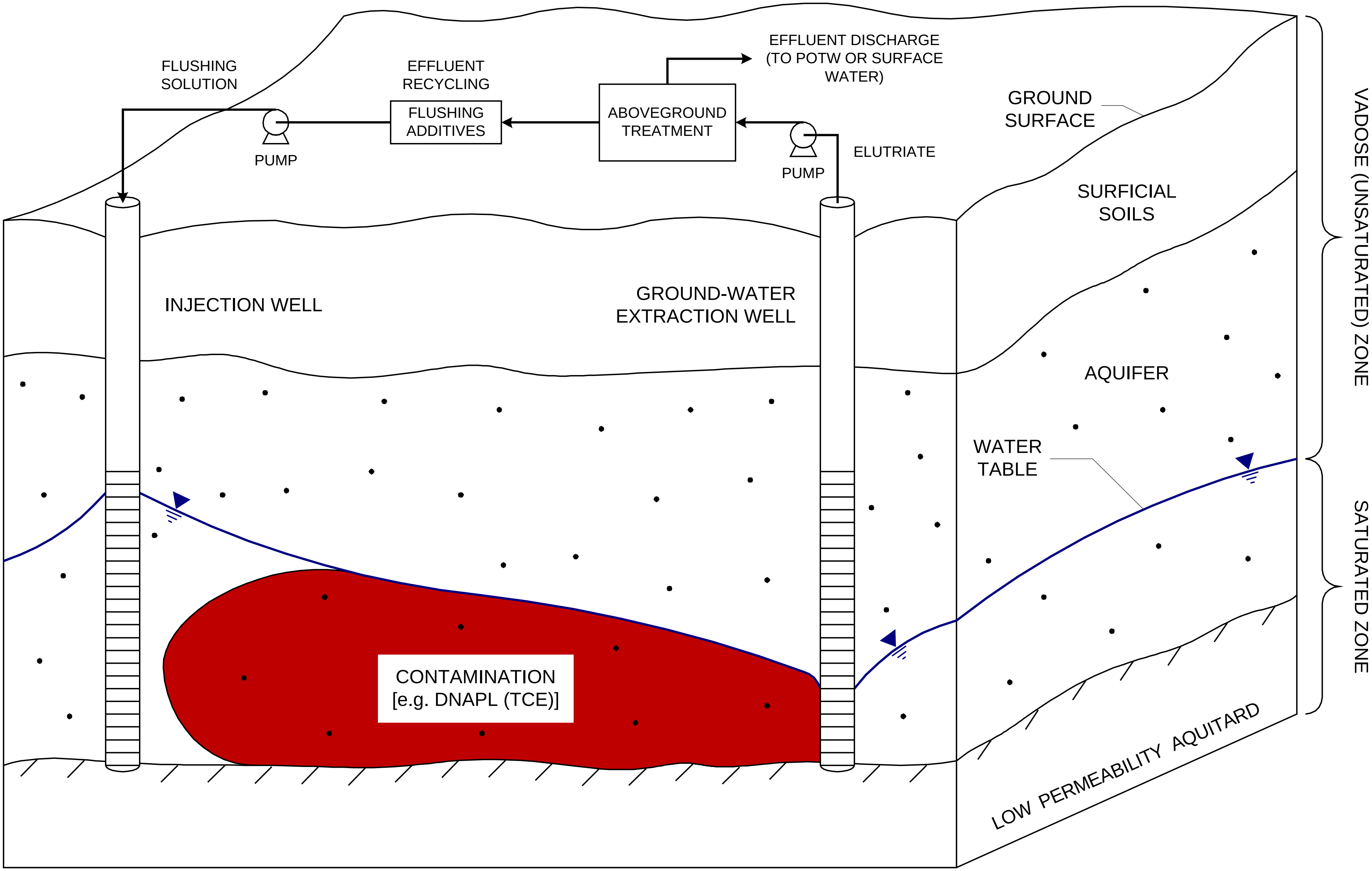
Subsurface contaminant transport mechanisms are accelerated during soil flushing, as they are in conventional pump and treat operations. These include mechanisms such as:

- advection;
- dispersion;
- molecular diffusion; and,
- depletion via volatilization or solubilization.

“Spent” flushing fluid containing contaminants mixes with the groundwater and is collected for treatment and reuse, or in rare cases, depending upon the depth, the contaminants and the fluids are left in place (2,4).

As ground-water extraction after flushing is by far the most common practice, this technology overview will not further discuss leaving the elutriate in place. The contaminated fluids can be recovered from a perched condition, or from a previously saturated aquifer. The ground-water collection or extraction system must be designed to ensure complete hydraulic control and contaminant recovery. The rate of ground-water withdrawal is a function of the flushing solution delivery rate and natural infiltration rate, as well as site hydrogeology. The ground-water withdrawal

Figure 1. Schematic of *In Situ* Flushing System.



Modified from U.S. EPA (1991) and U.S. Department of Energy (1996).

rate must exceed the flushing solution injection rate to ensure recovery of all of the elutriate. Hydraulic control of the flushing system is essential. Aboveground treatment/disposal of the elutriate takes place at this point; effluent should be recycled to the extent possible, and re-injected, possibly after the addition of additional flushing additives (2).

After *in situ* flushing treatment, it may be necessary to control infiltration through the treated area to prevent additional contaminant mobilization. *In situ* bioremediation after *in situ* flushing will often assist in removal of residual levels of contaminants. Use of enhanced *in situ* bioremediation techniques, such as bioventing, may be more easily applied after soil flushing due to increased permeability caused by the removal of the bulk of contaminants (4).

The following sections will detail some of the data requirements for consideration and design of an *in situ* flushing system, including values of key physical and contaminant properties important to successful application. They will also overview the principles of some flushing solutions use, and provide an overview of some of the physical constructions used to inject and extract flushing solutions.

3.1 MINIMUM DATA REQUIREMENTS FOR DESIGN AND CRITICAL SUCCESS FACTORS

Data requirements for design of a successful *in situ* flushing project generally include:

- detailed physical, biological, and chemical information specific to the site conditions and to the contaminant(s) of interest; and,

- regulatory standards and related logistical considerations.

Conducting laboratory and field treatability tests to assess the performance of *in situ* flushing at a particular site can be important, as its performance is highly dependent on contaminant and *in situ* site characteristics. Application of this technology depends on the ability to deliver, control the flow of, and recover the flushing solution. As such, many critical success factors (values of parameters related to the site conditions and contaminant) have been identified to assist in screening potential soil flushing sites. Table 1 presents these critical success factors and conditions for *in situ* flushing. The text below provides additional information, and additional detail on the tabulated factors.

3.1.1 Contaminant-Related Factors

The characteristics of the contaminant which must be known include its concentration, distribution (vertically and horizontally), NAPL vertical and horizontal distribution, adsorption to specific size fractions of soils, solubility, partition coefficient, retardation factors, vapor pressure, solubility products, reduction potential, and complex stability constants. Table 1 presents actual values recommended in the literature for successful application of *in situ* flushing for many of the contaminant related parameters. In addition, for inorganics, metals speciation must be determined as a function of the solubility and leachability of heavy metals (3,4,9,10,11).

3.1.2 Site-Related Factors

In addition, ambient physical and chemical soil characterization parameters must be determined. These include soil permeability, soil structure and texture, soil porosity, moisture content, total

Table 1. *In Situ* Flushing Critical Success Factors and Conditions

Critical Success Factor Site Related	Likelihood of Success Less Likely	 Marginal	 More Likely	Basis	Data Needs
Dominant Contaminant Phase and Equilibrium Partitioning Coefficient*	Vapor	Liquid	Dissolved	Contaminant preference to partition to extractant is desirable.	Equilibrium partitioning coefficient of contaminant between soil and flushing solution.
Hydraulic Conductivity*	Low (<10^{-5} cm/sec)	Medium (10^{-5} to 10^{-3} cm/sec)	High (>10^{-3} cm/sec)	Good conductivity allows efficient delivery of flushing fluid.	Geologic characterization (hydraulic conductivity ranges).
Soil Surface Area*	High (>1 m^2/kg)	Medium (0.1-1 m^2/kg)	Small (<0.1 m^2/kg)	High surface area increases sorption on soil.	Specific surface area of soil.
Carbon Content	High (>10% wt.)	Medium (1-10% wt.)	Small (<1% wt.)	Flushing typically more effective with lower soil organic content.	Soil total organic carbon (TOC).
Soil pH and Buffering Capacity*	NS	NS	NS	May affect flushing additives and construction material choice.	Soil pH, buffering capacity.
Cation exchange capacity (CEC) and clay content*	High (NS)	Medium (NS)	Low (NS)	Increased binding of metals, sorption and inhibit contaminant removal.	Soil CEC, composition, texture.
Fractures in Rock	Present	---	Absent	Secondary permeability characteristics render flushing fluid contact more difficult.	Geologic characterization.

Critical Success Factor Contaminant Related	Likelihood of Success Less Likely	 Marginal	 More Likely	Basis	Data Needs
Water Solubility*	Low (<100 mg/L)	Medium (100-1,000 mg/L)	High (>1,000 mg/L)	Soluble compounds can be removed by flushing.	Contaminant solubility.
Soil Sorption	High (>10,000 L/kg)	Medium (100-10,000 L/kg)	Low (<100 L/kg)	Higher capacity of contaminant to sorb to soil decreases flushing efficiency.	Soil sorption constant.
Vapor Pressure	High (> 100 mm Hg)	Medium (10-100 mm Hg)	Low (<10 mm Hg)	Volatile compounds tend to partition to vapor phase.	Contaminant vapor pressure at operating temperature.
Liquid Viscosity	High (>20 cPoise)	Medium (2-20 cPoise)	Low (<2 cPoise)	Fluids flow through the soil more readily at lower viscosity.	Fluid viscosity at operating temperature.
Liquid Density	Low (<1 g/cm^3)	Medium (1-2 g/cm^3)	High (>2 g/cm^3)	Dense insoluble organic fluids can be displaced and collected via flushing.	Contaminant density at operating temperature.
Octanol/water partition coefficient*	NS	NS	10-1,000 (dimensionless)	More hydrophilic compounds are amenable to removal by water-based flushing fluids.	Octanol/water partitioning coefficient.

Modified from U.S. EPA (1993) and Mann, et al. (1993)

NS Indicates no action level specified
* Indicates higher priority factors

organic carbon (TOC), cation exchange capacity (CEC), pH, and buffering capacity. Table 1 summarizes literature values of these and other site-related factors recommended for successful application of *in situ* flushing. High humic content and high soil TOC or CEC are undesirable as they may reduce *in situ* soil flushing efficiency. Organic contaminants may adsorb to humic materials or clay, and metals may bind with clay due to its CEC. The pH (buffering capacity) of the soil may affect the amount of flushing solution needed, especially when acids and bases are used. Analysis of groundwater for a suite of parameters relevant to natural ground-water geochemistry should also be performed along with the soil analyses to allow evaluation of the potential for inducing reactions by introduction of the flushing solution. These parameters may include silica, iron, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, dissolved solids, hardness, specific conductance, pH, acidity, alkalinity, and others. Precipitation reactions, which may result in clogging of soil pores, can occur due to pH changes in the flushing fluid caused by neutralization by high soil/ground-water pH. Ambient soil/ground-water pH also can affect speciation of metals, affecting solubility of metals in the flushing solution. Geochemical stability diagrams may be used to assess the potential for dissolution and precipitation of metals as conditions are changed during the flushing operation (4,9,12).

All of these data are needed to assist in determining the type, amount, and concentration of flushing solution required; flushing solution compatibility; and changes in flushing fluids with changes in contaminants. Residual flushing additives remaining in the soil may also be of concern and must be considered (3,10,11).

From a hydrogeological perspective, detailed information on the configuration of the subsurface and hydrologic budget is critical to the success of an *in situ* flushing operation. Hydrogeologic data which must be collected include seasonal fluctuations in water level, direction and rate of vertical and horizontal ground-water flow, porosity, vertical and horizontal hydraulic conductivities, vadose zone saturation, transmissivity (aquifer saturated thickness multiplied by hydraulic conductivity), aquifer confinement, use of adjacent aquifers, and data pertinent to infiltration rates (such as precipitation, evaporation, transpiration, and percolation). The distribution of non-contaminant debris in the subsurface is also important to consider in terms of ease of contact of the treatment agents within the target area (2,9).

A critical concept in the application of *in situ* flushing is that of pore volume. Pore volume is the volume of water contained within a defined volume of porous media. In *in situ* flushing systems, pore volume is defined as the volume of groundwater contained within the contaminated zone or between an injection and extraction point. The time in which a pore volume travels from injection to extraction point, and the number of pore volumes which must flush through the system to achieve remediation goals, are critical in determination of the overall efficiency of remediation by *in situ* flushing, and to allow comparison with baseline pump and treat efficiency. In addition to several of the hydrogeologic parameters listed above, soil moisture content is used to calculate pore volume to determine the rate of treatment as well as amount of flushing solution initially needed (2).

3.1.3 Other General Factors

In addition to the site characterization criteria and flushing solution selection criteria discussed above, some additional considerations for design of an *in situ* flushing system include:

- Excessive infiltration during operation may cause dilution of flushing solution and loss of hydraulic control. Freezing could be problematic for shallow injection systems and aboveground treatment systems (installation of runoff and temperature control structures/equipment will minimize these potential problems) (2).

- Biogrowth may foul injection and extraction systems and treatment units, especially if ambient groundwater contains a high concentration of iron, or if biodegradable reagents are used in the flushing solution (2).

- Costs associated with flushing additives, and management of these additives in the residuals/wastewater streams (such as within washed soil and wastewater treatment sludge), must be carefully considered (2).

- Due to the need to use flushing solutions that are contaminant-specific, the presence of multiple, diversely propertied contaminants at a site may render implementation of *in situ* flushing very complex. Sequential steps with frequent changes in the flushing solution formula can be designed for these circumstances (1,2).

3.1.4 Regulatory/Logistical Considerations

The site-specific remediation goals (cleanup levels for soil and groundwater) must be known prior to evaluation of whether *in situ* flushing will be part of an effective site remediation. In addition to the remediation goals, consideration of whether the remediation will cause unacceptable alteration of soil conditions, or whether injection of treatment chemicals is consistent with Land Disposal Restrictions and other regulations, will be needed. For CERCLA sites, the remedial alternative must satisfy Applicable or Relevant and Appropriate Requirements (ARARs). Non-CERCLA sites may also have potentially applicable regulations at the state or federal level. In particular, Underground Injection Control (UIC) regulations may be applicable for CERCLA or non-CERCLA sites (9).

It is typically necessary, if hydraulic control is to be maintained, that some of the extracted and treated groundwater be discharged via a publicly owned treatment works (POTW) with a National Pollutant Discharge Elimination System (NPDES) permit or via a direct NPDES permit. The logistics required to obtain these permits, and monitoring requirements, are additional items to be considered. The time available for remediation, in terms of risk reduction or property re-use within a reasonable time frame, must also be weighed during the decision making process.

3.2 FLUSHING SOLUTIONS

The solutions used for *in situ* flushing may consist of one or more of the following:

- plain water;
- surfactants and/or cosolvents;
- acids or bases;
- oxidants;
- chelants; or,
- solvents.

The flushing solutions serve to increase the mobility and/or solubility of the contaminants. Unconventional soil flushing techniques may include waterflooding, gaseous and chemical processes, and thermal methods, and are not further discussed in this overview report (4).

3.2.1 Plain Water Flushing

Plain water flushing is most effective for soluble (hydrophilic) organics (those with octanol/water partition coefficients (K_{ow}) less than 10 (log K_{ow}<1)), such as lower molecular weight alcohols, phenols, and carboxylic acids, as well as some inorganic salts such as sulfates and chlorides, and soluble heavy-metal salts. Medium solubility contaminants (K_{ow} = 10 to 1000) removable by water or water and surfactant flushing include low to medium molecular weight ketones, aldehydes and aromatics, and lower molecular weight halogenated hydrocarbons such as trichloroethylene (TCE) (2).

3.2.2 Surfactants/Cosolvents

Low solubility (hydrophobic) organics, such as chlorinated pesticides, PCBs, SVOCs (chlorinated benzenes and PAHs), petroleum products (gasoline), aromatic solvents (BTEX), and chlorinated solvents (such as TCE) may be removed by selection and application of the appropriate surfactant. Surfactants may consist of detergents or emulsifiers which are effective at removal of hydrophobic contaminants such as petroleum products and NAPL. Cosolvents may consist of reagents such as alcohol, and assist in enhancing solubility of hydrophobic contaminants (1,2,3,13).

3.2.3 Acids/Bases

Acidic solutions are applicable for removal of metals and basic organic contaminants; dilute acid solutions may also be used for flushing some inorganic-metal salts, such as carbonates of nickel, zinc and copper. (Metals may also require chelating or complexing agents or reducing agents.) Basic solutions may be used to treat phenols and metals which may be bound to the soil organic fraction.

3.2.4 Reductants/Oxidants

Oxidation and reduction (redox) reactions are a key component of geochemical processes occurring in groundwater. Evaluation of the presence of dissolved species that participate in several common redox reactions, as well as examination of applicable Eh-pH diagrams are needed to properly plan and design for beneficial redox reactions, in terms of creating a desired reduction in contaminant toxicity or mobility. Reducing agents may reduce iron and manganese oxides that can bind metals in soils. Reductants and oxidants can convert heavy metals to more soluble compounds. The use of oxidants to oxidize chlorinated solvents to inorganic products, and organic solvents such as ethanol is also under investigation (1,2,3,13).

3.3 PHYSICAL CONSTRUCTIONS FOR INJECTION/EXTRACTION

3.3.1 General Types of Injection/Extraction Systems

A variety of delivery techniques are available to apply or inject flushing solutions into the subsurface. The types of injection/extraction systems can generally be classified as gravity-driven or pressure-driven. Gravity-driven methods rely on infiltration and/or collection due to "natural" hydraulic gradients. Pressure-driven methods rely on pressure gradients supplied by a source and/or extraction pump.

Gravity delivery of the flushing solutions may occur through such mechanisms as:

- application by trench;
- infiltration galleries; or,
- aboveground spray irrigation or leach fields.

Elutriate collection may occur via open ditches, subsurface collection drains or trenches, or wells. For surface flooding applications, the infiltration and percolation rates are important as functions of the number of pore volumes required to achieve the intended remediation goal.

Pressure-driven injection may take place through mechanisms such as:

- vertical injection wells or wellpoints; or,
- angled/horizontal wells.

Elutriate collection would typically occur through recovery (extraction) wells or trenches.

The injection/extraction systems typically rely on flow patterns determined by the subsurface stratigraphy, as detected through the design and placement of monitoring wells or the injection drains/wells. In special cases, modification of subsurface conditions through use of innovative techniques to improve ground-water flow rates, or flow control is employed. These innovative approaches may include enhancement of hydraulic conductivity in the treatment zone through hydraulic or pneumatic fracturing, radial well drilling, jet slurrying, and kerfing (physical cutting) (9). The funnel and gate systems, typically described as a type of passive treatment wall remediation, may also have some applicability to enhance natural subsurface conditions for *in situ* flushing projects. Some researchers are also investigating the use of prefabricated vertical drains (PV-drains) for use in enhancing the performance of *in situ* flushing. PV-drains consist of multiple injection or extraction wells connected via a manifold system, and may be used to decrease the flow path and, hence, shorten the travel time between injection/extraction points and the contaminated zone. PV-drains may prove useful for geologic materials of relatively low hydraulic conductivity, such as soils containing appreciable silt or clay (15).

3.3.2 Hydraulic Benefits and Effectiveness of Injection/Extraction

The injection of a flushing solution into the subsurface, in addition to chemically enhancing contaminant mobility in the vadose and saturated zones, also enhances physical ground-water flow through the saturated zone by increasing the hydraulic gradient between the injection point and the extraction point. When injection applications are utilized, the concepts of vertical and volumetric sweep, terminology commonly used in the field of enhanced oil recovery in the oil industry, are important to consider in predicting and determining effectiveness of the physical aspects of the flushing system (4,9,14).

Regardless of the physical type of injection and extraction systems utilized, the success of the *in situ* flushing operation will depend on the delivery and movement of the flushing solution through the contaminated zone, and the complete recovery of the elutriate. The design and construction of these systems in a competent manner consistent with the site-specific hydrogeologic conditions is thus essential. Hydrogeologic modeling may be employed to assist in the design and operation of the injection/extraction system, once all necessary data are collected and verified. Modeling can assist in representation of velocity plots and capture zones of wells, and in elimination of dead spots within the wellfield, both essential for complete elutriate capture and successful remediation performance (3,4).

At least one study has been performed in which different configurations of wellfields typically used for bioremediation projects were compared for effectiveness (14). In this study, well placements upgradient from the plume, downgradient from the plume, interior of the plume in the most contaminated portion of the plume, areally distributed throughout the plume, and outside the areal boundaries of the plume were compared for effectiveness of plume control over one year, based on modeling results and estimated cost. Although it is acknowledged that the optimal well configurations are highly site-specific, the results of the study suggest that some configurations may perform better than others. With other factors constant, it was found that greater chemical mass reductions occurred when injection or extraction wells were placed in either the most concentrated portion of the plume, or throughout the majority of its areal extent.

3.4 OPERATION OF AN *IN SITU* FLUSHING SYSTEM PROJECT

Construction and operation and maintenance of the following potential components of an *in situ* flushing project should be considered in the design and/or cost analysis phase:

- flushing solution mixing, holding, and delivery system and additives;
- injection/extraction systems (gravity- or pressure-driven);
- permeability enhancements;
- containment system (physical or hydraulic);
- aboveground treatment (separation of flushing additives, ground-water treatment);
- runoff and temperature control;
- disposal of solid/liquid waste; and,
- performance monitoring requirements.

In addition, prediction of the duration for an *in situ* flushing project is an important operational consideration impacting the decision to use this technology for ground-water remediation, and for planning. The concept of pore volume, potentially combined with infiltration/percolation and/or vertical and volumetric sweep, are important tools in prediction of duration. In many cases, predictions of success and timeframe based on laboratory treatability studies have not translated well to pilot scale. This may largely be due to the difficulties inherent in understanding complex biogeochemical relationships and in precise characterization of flowpaths in the actual subsurface due to heterogeneities. Mathematical modeling may assist in these predictive efforts (4).

The Augustijn et. al. Model has been utilized to understand and quantify the relationship between retardation, sorption, flow rate, and concentration of organic compounds in soil when flushed with water and a cosolvent in bench-scale studies (16). A discussion of mathematical modeling and development for surfactant-enhanced aquifer remediation has been presented (7). Predictions of decreases in soil and ground-water contaminant concentrations which can realistically be expected must account for non-linear sorption, non-equilibrium kinetics, and spatial variability in hydrology or chemistry, or they may otherwise be too optimistic. A research project currently underway is utilizing the ECOSTAT chemical equilibrium model to compare prior predictions of remediation efficiency with actual results from full-scale soil venting remediations (17).

3.5 ABOVEGROUND TREATMENT

Upon recovery of the elutriate, aboveground treatment is typically necessary to meet appropriate discharge standards prior to recycle or release to a POTW with a NPDES permit, or to receiving streams via a direct NPDES permit. Recovered fluids are usually recycled into the *in situ* flushing process as much as possible for maximum efficiency, though it is typically necessary to waste at least a portion of the recovered fluids via a POTW or NPDES discharge. Treatment of the elutriate and separation of the reagents used in the flushing solution for re-injection is a major factor to consider in the cost of *in situ* flushing operations. Treatment of VOC-impacted air emissions and treatment and disposal of spent carbon, ion exchange resin, etc. must also be considered (10,11).

The aboveground treatment system will require resources for capital and operation and maintenance (O&M) expenses associated with the equipment and procedures appropriate for the extracted elutriate chemistry. These treatment systems may include options such as air stripping, UV oxidation, physical/chemical separation, granular activated carbon (GAC) adsorption, bioreactors, and ion exchange.

4.0 TECHNOLOGY PERFORMANCE

In situ flushing is a developing technology that has had limited use in the United States. As of May 1997, *in situ* flushing was selected as part of the source control remedy at 18 Superfund sites. In most, if not all, of these 18 cases, treated site groundwater with no additives is being used as the flushing solution. The U.S. EPA also completed construction of a mobile soil-flushing system, the *In Situ* Contaminant/Treatment Unit, in 1988 (4, 10). This mobile soil flushing system is designed for use at spills and uncontrolled hazardous waste sites.

The limited use of *in situ* flushing technology to date is likely due to the current lack of information on performance and cost/benefit analysis, uncertainties involved in upscaling from bench- to pilot- to full-scale implementations, as well as general concerns regarding an innovative technology where the potential for spreading of contaminants exists if the application is not appropriately controlled.

4.1 GENERAL

Data on removal effectiveness for specific contaminants is reproduced below. Although the original reference acknowledged that the quality and comparability of this information has not been determined, it should provide some indication of the effectiveness of *in situ* soil flushing (2). Further detail on available case studies compiled for this technology are available in GWRTAC's *In Situ* Flushing Status Report (9). Following are examples of performance of various *in situ* flushing projects.

At a German TCE spill site, a high permeability (5.1 x 10^{-2} cm/second) aquifer overlying a clay was flushed by infiltrating water into the ground via ditches, although the type of flushing additives was not indicated. Eight recovery wells were used to recover elutriate, and within 18 months, 17 metric tons of chlorinated hydrocarbons were recovered (2).

At a site with chromium-contaminated soils in Oregon, two percolation basins were used to flush remaining soils after excavating 1,100 tons (1.1 million kg) of soil. The soil flushing project was to remove hexavalent chromium from an estimated 2.4 million gallons (9.1 million liters) of contaminated groundwater. Since the project began in August 1988, 23 extraction wells removed over eight million gallons (30.3 million liters) of groundwater, containing over 25,000 pounds (11,000 kg) of chromium. Average monthly chromium concentrations in groundwater decreased from 1,923 mg/L (August 1988) to 96 mg/L (March 1991). It was anticipated at project inception that the ground-water remediation goal of 10 mg/L chromium would take up to 25 years to achieve (2).

At a Wyoming project site with creosote-contaminated alluvial sands and gravels, two *in situ* soil flushing tests were performed. First, the soil surface was slowly flooded with plain water to perform primary oil recovery. Although the timeframe was not given, the average total extractable organics (TEO) concentration was reduced from 93,000 mg/kg to 24,500 mg/kg after the plain water flushing. The second test involved sequential treatment with alkaline agents, polymers, and surfactants. Over eight months, TEO concentrations were reduced to 4,000 mg/kg (2).

Laboratory column tests on Volk Air Force Base, Wisconsin soils contaminated with oil and grease at concentrations of 10,000 and 6,000 mg/kg were performed using a 1.5 percent surfactant solution. The tests indicated that 75 to 94 percent of the initial hydrocarbon contamination could be removed by flushing with 12 pore volumes of flushing solution. Later, field tests were not successful in removing the same contaminants. Seven flushing solutions, including the solution used in the laboratory, were tested in field test cells which measured one foot (0.3 meters) deep and one to two feet (0.3 to 0.6 meters) square. It was planned to deliver 14 pore volumes to each test cell. Two test cells plugged completely, precluding further infiltration of flushing solution; the plugging may have been related to formation of flocs or micelles from the surfactant solution, or suspension of soils in the flushing fluid. Only three of the seven tests achieved the target delivery of 14 pore volumes. No statistically significant removal of contaminants due to soil flushing was noted (2).

4.2 COST INFORMATION

Literature references generalize the cost of *in situ* soil flushing as approximately \$75 to \$210 per ton (\$0.07 to \$0.21 per kg) of contaminated soil, and list low hydraulic conductivity and expensive solubility enhancement additives as factors which may increase cost. The cost of *in situ* flushing is comparable to other *in situ* technologies such as *in situ* stabilization/solidification, steam injection and extraction, and enhanced bioremediation (9).

Estimated costs (not based on field studies) are indicated as being in the range of \$75 to \$200 per cubic yard (\$98 to \$262 per cubic meter) of contaminated material, depending on the waste quantity. For the Superfund site at Palmetto Wood, South Carolina, capital costs of \$185 per cubic yard (\$242 per cubic meter) and operation and maintenance costs of \$15 per cubic yard (\$20 per cubic meter) per year were cited for an *in situ* flushing operation (9).

5.0 TECHNOLOGY ADVANTAGES AND LIMITATIONS

5.1 TECHNOLOGY ADVANTAGES

Potential advantages of *in situ* flushing include:

- as an *in situ* technology, the need to excavate, handle, and transport large quantities of the original contaminant is eliminated (1);
- enhancement to conventional pump and treat may speed site remediation and closure (2);
- potentially applicable to a wide range of contaminants in both vadose and saturated zones (2); and,
- may be used in conjunction with other technologies or in stages for complex cases (2).

5.2 TECHNOLOGY LIMITATIONS

Factors which limit the effectiveness or implementability of *in situ* flushing include:

- lengthy remediation times due to the slow rate of diffusion processes in the liquid phase (2);
- potential for spreading contaminants beyond the capture zone, laterally or vertically, if the extraction system is not properly designed or constructed, hydraulic control is not maintained, or a ground-water discharge zone captures flow from treatment zone (installation of physical barriers such as slurry walls will minimize this potential) (2,3,9,10);
- limited regulatory acceptance due to the potential for spreading contaminants, and concern with introducing flushing solutions into the subsurface which may remain in residual quantities (1,10);
- uncertainties involved in prediction of performance and duration to achieve clean up goals;
- presence of man-made obstructions, such as pipes/utilities may limit effectiveness, especially at underground storage tank sites (4);
- site geologic setting conditions (2,4,9,10), e.g., low permeability, high clay or organic content, high degree of heterogeneity or secondary permeability, and close proximity to sensitive recharge areas or potable aquifers;
- use of flushing solutions which can adhere to soil, accelerate biogrowth, or cause precipitation or other reactions with ambient soil or groundwater, thereby reducing effective soil porosity (10); and,
- inability to separate flushing additive from elutriate may result in high consumption of flushing additive, rendering costs prohibitive (4).

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