In Situ Flushing with Surfactants and Cosolvents

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Prepared by

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NOTICE

FOREWORD

In situ flushing with surfactants and cosolvents recently has been emerging as a successful means of remediation of contaminated soils and groundwater. EPA's Technology Innovation Office (TIO) provided a grant through the National Network for Environmental Management Studies (NNEMS) to prepare a technology assessment report on subsurface barrier technologies that prevent the migration of contaminated material. This report was prepared by a junior graduate student from Northwestern University during the summer of 1999. It has been reproduced to help provide federal agencies, states, consulting engineering firms, private industries, and technology developers with information on the current status of this technology.

About the National Network for Environmental Management Studies (NNEMS)

NNEMS is a comprehensive fellowship program managed by the Environmental Education Division of EPA. The purpose of the NNEMS Program is to provide students with practical research opportunities and experiences.

Each participating headquarters or regional office develops and sponsors projects for student research. The projects are narrow in scope to allow the student to complete the research by working full-time during the summer or part-time during the school year. Research fellowships are available in Environmental Policy, Regulations, and Law; Environmental Management and Administration; Environmental Science; Public Relations and Communications; and Computer Programming and Development.

NNEMS fellows receive a stipend determined by the student's level of education and the duration of the research project. Fellowships are offered to undergraduate and graduate students. Students must meet certain eligibility criteria.

About this Report

This report is intended to provide a basic summary and current status of *in situ* flushing technologies using surfactants and cosolvents. It contains information gathered from a range of currently available sources, including project documents, reports, periodicals, Internet searches, and personal communication with involved parties. No attempts were made to independently confirm the resources used.

The report is available on the Internet at http://www.clu-in.org.

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FIGURES

Purpose

This report has been divided into three distinct sections with the following purposes:

Section one is a brief summary of the processes of surfactant and cosolvent *in situ* flushing. In 1997, the Advanced Applied Technology Development Facility (AATDF) at Rice University published a report entitled, *Technology Practices Manual for Surfactants and Cosolvents*, containing an extensive explanation of the *in situ* processes. Section one is a synopsis of information obtained from this and other reports, outlining the major principles associated with the use of surfactants and cosolvents. For a more detailed description of the processes refer to the manual and other references cited.

Section two contains a number of case studies demonstrating the recent use of this technology in the field. In 1998, the Ground-Water Remediation Analysis Technologies Center (GWRTAC) published a technology status report on *in situ* flushing containing 84 case studies involving flushing experiments using surfactant, cosolvents, cyclodextrins, and treated or untreated groundwater. Section two contains updates of the various surfactant and cosolvent projects that were considered in progress or scheduled at the time of that report. This section also contains other surfactant and cosolvent flushing projects that have been started since the time of that report.

The final section, section three, provides a brief summary of the status of *in situ* flushing with surfactant and cosolvents and outlines areas in need of future research.

1.0 Overview of *In Situ* Flushing

In situ flushing is an innovative approach to remediation of contaminated soils and groundwater. The process involves the injection of an aqueous solution, commonly through vertical wells, into a contaminated zone; this may be within the vadose zone (the soil above the watertable), the saturated zone, or both (Figure 1). The solution then flows through the contaminated zone and the resulting effluent is extracted downgradient where it is treated and discharged or re-injected. The aqueous solution injected most commonly contains surfactants, cosolvents, or treated groundwater.

The goal of *in situ* flushing is to enhance conventional pump and treat methods of remediation by enhancing the solubility or mobility of the contaminants, thus accelerating the remediation process. This procedure is an innovative technology developed to treat chemicals with low solubility, such as Dense Non-Aqueous Phase Liquids (DNAPL), which can remain in the soil for decades, slowly dissolving into the groundwater plume. By increasing the solubility or mobility of these contaminants at the source, *in situ* flushing can provide a faster, more efficient method for soil and groundwater remediation.

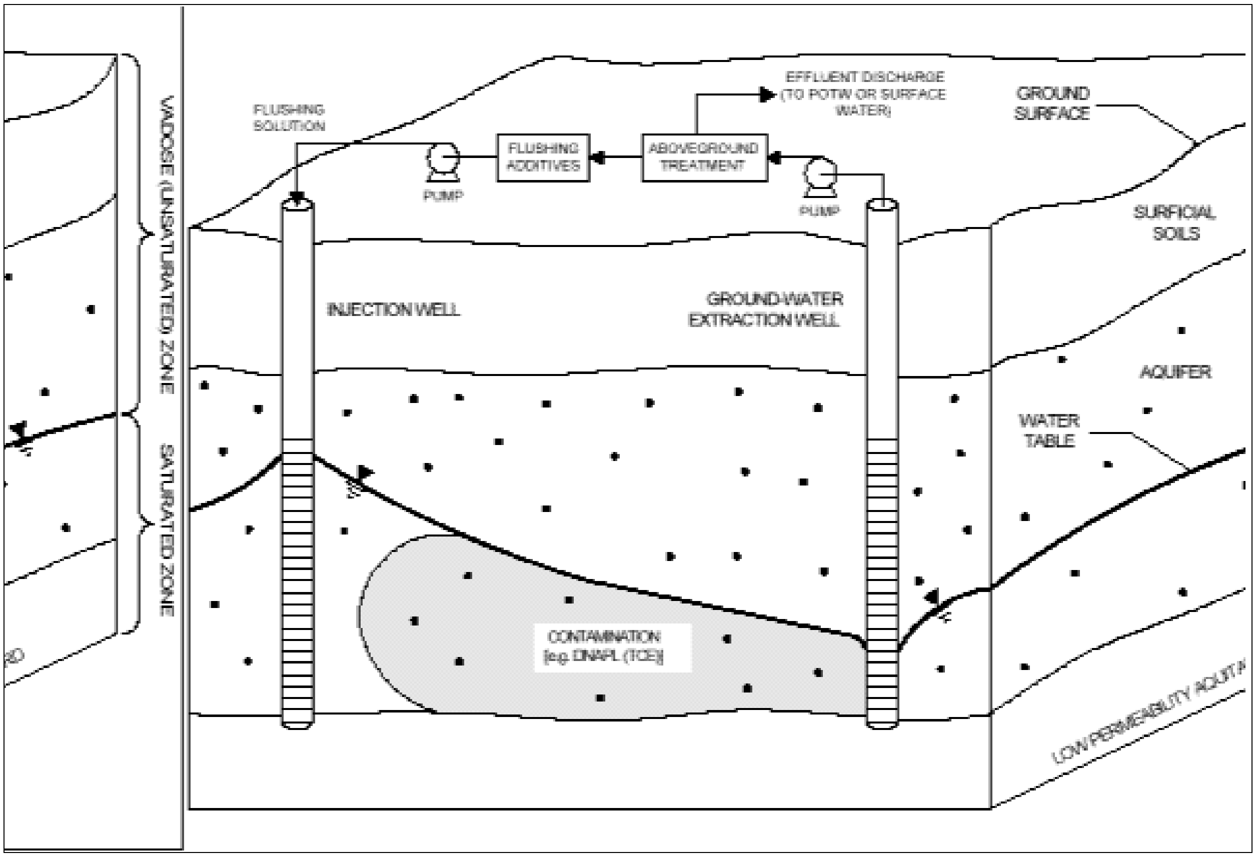

Figure 1. Schematic of an *In Situ* Flushing System.
Source: Ground-water Remediation Technologies Analysis Center, Technology Status report *In Situ Flushing*, November 1998.

1.1 Non-Aqueous Phase Liquids

In situ flushing is mostly used to remove synthetic organic contaminants, a type of contaminant not easily removed by conventional methods such as pump and treat. Most synthetic organic compounds exhibit low solubility in water and; therefore, exist as a separate phase, commonly referred to as a Non-Aqueous Phase Liquid (NAPL). DNAPLs are heavier than water and exist below the water table. DNAPLs are often a complex mixture of contaminants, but can commonly be classified into two groups: chlorinated solvent DNAPLs such as trichloroethylene (TCE) and tetrachloroethylene (PCE); and polycyclic aromatic hydrocarbons (PAH) such as coal tar and creosote (Fountain, 1998). Polychlorinated biphenyl (PCB) can also be found as a common DNAPL component. Light Non-Aqueous Phase Liquids (LNAPLs) on the other hand are lighter then water and exist above the water table. Gasoline, jet fuel, and heating oils are common LNAPLs. The majority of *in situ* flushing cases deal with DNAPLs although it has been demonstrated as an effective means of remediation for LNAPLs as well.

1.1.1 Characteristics of NAPLs in the Subsurface

From the point of the spill, NAPLs spread through the subsurface in an often highly irregular pathway, adding to the difficulty of characterization and remediation (Fountain, 1998). DNAPLs flow downward through the vadose zone with relatively little spreading (Schwille, 1988; Pankow and Cherry, 1996). Due to capillary forces though, a small amount of DNAPL is often retained in each pore, accumulating what is commonly called residual DNAPL. Below the water table, migration of DNAPL is highly irregular and dependent on factors such as geologic distribution and entry pressures resulting from capillary forces between the DNAPL and the water that exists in the saturated zone. These forces result in lateral migration of DNAPL forming large horizontal layers referred to as pools. There is also a tendency for the DNAPL to follow preferential pathways in this zone, resulting in highly heterogeneous distribution. DNAPL distribution in the saturated zone usually consists of a series of horizontal pools connected by narrow vertical pathways.

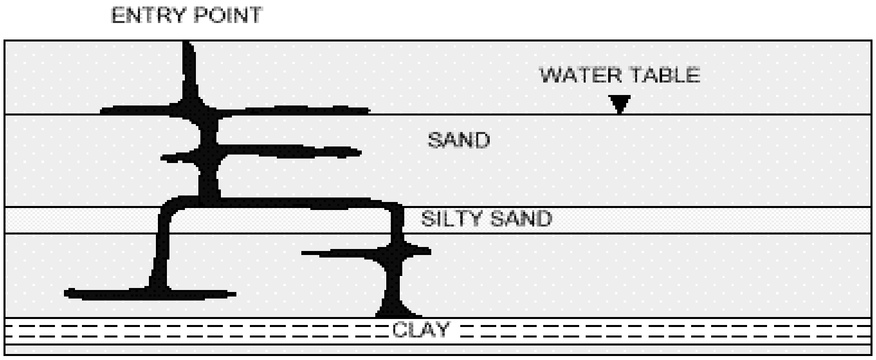

Figure 2. Typical DNAPL Distribution in the Subsurface.
Source: Ground-Water Remediation Technologies Analysis Center, Technologies for Dense Nonaqueous Phase Liquid Source Zone Remediation, December 1998.

LNAPL flow through the subsurface is similar to that of DNAPL, except in the area of the watertable. The lighter density of LNAPL causes significant pooling. LNAPL does not merely float on the watertable, but exists at positive pressure below the watertable, and negative pressure above (AATDF, 1997).

1.2 Surfactants and Cosolvents

In situ flushing is commonly applied to contaminated sites using surfactants or cosolvents as the primary flushing agents. Surfactants (surface-active-agents) are chemical compounds frequently used in detergents and food products that alter the properties of solution interfaces. Surfactants typically consist of a strongly hydrophilic (water loving) group, the “head” of the molecule, and a strongly hydrophobic (water fearing) group which is the “tail.” The hydrophilic portion causes surfactants to exhibit high solubility in water, while the hydrophobic portion prefers to reside in a hydrophobic phase such as LNAPL or DNAPL. This enables surfactants to enhance the solubility of the contaminant through micellar solubilization, the process by which aggregations of surfactant monomers form a micelle that the NAPL molecule can occupy (AATDF, 1997). The concentration of the surfactant needed to produce this formation is called the critical micelle concentration (CMC). The addition of a surfactant can also be used to enhance the mobility of the contaminant rather than the solubility by reducing the NAPL-water interfacial tension (AATDF, 1997). This reduction results in the decrease of the capillary forces, the forces responsible for the retention of residual and the formation of pooled NAPL, which subsequently results in contaminant mobility.

Cosolvent flushing involves injection of alcohols such as methanol, ethanol, and propanols as the primary flushing agent. Similar to surfactant flushing, this can also enhance the solubility of many organic contaminants through what is commonly known as the cosolvent effect (AATDF, 1997). The alcohols used in cosolvent flushing are mutually miscible in both water and NAPL and when added to the flushing system can bring about changes in the bulk properties of the contaminated zone. When larger amounts of alcohol are used, the alcohol may partition into both the NAPL and water phases and can result in the reduction of the NAPL-water interfacial tension to zero facilitating mobilization of the NAPL. Addition of a cosolvent to a surfactant flushing solution is also frequently implemented to increase the efficiency of the flush by lessening surfactant loss due to sorption, manipulating the viscosity of the surfactant solution, and preventing restricting phenomena such as liquid crystal formation (Baran *et al.*, 1994).

1.3 Pertinent Factors and Limitations of Surfactant and Cosolvent Flushing

There are many factors to consider before applying a surfactant or cosolvent *in situ* flushing system. Site conditions, including geological and contaminant properties, must be thoroughly analyzed to determine the applicability and effects of an *in situ* flush to the subsurface conditions. Proper selection of a flushing agent is key to the success of the flush once applicability has been verified. Finally, cost factors play a large role in determining the economic feasibility of *in situ* flushing at a site.

1.3.1 Subsurface Conditions

Specific site geologic conditions and contaminant properties are the main factors in determining the applicability of an in-situ flushing system. The most applicable sites currently have contained chlorinated hydrocarbon NAPLs in sand or gravel sediments with relatively high permeability underlain by a confining clay unit with low-permeability. In general poor results have been obtained when flushing through fractured rocks, clays, and sites with low-permeability, due to the inability to deliver the flushing solutions to the contaminants. At sites not containing an underlying layer, *in situ* flushing may result in vertical migration of the contaminant rather than desired removal. Other geological conditions to consider include hydraulic conductivity, soil surface area, carbon content, soil pH and buffering capacity. Pertinent contaminant factors include viscosity, density, water solubility, and octanol/water partition coefficient (Roote, 1997).

Limiting geological factors have been the focus of much current research in the field of *in situ* flushing. An approach that has been recently applied to heterogeneous sites with low-permeability is the surfactant/foam process (Szafranski *et al.*, 1998). In this process, air is periodically injected along with the surfactant solution. The air, which flows, into the same preferential high-permeability zones as the surfactant, forms a foam serving to block further flow of the surfactant. The surfactant is then diverted to the contaminated low-permeability zones. This process has not been widely used, but has been demonstrated in the field at a DNAPL contaminated site at Hill Air Force Base (AFB) in 1997 (Roote, 1998; Szafranski *et al.*, 1998).

An 89% reduction of DNAPL in the test zone was seen. Current research has also focused on applying *in situ* flushing to sites where there is no confining clay aquitard present to minimize the risk of vertical contaminant migration (Section 2.14).

1.3.2 Flushing Agent Selection

Proper selection of a flushing agent is essential for the efficiency of the flush and extensive laboratory research is often required. The concentration of the flushing agent and contaminant properties are important to tailor a system for solubilization or mobilization. Other factors such as the sorption, precipitation, and emulsion formation of a flushing agent must also be taken into account to prevent agent loss and restricting phenomena. Pertinent system factors to be evaluated include the salinity, water hardness, temperature, and hydraulic gradient. The degradation and toxicity of the flushing agent must also be considered as a small amount of the flushing agent is generally left in the subsurface.

1.3.3 Cost

The cost of an *in situ* flushing project is highly variable and is dependent on many factors such as site conditions, contamination, flushing agent, and regulatory factors. The initial cost of the flushing solution plays a major role in the overall cost of *in situ* flushing. Depending on the size of the site, geological characteristics, and the number of pore volumes (the volume of water contained within the contaminated zone) required, this initial cost can be relatively low or extremely high. Reuse of the flushing solution has shown potential to greatly reduce the cost of *in situ* flushing by reducing the volume and; therefore, the cost of the initial flushing solution. Reuse also reduces the volume of the waste produced and the subsequent cost associated with proper disposal of the waste. Various decontamination and reconcentration processes for surfactants and cosolvents have been identified by researchers for potential use in flushing systems and are listed in Appendix A.

2.0 *In Situ* Flushing Case Studies

A number of *in situ* flushing case studies involving surfactants or cosolvents have been conducted in the past two years. This section provides information on recent surfactant and cosolvent flushing projects conducted at lab/bench scale, field-scale (or pilot-scale), and full-scale remediation. A list of these case studies, including the site owner and technical team member, is included in Appendix B. For additional information regarding any of these projects, contact information is provided in Appendix C.

2.1 Alameda Point Naval Air Station Site, Alameda, CA

A field-scale demonstration of surfactant flushing including surfactant recovery was implemented at the Naval Air Station (NAS) Alameda in June 1999. The site selected for implementation contains DNAPL contamination in the residual phase in relatively homogeneous conditions of sands and clayey sands. High concentrations of various volatile organic compounds (VOCs), especially trichloroethane (TCA) and TCE have been detected in both soils and groundwater at the site. The main treatment zone exists 17 feet below ground surface (bgs) with VOC concentrations ranging from 71 to 40,970 milligrams per kilogram (mg/kg). TCA concentrations in this area range from 36 to 32,000 mg/kg. The hydraulic conductivity ranges from 8.14 to 20.48 feet per day (ft/day). The primary objective of the surfactant flush is to compare improvements in the efficacy of the existing pump and treat system at the site. The US Navy targeted cleanup goals for this site of 95% DNAPL removal and 93% surfactant recovery.

Prior to field implementation groundwater modeling was conducted using MODFLOW and MT3D96 to determine well location and the fate and transport of the surfactant solution remaining in the subsurface. Various laboratory screening tests conducted prior to the demonstration to determine the most appropriate surfactant solution for field implementation included: critical micelle concentration (CMC) measurements, contaminant solubilization, partitioning tests, partitioning tracer tests, and biodegradability tests.

Results from the modeling study indicated the time to flush one pore volume was approximately one day indicating the total test duration may require up to ten weeks assuming ten pore volumes are needed. A line drive well scenario was implemented as also suggested by the modeling study consisting of 2 injection, 2 fresh water injection, 4 recovery, and 4 monitor/recovery wells, and 2 multi-level samplers. The surfactant concentration remaining in the subsurface after the flush was estimated as 300 parts per million (ppm). The results of the laboratory analysis indicated that Dowfax (5 wt.%) + AMA (2 wt.%) + NaCl (3 wt.%) + $CaCl_2$ (1 wt.%) was the most suitable surfactant for the demonstration because of its low sorption, resistance to precipitation or phase behavior, and absence of pressure increase during the column study.

Field implementation began in June 1999 and was scheduled for completion by September 1999. Preliminary data indicated that a significant amount of the NAPL was removed from the site. The surfactant used did not exhibit any adverse pressure effects during the flushing stage indicating it would successfully remove the residual NAPL at the site.

2.2 Bachman Road Residential Wells Remediation Project, Ann Arbor, Michigan

Preliminary testing for a field-scale demonstration of surfactant flushing was initiated in March 1997 at the Bachman Road Site. This site is contaminated with TCE, PCE, and 1,2-DCE (dichloroethene). PCE has been measured in aqueous concentrations of 50 ppm. The aquifer is mainly composed of fine to medium grained sand with a low organic content, underlain by a clay layer at 18-24 feet bgs with a low conductivity and high sorptive capacity. The water table is located 5-10 feet bgs. DNAPL contamination is suspected in two regions; one roughly 11 feet bgs, approximately 2 feet below the water table, and the other roughly 24 feet bgs in the transition zone immediately above the clay layer.

The surfactant flushing project was divided into three phases. Phase I consists of site characterization and surfactant selection, Phases II-III incorporate a pilot-scale field demonstration focused primarily on evaluating the effectiveness of the proposed methods by developing monitoring strategies and delivery systems for surfactants and determining end points in the field.

Phase I was completed in December 1998. The existence of non-aqueous phase PCE was confirmed and detected in the form of pools, rather than entrapped residual, therefore surfactant-enhanced solubilization will be pursued rather than mobilization. The total extent of the PCE source region was not determined due to sparse sampling in the vicinity of a building on site; consequently the test will be designed only to treat the source zone. Tween 80 was selected as the surfactant for Phases II-III based on its high solubilization capacity, low toxicity, and biodegradability. Additional laboratory work will be performed on Tween 80 prior to the pilot test to assess potential extent of *in situ* microbial transformation of the surfactant during the flush.

Phase II was scheduled for completion in October 1999. Preliminary pilot test design calls for injection and recovery of approximately two pore volumes of surfactant and a project duration of three months. Cost estimates for the pilot test are $254,000. The final results from Phase II will be used to evaluate the final pilot test design and decide whether to proceed with Phase III, the implementation of the field demonstration.

2.3 Biosurfactant Flushing and Enhanced Remediation: *In Situ* Biostimulation Strategy for Intractable Shoreline Sediment Contaminated with Diesel Fuel, Australia

A full-scale remediation project was conducted at an earthmover refueling bay in Western Australia, the site of a diesel fuel spill. The bay is constructed 8 meters (m) above sea level on a rockfill battered steeply to the high tide mark. Receding tides expose 25 m of gently sloping, rocky intertidal zone. The shoreline sediments are comprised of fine silts, fine and coarse sands, skeletal particles, shattered shells, pebbles and stones and is overlain by rocks up to 1 meter in diameter. Contaminant concentrations immediately after the spill are unknown, estimations are 17,500- 20,000 mg/kg total petroleum hydrocarbons (TPH). At week 112 (weeks since the spill), before introduction of the biosurfactant, TPH concentrations on the shoreline sediments were 15,000-27,000 mg/kg, indicating that fresh diesel was still being released from the rockfill.

Due to the characteristics of the site, a rocky, intractable, and highly heterogeneous intertidal zone, a non-invasive sampling and remediation strategy was required. The intractable rock covering resisted access to the contaminated zone underneath, consequently impeding site investigation and remediation activities. Natural attenuation and biodegradation of the contaminants was observed, but trapped contamination in the rockfill was continually released. The remediation strategy designed consisted of flushing the rockfill through agricultural drains with biosurfactant and soluble nitrogen/phosphorous/potassium (N/P/K) nutrient formula to disperse and flush the remaining diesel onto shoreline sediments. Rockfill flushing was repeated at weeks 121, 131, 177, and 183 (weeks since spill). Biosurfactant and soluble N/P/K nutrient formula were also sprayed over the rocks and sediments in the intertidal zone at weeks 132, 173, 177, and 183 and slow release N/P granules were distributed to all accessible areas of sediment. A floating boom was used to prevent further discharges to sea. The three goals of the strategy were to prevent further discharges to the sea, remove residual diesel from the rockfill, and enhance natural biodegradation processes already active in the shoreline sediments.

After 69 weeks of treatment, 41 of which featured no treatment activity due to labor shortages (weeks 132-173), TPH concentrations were reduced to 23-190 mg/kg, with many of the sampling sites at non-detectable limits. The biosurfactant proved to successfully mobilize the trapped diesel fuel in the rockfill and break up the high concentrations within the sediments along the shoreline. Once this was accomplished, stimulation of natural biodegradation processes was possible.

2.4 Boston Logan Airport Area, Boston, Massachusetts

A field-scale remediation project was implemented to remove petroleum hydrocarbons resulting from jet fuels. The treatment zone consists of low-permeability soils located under a maintenance facility at a busy airport terminal.

The primary goal of this project was to create a non-intrusive remediation strategy that would allow for the continued use of the affected airport terminals. A mobile environmental equipment trailer was designed and built for remediation that has the capability to deliver six *in situ* remediation processes depending on the specific characteristics of the site. The process chosen was the injection of surfactant biostimulating agents to enhance the *in situ* bioremediation of the petroleum hydrocarbons. Three-dimensional numerical groundwater flow, particle tracking, and transport modeling was used to determine remediation design parameters based on the characteristics of the soil and the migration pattern of the jet fuel plume. The parameters helped determine the number, placement, and depth of injection wells, and effective injection flow rates and pressures.

In August 1999, the field scale demonstration was in its final stage and analytical analysis and confirmatory sampling was underway to assess the effectiveness of the remediation strategy. This process proved non-intrusive and did not interrupt the on-site operations.

2.5 Camp Lejeune Surfactant-Enhanced DNAPL Removal, Marine Corps Base Camp Lejeune, North Carolina

A field-scale surfactant flush was conducted at the Marine Corps Base Camp Lejeune. The Naval Facilities Engineering Service Center (NFESC) at Port Hueneme, California identified the central dry cleaning facility at Camp Lejeune as a suitable site for implementing a surfactant demonstration due to the presence of PCE and Varsol, a petroleum distillate once used as a dry cleaning solvent, at the site. The geology of the site consists of fine to very fine sands with low permeability, underlain by a clay layer serving as a barrier to further vertical migration of the contaminant. The PCE was detected in the groundwater in concentrations up to its solubility limit, approximately 240 mg/l, located under and adjacent to the central dry cleaning facility approximately 17 to 20 feet bgs. Varsol has also been detected at low concentrations smeared across the water table at approximately 7 to 10 feet bgs.

Prior to the flush, site investigations were conducted in three phases. Phase I served to locate and characterize the DNAPL zone through soil borings. The analytical results were then applied to a computer code to estimate the fraction of PCE present as residual DNAPL. The wellfield, comprised of three injection, six extraction, and two hydraulic control wells, was also installed. Phase II entailed the design of a partitioning interwell tracer test (PITT), in which a partitioning tracer is injected to measure volume and distribution of the DNAPL. Following soil column testing to select tracers, UTCHEM, a three-dimensional flow simulator, was used in designing the PITT. Phase III included recovery of free-phase DNAPL followed by a conservative tracer test (CITT), a non-reactive tracer test used to estimate travel times representative of the mass flow of the bulk aqueous phase fluid. The CITT was used to provide more information on the degree of aquifer heterogeneity and to identify any need for modifications of the final PITT design. A surfactant recovery process was also constructed by teams from the EPA and the University of Oklahoma at Norman (OU). The process included decontamination of the effluent (a mixture of groundwater, DNAPL, and surfactant) by a membrane technology called pervaporation, followed by surfactant recovery using micellar enhanced ultrafiltration.

The PITT was performed during May and June of 1998, lasting 40 days and indicating 74-88 gallons of DNAPL present in the 4,800 gallon swept pore volume of the test zone. The surfactant flush demonstration was implemented in spring 1999 and completed in July 1999. This was followed by a posttest PITT and soil sampling conducted in August 1999 to provide estimations of the total volume of DNAPL remaining. The final technical report was tentatively available by December 1999. Additional laboratory studies are also being conducted at the EPA's Kerr Environmental Research Center in Ada, Oklahoma to assess the impact of the surfactant solution on the native microbial population. This was the first field demonstration of surfactant injection, extraction, separation, and reinjection in the United States. The recovered surfactant was acceptable for reinjection under North Carolina regulatory requirements of 95% contaminant removal.

2.6 Dover AFB, Test Cell 3 Cosolvent Solubilization, Dover, Delaware

Researchers at the Groundwater Remediation Field Laboratory (GRFL) at Dover AFB have constructed two test cells, both approximately 10.5 feet by 15.75 feet, to conduct field demonstrations for quantitative analyses. The cells allow researchers to release a measured volume of contaminant into the soil and groundwater within the cell and then apply an in-situ technology. Accurate measurements of contaminant before and after the demonstration can therefore be obtained. The cells are enclosed by sealable-joint sheet pile walls keyed into an underlying clay unit 40 feet bgs. The geology in the cell consists mainly of medium to fine grain sands with gravely sand, silt, and clay lenses. The water table ranges from 35-38.5 feet bgs. Approximately 24.3 gallons of PCE were released into one test cell for cosolvent solubilization. The PCE was released between 35 feet bgs and the underlying clay unit, roughly 41 feet bgs.

Pre-release tracer tests were conducted from late May to early June 1998, followed by the DNAPL release in June 1998. Immediately following the release groundwater sampling and conservative tracer tests were conducted. Subsequent to the conservative tracers, pre-demonstration partitioning tracer tests were conducted in July 1998. The cosolvent-solubilizing flood began in February 1999. The remedial fluid consisted of 95% spirits-grade ethanol and 5% water. Six injection wells and two extraction wells were used to distribute the cosolvent throughout the test area. When effluent ethanol concentrations from the extraction wells reached

65% (after approximately seven days), the waste stream was treated with activated carbon for decontamination and then reinjected, adding fresh ethanol when necessary. Low concentrations of PCE did remain in the waste stream after treatment; these concentrations were monitored to quantify the mass of PCE reinjected into the cell. The flush continued for 40 days, flushing a total of eight pore volumes through the cell. Adjustments to the well configuration were made during the flushing to target the "hot spots." A post-demonstration partitioning tracer test was then conducted in May 1999.

An estimated 16.01 gallons of PCE were removed from the test cell during the 40-day flush, leaving approximately 8.3 gallons. The rate of PCE removal remained relatively high at the end of the demonstration, indicating continued extraction. To maintain a project schedule, the cosolvent flood was discontinued at this point. Sufficient data was collected to develop a performance curve for the technology which indicated additional PCE could have been removed with a longer flood.

Seven technologies are being tested at the Dover National Test Site (DNTS): air sparging/soil vapor extraction experiment, surfactant solubilization, surfactant mobilization, complexing sugar flush, cosolvent mobilization, and a single-phase microemulsion (SPME) process.

2.7 Sages, Jacksonville, Florida

A field-scale demonstration of cosolvent flushing was completed at an abandoned dry cleaning facility contaminated with PCE. The contaminant was located in an unconfined aquifer 26 to 31 ft bgs in an area roughly 24 by 9 ft and was detected in soils at concentrations as high as 40,000 mg/kg. The geology consists of unconsolidated sediments, primarily well-sorted sand/gravel.

Three injection, six recovery, and fifteen monitoring wells were installed between June 23 and July 3, 1998. Soil samples were also collected and analyzed. Seven multi-level samplers (MLSs) were installed in July 1998. Pre-pilot PITTs were conducted to estimate the mass of the PCE. An interfacial tracer test was performed in addition to the PITT to further estimate the swept volume of the injection and recovery wells and to estimate the travel time of the cosolvent to the recovery system. Modifications were then made to the system according to modeling studies and the pretest tracers. The primary goal of this project was to demonstrate if *in situ* flushing with a cosolvent could be an effective means of remediation.

The pilot flushing began in August 1998. Originally, water was flushed to determine the size of the capture zone. Over the next four days, roughly 9,250 gallons of the cosolvent, consisting of 95% ethanol and 5% water, were injected. The flushing procedure was followed by posttest PITTs. The cosolvent was not recycled, but treatment of the effluent resulting in cosolvent separation was demonstrated. The extracted effluent was treated with a macro-porous polymer extraction (MPPE) system, which consists of a column containing MPPE material into which the PCE will preferentially partition, to separate the PCE from the cosolvent. The separated PCE columns resulting from this treatment were then regenerated with low-pressure steam stripping and the vaporized steam was condensed into free-phase PCE, which was then disposed.

During this five-day study at least 80% of the original PCE detected was recovered. Treatment of the extracted mixture by the liquid-liquid extraction system, MPPE, proved to efficiently remove the PCE from the effluent, leaving a non-hazardous mixture of alcohol and water. The use of the MPPE system allowed for recovery of 92% of the originally injected cosolvent. Based on regulatory constraints, the ethanol/water mixture was not reinjected during this demonstration. The total cost of this test was approximately $440,000. Plans for full-scale flushing were in design stage as of September 1999. Plans incorporated reevaluation of the injection and recovery well layout to minimize number of stagnation zones, alcohol reuse through removal of PCE by a MPPE system along with additional process for alcohol reconcentration, and establishing a trailer mounted injection and extraction system. These improvements will likely establish a more cost efficient system; researchers believe that alcohol reinjection alone could reduce the cost of the project by 50%.

2.8 Gulf Power, Lynn Haven, Florida

A full-scale *in situ* flushing was implemented in November 1994 to enhance traditional pump and treat remediation of a dissolved arsenic plume. The arsenic contamination resulted from the use of an arsenic-based herbicide. The contaminant is present in the groundwater, roughly 5 feet bgs, in concentrations ranging from nondetectable to 5.2 ppm. The geology consists of silty fine sand present to 25 feet bgs. This is underlain by a 1 foot thick clay layer.

The project included an injection and extraction system of 14 wells; each equipped with piping allowing it to function as either an injection or extraction well. Monitoring wells were also installed. Originally citric acid was used as the primary flushing agent, but was then switched to a proprietary compound. Roughly 10 gallons per minute (gpm) of groundwater was extracted, treated above ground, supplemented with the additives, then reinjected. Site remediation goals were to achieve maximum contaminant levels (MCLs), which for arsenic is 50 parts per billion (ppb).

By the summer of 1998, MCLs were achieved in 80% of the arsenic contaminated plume. The remaining 20% of the plume has been declared stable and remediation through natural attenuation processes is taking place. Monitoring on the site will be continued to confirm these processes are occurring. This project was the first known full-scale application of an *in situ* flushing procedure using additives to achieve enhanced contaminant recovery in the United States.

2.9 Hill AFB Operable Unit (OU) 2 Full-Scale Surfactant Flood, Layton, Utah

A full-scale surfactant flood are planned for Operable Unit 2 (OU2) at Hill AFB. This site was formerly used as a solvent disposal area, resulting in mixed DNAPL contamination consisting of both chlorinated and nonchlorinated degreasers. Over 1,000 gallons of DNAPL is located roughly 45 feet bgs. The geology consists of primarily unconsolidated sediments, poorly sorted and predominately coarse grained, underlain by a layer of low permeability lacustrian clay. Much of the free-phase DNAPL was recovered using traditional pump and treat methods, but a large amount of residual contaminant was still present in the subsurface. The treatment zone spans an area of 500 linear feet of the subsurface channel underlain by the layer of clay. Due to the large extent of the treatment zone, it was divided into five separate zones in which five flushing procedures were scheduled to take place.

Phase I of this project entailed five pretest PITTs, one conducted in each flushing zone. The PITTs were completed in August 1999. The first surfactant flush, covering 1/5 of the total treatment zone, was scheduled for September 1999. Flushing in the remaining four zones took place subsequently.

This project is the last of nine projects conducted at Hill AFB. The previous eight projects conducted consisted of a cyclodextrin flush, a surfactant/foam flood, a cosolvent mobilization, a surfactant mobilization, a cosolvent solubilization, a surfactant solubilization, a surfactant/cosolvent solubilization, and a micellar flood. More information on these projects can be found in Roote, 1998. A final report detailing the result of these demonstrations is currently being prepared by EPA.

2.10 Howard University – The Use of Pervaporation and Ultrafiltration Membranes for the Separation, Recovery, and Reuse of Surfactant Solutions, Washington, DC

Researchers in TRAC II of the Great Lakes Mid-Atlantic Center (GLMAC) for Hazardous Substance Research are currently researching various methods to improve the technical feasibility and cost effectiveness of DNAPL recovery technologies. Surfactant flushing often requires reuse of the surfactant solution for cost effectiveness. Methods such as liquid-liquid extraction have shown success in recovering surfactant solutions, but depend on the solubility of the contaminant. Researchers are currently conducting a bench-scale study investigating the potential use of a combined pervaporation (PV)/ultrafiltration (UF) system for surfactant recovery and reuse. The overall goal of the research is to determine the feasibility of using a combined PV and UF system for the recovery and reconcentration of surfactant solutions for subsequent reuse. This research will also be expanded to include application-specific information, such as cost and flux/selectively models for different systems. Various surfactants are being tested, including Witconol 2722, and the contaminants tested are PCE and TCE.

This project has been divided into four tasks:

(1) Evaluate capacity of PV membrane to permeate VOCs while retaining surfactant. This task involves the use of very high surfactant concentrations (10- 100 times the CMC) at which the flux and selectivity of the PV membranes is unknown.

(2) Vary feed-flow rate, temperature, and permeate pressure to determine optimal conditions for contaminant separation by pervaporation. These parameters will be varied to control and quantify mass transfer properties.

(3) Determine the flux and retention of surfactant using UF membranes. Adsoprtion behavior of the surfactant, which can effect the flux and retention of the membrane, will be determined under different conditions of pH, ionic strength, and time of exposure using

three different membrane materials: cellulose acetate, acrylonitrile, and polyamide. Surfactant structure has been determined to influence filtration behavior. This task will also investigate the retention of different surfactants to determine which surfactant has a higher retention.

(4) The final task involves a field study to test the feasibility of the membrane system for surfactant recovery and reuse. Results from the previous tasks will be incorporated into the design of a pilot system using contaminant concentrations from the Bachman Road Site. Results from this task will be incorporated into a pilot membrane system for the field use at the Bachman Road Site.

Task I of this project was started in March 1999. Tasks 1-4 are scheduled to be completed by August 2000. Following the 18-month evaluation at bench-scale, a pilot-scale membrane system will be constructed for field use at the Bachman Road Site. The membrane system will be evaluated for efficiency for six months. This technology transfer will provide data for evaluating scale up and cost issues.

2.11 Ivey Environmental Services – Clark Oil Company, Fredericton, New Brunswick, Canada

A full-scale remediation was conducted at this site using Ivey-sol, a patent-pending phase transfer technology from Ivey Environmental Services, Ltd. The main contaminant was fuel oil resulting from a leak in an above ground storage tank in November 1992. Approximately 238 gallons were spilled from the storage tank into surrounding soils and bedrock aquifer. Shallow soil samples taken in November 1993 contained 3,747 ppm TPH. Water samples also taken at that time revealed concentrations of 1,400 ppm TPH. The geology of the site consists of 3 feet of silty sand and gravel overburden soil layer and a weathered to competent gray shale. The water table exists 20 feet bgs.

Ivey-sol is a proprietary compound used to remove petroleum hydrocarbons and PAHs through micellar enhanced solubilization. An injection gallery consisting of four injection wells was installed with a recovery well. Injection began in December 1993 and continued until April 1995 with injections at monthly to bi-monthly intervals. Environment Canada established clean-up objectives at 10 ppb TPH for groundwater and 20 ppm TPH for soil.

TPH concentrations in the recovery well were reduced from the 1,400 ppb measured in November 1993 before injection, to non-detectable in June 1996 indicating an eventual 99% reduction in TPH levels.

2.12 Ivey Environmental Services – Commercial/Residential Site, Fredericton, New Brunswick, Canada

A full-scale remediation was conducted at an earth floor basement of an apartment building contaminated with fuel oil from a storage tank spill in May 1998. Approximately 290 gallons of fuel oil were spilled contaminating the soil and shallow groundwater table under and adjacent to the building. The earth floor is enclosed by a four foot thick rock wall foundation and consists primarily of overburden soils comprised of sand with some silt content with a hydraulic conductivity of 3.3 x 10^{-5} ft/sec. The water table exists at 13 feet bgs. Groundwater sampling revealed original contamination levels of 9,500 ppb TPH in May 1998, which then climbed to 81,000 ppb TPH in August 1998.

In situ flushing with Ivey-sol was initiated in May 1998 with monthly injections continued for eight months. Site equipment included an Ivey-sol injection gallery system, consisting of three injection wells, and a pump and treat system including a recovery well underneath the foundation of the building. Four monitoring wells were also installed, two underneath the building's foundation and two beside the building. Objectives of this project were to remediate the site to 1,000 ppb TPH groundwater TPH and 100 ppm TPH in soils without evacuation of the apartment building.

By January 1999, after eight months of treatment, contamination levels in groundwater sampling were reduced to 220 ppb. Overall, a 98% TPH reduction was observed.

2.13 McClellan AFB – Surfactant/Cosolvent Enhanced Subsurface Remediation of DNAPLs, McClellan AFB, California

Four sites at McClellan AFB were screened for applicability for a field-scale surfactant flush. Site investigations included soil borings, installation of monitoring wells, collection of soil and groundwater samples, aquifer testing, and surfactant aquifer screening/push-pull tests. The site chosen for the demonstration consists of silts, sandy silts, and a few clayey silts near the surface, interbedded with thin beds of sands and silty sands and a cemented silt layer present approximately 125 feet bgs. The water table is approximately 106 feet bgs, with a relatively low groundwater hydraulic conductivity of 0.58 to 1.68 ft/day. The main contaminant is TCE, found in the groundwater in concentrations up to 31,600 ug/l TCE. A push-pull test, used to evaluate surfactant sorption and contaminant solubilization, indicated an increased TCE concentration of two to three times background, which indicates the potential presence of DNAPL.

Nine surfactants were investigated in laboratory studies with TCE, the target contaminant. Surfactant screening included CMC measurement, contaminant solubilization, surfactant sorption and precipitation, surfactant-TCE phase properties, contaminant extraction column studies, equilibrium partitioning tests, surfactant reconcentration/micellar enhanced ultrafiltration testing, partitioning tracer test, and biodegradability tests. Two surfactants, Dowfax 8390 and Isalchem 123-2PO, were found applicable after the screening. The Dowax system exhibited lower sorption and absence of a pressure increase, while Isalchem has a higher solubilization potential and is more amenable to natural attenuation. Groundwater modeling systems MODFLOW and MT3D96 were used to determine optimum well scenario and to analyze the fate and transport of the surfactant. The results also indicated estimated time to flush one pore volume is 10 days; assuming 10 pore volumes are required, the total test may last 100 days and 172,000 gallons of water will be produced during the flooding portion of the project. The primary elements of the demonstration include tracer studies to assess contamination, surfactant injection, followed by NAPL and surfactant recovery, surfactant re-injection, and finally post-test tracers for performance evaluation.

Additional well installation and tracer tests were scheduled for August 1999. Subsequent evaluation of tracer test data and equipment installation will be followed by surfactant injection scheduled to begin in late September 1999.

2.14 OK Tool Area at Savage Well Site, Hillsborough County, New Hampsire

Researchers from Idaho National Engineering and Environmental Laboratory (INEEL) and Duke Engineering & Services (DE&S) plan to demonstrate the effectiveness of Surfactant Enhanced Aquifer Remediation-Neutral Buoyancy (SEAR-NB) at the OK Tool Area at Savage Well Site. SEAR-NB was developed for surfactant remediation at sites without a confining aquitard, which may allow for vertical migration of the contaminant. SEAR-NB was created to minimize the vertical migration of the contaminant by manipulating bouyancy (caused by unfavorable density differences) and the horizontal driving forces that can increase the vertical migration of the contaminant. The site chosen for the field-scale demonstration contains TCE contamination, resulting from a leaky TCE pit at the tool site, located 60-65 feet bgs in three horizontal flow zones situated on top of fractured bedrock. The geology consists of unconsolidated sediments, poorly sorted outwash plain materials that are predominately coarse grained. A slurry wall is in place confining the demonstration area, keyed into a till layer of lower hydraulic conductivity than the target treatment zone.

CITTs were conducted in spring 1998 to provide information on travel and residual times of the subsurface flow. PITTs were subsequently conducted in July 1998. The well configuration consists of three injection wells in the middle of the site with two water injection wells on either side to maintain hydraulic control. The surfactant injection rate will be approximately 50-150 gpm. Two rows of three extraction wells were situated parallel to the row of injection wells. Each extraction well contains three pumps corresponding to the three horizontal flow zones. The effluent will be treated upon extraction, but the surfactant will not be reinjected due to various factors including high injection rate.

Surfactant flushing was scheduled to begin in September 1999. This was followed by a final, postest PITT in October. This was the first field demonstration of the SEAR-NB technology.

2.15 Millican Field, Pearl Harbor, Hawaii

A field-scale surfactant flush was implemented to remediate petroleum hydrocarbons present as LNAPLs. The LNAPL is mainly Navy Special Fuel Oil (NSFO), a fuel with high viscosity (2,000-3,000 centipoise) and low volatility. The contaminant is located within two geological layers of highly fractured volcanic tuff approximately two feet thick and located between 7 and 14 feet bgs. The two tuff layers are separated by a significantly lower permeability clayey silt layer and mostly underlain by a clay zone although certain areas are underlain by calcareous marine sand. Due to the high viscosity and low permeability of this contaminant, this site was determined not suitable for remediation by methods such as pumping, waterflooding, and soil vapor extraction (SVE), therefore thermally enhanced surfactant solubilization was chosen.

The field demonstration includes two PITTs conducted before and after the flush to measure the volume of LNAPL. A CITT was also conducted with sodium bromide to demonstrate hydraulic control of the injectate, determine the actual swept pore volume of the test zone and to provide empirical data to fine tune the final design of the demonstration. The CITT confirmed hydraulic control of the wellfield, consisting of an injection well, a hydraulic-control backstop well and three extraction wells, and estimated that ten pore volumes of surfactant are required for the surfactant flood. The major challenge of the project was development of a surfactant capable of solubilizing the contamination, which is not readily solubilized by commercially available surfactants. A surfactant consisting of 4 wt.% Isalchem 123 $(PO)_{7.7}$ sodium ether sulfate with 8% SBA cosolvent was chosen for remediation and will be heated to 50°C as a decrease in the viscosity of the contaminant is observed with an increase in temperature. In laboratory testing this surfactant recovered 87.5% of the LNAPL in soil testing at 49°C.

Preliminary PITTs were scheduled to begin in July/August 1999 followed by the flush and posttest PITTs. In addition to the surfactant, the subsurface will also be heated during the PITTs and the flush to further facilitate contaminant recovery by decreasing the high viscosity of the NSFO.

2.16 Strategic Environment Research and Development Program (SERDP) - Evaluation of Surfactants for the Enhancement of PCB Dechlorination in Soils and Sediments, Atlanta, Georgia

Researchers have observed that the limited availability of PCBs to microbial populations acts as a primary barrier to effective PCB bioremediation. The overall goal of this bench-scale study is to identify and evaluate surfactants capable of enhancing the dechlorination of PCBs in soils and sediments. Specifically this study serves to assess the feasibility of using surfactants to enhance rates of PCB desorption and biodegradation and to evaluate mechanisms governing PCB bioavailability. Column studies were conducted using Ottawa sand and various types of soil. The contaminants used were PCB congeners and 4-chlorobiphenyl (4-CBP).

Project objectives include:

(1) Investigate the ability of two aerobic bacteria, Rhodococcus erythreus (NY05) and Comamonas testosteroni (VP44), to grow on biphenyl and specific PCB congeners in the presence and absence of three surfactants: Witconol SN-120, Tergitol NP-15, and Tween 80.

(2) Evaluate and quantify the effects of the addition of the surfactants on the microbial transformation of PCB congeners in liquid and solid-liquid systems containing native and engineered strains of the bacteria.

(3) Investigate effects of design parameters and operating conditions, such as surfactant concentration and soil-solution ratio, on rates of PCB transformation in bioreactors.

(4) Develop a mathematical model to describe the coupled sorption/desorption, micellar solubilization, and transformation of PCB congeners under aerobic conditions.

The first objective has been completed. Both strains of the bacteria exhibited rapid growth on biphenyl alone. Neither strains grew in solutions of Witconol SN-120, Witconol SN-120+ biphenyl, or Witconol SN-120+4-chlorobiphenyl. These results indicate that Witconol SN-120 is unsuitable for use in enhanced PCB bioremediation. Growth of the bacteria in Tween 80, Tween 80+biphenyl, and Tween 80+4-chlorobiphenyl was virtually the same as in biphenyl alone. Data indicated that Tween 80 was readily used as a food source and, although it does not inhibit growth, may not be suitable in enhanced bioremediation systems because of the possibility it could be used as a preferential substrate.

For both strains, no growth was observed on Tergitol NP-15 alone over concentrations of 187 ppm to 4,000 ppm. Growth was observed unexpectedly in the presence of Tergitol NP-15 on biphenyl and 4-chlorobiphenyl. These findings suggest that Tergitol NP-15 neither inhibits growth nor acts as a preferential growth substrate and therefore may be an ideal candidate for use in PCB bioremediation systems. Additional growth experiments conducted from April to May 1998 included bacterial growth of strain VP44 on both 4-CBP and the dichlorobiphenyl, 2,2'-CBP. These experiments illustrated the ability of microorganisms to grow on 4-CBP as the sole food substrate. No microbial growth was detected in the presence of 2,2'-CBP.

PCB and surfactant degradation experiments, objective two, were also conducted. In degradation experiments with Tergitol NP-15 and 4-chlorobiphenyl (4-CBP), the 4-CBP concentrations typically disappeared within two to three days after the addition of microorganisms to the systems. 4-chlorobenzoic acid (4-CBA), the dead-end product of 4-CBP metabolism, was then detected.

Batch reactor studies for objective three have begun with surfactant sorption studies. This phase will also include measurements of PCB desorption from contaminated soils in the presence of surfactants. Objective four, mathematical modeling, has also begun with preliminary equations for the solubility of a compound in the presence of a surfactant and the solubility including the effect of sorbed-phase surfactant on the distribution of solute between the solid and aqueous phases. This preliminary model will be adapted to account for rate-limited sorption and desorption of both surfactant and PCB congener. Experimental data will also be collected to evaluate the ability of the model to predict coupled sorption of PCBs and surfactants. Plans for this project also include field implementation in FY99 and FY00 at one of two potential sites, Lake Ontario and Picitinnay Arsenal, New Jersey.

2.17 U.S. Department of Energy (DOE) Paducah Gaseous Diffusion Plant, Paducah, Kentucky

Extensive TCE contamination was found at this site in 1997 in both the soil and groundwater during a environmental Remediation Investigation (RI). High concentrations of TCE above 225,000 µg/kg in the vadose zone and shallow soils indicated the presence of DNAPL. The geology includes thick clayey silts, silt/clay layers with sand and gravel interbeds, and a basal thick silt/clay interval serving as a semi-confining layer. The water table exists in the silt/clay layer interbedded with sand and gravel roughly 36 to 48 feet bgs.

The purpose of this bench-scale study was to evaluate a number of surfactant and cosolvent solutions for field implementation at the Paducah Gaseous Diffusion Plant. The feasibility and cost effectiveness of recycling the surfactant or cosolvent solutions was also evaluated along with potential impacts remediation may have on Tc^{99} concentrations present at the site and vice versa. The laboratory studies consisted of evaluating 100 surfactant and/or cosolvent systems. The study included various column studies to determine the solubilization and mobilization capacity of the numerous surfactant/cosolvent systems. Soils from the site were also tested for physical and chemical parameters pertinent to the surfactant/cosolvent process. Various recycling systems were evaluated upon selection of possible surfactant/cosolvent systems.

Two surfactant system were identified as meeting the criteria for field implementation: 5% Dowfax 8390 + 2% Tartaric Acid + 1% CaCl (Dowfax) and 8% AMA-80 + 4% Isopropanol + 1% NaCl (AMA). Both of these systems demonstrated good solubilization capacity for the TCE in column studies and achieved 99% TCE removal in less than 10 pore volumes. The potential to mobilize trapped TCE was also evaluated. Column tests indicated that mobilized NAPL could be controlled through gradient flushing or vertical hydraulic gradient and suggested pilot scale implementation should be initiated with a lower solubilization potential (higher interfacial tension) and increased salinity to improve removal efficiency. The Tc^{99} did not show any adverse affect on the surfactants and no detectable concentrations of Tc^{99} were found in the column effluents.

Further testing concluded the Dowfax system would be used for the pilot scale analysis because it is recyclable. The pilot scale design incorporates air stripping and micellar enhanced ultrafiltration (MEUF). In laboratory testing, the MEUF showed effective 90-95% recovery of Dowfax. Only 50-60% of the AMA was recoverable. Groundwater modeling was also conducted for injection/recovery design and preliminary cost estimates for full-scale remediation were determined.

3.0 Conclusions

In situ flushing with surfactants or cosolvents is a developing technology that has shown promising results for remediation of contaminated soils and groundwater. Under appropriate site conditions, removal rates of 80% or higher can be expected with surfactant/cosolvent flushing (AATDF, 1997). Rates as high as 99% removal of the original DNAPL mass have been observed at some sites (Londergan, 1997). *In situ* flushing is also able to achieve this removal in months, and sometimes even days; therefore, potentially reducing or eliminating the need for the long term operating and maintenance costs associated with comparable pump and treat systems.

Current research has focused on the major limitations of *in situ* flushing such as unfavorable geological, contaminant, and cost factors. New developments and recent activities in the field such have served to increase the applicability of *in situ* flushing, but future research is still needed before routine application at the full-scale level. Areas in need of future research include:

(5) Effects of the flushing agents on the native microbial population and biomass during and after the flush;

(6) Deliverability and recovery methods in highly heterogeneous media and fractured bedrock;

(7) Surfactant and cosolvent recovery/reuse systems;

(8) Site characterizations techniques to quantify and identify contamination mass and location before and after flush;

(9) Evaluation of realistic end-points achievable through *in situ* flushing;

(10) Full-scale cost analyses; and

(11) Comparison with other *in situ* remediation methods such as *in situ* chemical oxidation and thermal treatment.

Appendix A: Decontamination and Reconcentration Processes for Surfactants and Cosolvents

Table 1: Decontamination Processes for Surfactant Solutions

Contaminant Removal Process	Separation Process	Potential Contaminants	Main Advantages	Primary Concerns
Air Stripping	Effluent contacts air stream, contaminants partition to air stream	Volatile	Low cost, effective, commercially available	May require anti-foaming compound, addition of water treatment chemicals
Liquid/Liquid Extraction	Effluent contacts liquid extractant, contaminant partitions to extractant	Volatile, semi-volatile, inorganics	Wide applicability, no foaming, minimal fouling	Surfactant may partition to extractant, and vice-versa
Pervaporation	Consists of non-porous hydrophobic membrane with gas purge/vacuum on other side; contaminants partition into membrane and evaporate into purge/vacuum	Volatile	No foaming, contaminants collected in condensed form, can recover alcohols from surfactant	Precipitates may cause plugging, membrane leaks may lead to foaming
Precipitation	Properties of effluent altered to achieve precipitation of surfactant	Volatile, semi-volatile, inorganics	Generally inexpen-sive, wide range of contaminants, easy reuse of separate phase surfactant	Contaminants may partition into surfactant, surfactant may not flocculate well

Source: Personal Communication; Leland Vane.

Table 2: Recovery/Reconcentration Processes for Surfactants

Surfactant Recovery/ Reconcentration Process	Separation Process	Main Advantages	Primary Concerns
Micellar Enhanced Ultrafiltration (MEUF)	Surfactant passes through membrane, micelles are retained while water, monomers, salts/ alcohols pass through	Low cost, commercially available, efficiently recovers surfactant micelles	Not as effective if particular surfactants CMC is high or influent surfactant concentration is low
Nanofiltration (NF)	Surfactant passes through nanofiltration membrane; monomer and micelles retained	Recovers monomers and micelles, commercially available	H igher pressures required (vs. MEUF), more susceptible to fouling
Foam Fractionation	Foam is generated by sparging air through surfactant solution, then separated and resulting water is allowed to coalesce, creating high concentration surfactant solution	Low cost, efficient recovery of surfactant monomers	If influent surfactant concentration is high (in term of number of CMC), many fractionation stages are necessary.

Source: Personal Communication; Leland Vane.

Table 3: Decontamination Processes for Cosolvent Solutions

Contaminant Removal Process	Separation Process	Potential Contaminants	Main Advantages	Primary Concerns
Distillation	Cosolvent solution exposed to sequences of vapor-liquid equilibrium stages w/temp profile in packed or tray type column	Volatile, semi-volatile, inorganics	Commercially available w/existing design equations, may achieve both contaminant and water removal, cost effective	Energy intensive, formation of water-alcohol azeotropes; fate of contaminant in distillation column (may stay with cosolvent)
Liquid/Liquid Extraction	As with surfactants, effluent contacts liquid extractant, contaminants partition to extractant	Volatile, semi-volatile, inorganics	Applicable for all types of contaminants, great deal of research in this area	Solvents may partition to extractant, extractant may dissolve in cosolvent
Pervaporation	Same as used in surfactant system; contaminants partition into membrane, evaporate into purge/ vacuum	Volatile	Contaminants collected in condensed form	Requires larger membrane area due to reduced activity of contaminant in cosolvent solution

Source: Personal Communication, Leland Vane.

Appendix B: List of Case Studies

Table 4: List of Case Studies

Case Study No.	Case Study Name	City	State/ Province	PRP/Site Owner	Primary Technical Team Member	Scale	Contaminants	Flushing Solution	Status (as of September 1999)
2.1	Alameda Naval Air Station	Alameda County	CA	U.S. Navy	Surbec	Pilot/Field	TCA, TCE	Surfactant	In Progress
2.2	Bachman Road Site; GLMAC	Oscoda	MI	not specified	GLMAC- TRAC II	Pilot/Field	PCE	Surfactant	In Progress
2.3	Biosurfactant Flushing and Enhanced Remediation	not specified	(Australia)	not specified	University of Melbourne	Full	Diesel Fuel	Biosurfactant, N/P/K nutrient	Completed
2.4	Boston Logan Airport Area	Boston	MA		Dames & More	Pilot/Field	Petroleum Hydrocarbons	Surfactant	Completed
2.5	Camp Lejeune Marine Corps Base	Camp Lejeune	NC	U.S. Marine Corps	Duke Engineering & Services	Pilot/Field	PCE, Varsol R	Surfactant	Completed
2.6	Dover AFB	Dover	DE	U.S. Air Force	Mantech Environmental, University of Florida, U.S. EPA	Pilot/Field	PCE	Cosolvent- 95% ethanol, 5% water	Completed
2.7	Sages, Jacksonville, FL	Jacksonville	FL	not specified	Levine-Fricke-Recon, University of Florida, U.S. EPA ORD, U.S. EPA TIO	Pilot/Field	PCE	Cosolvent- 95% ethanol, 5% water	Completed
2.8	Gulf Power	Lynn Haven	FL	Gulf Power Company	Southern Company Services	Full	Arsenic	Proprietary Compound	Completed
2.9	Hill AFB-OU2 Full Scale Surfactant Flood	Layton	UT	U.S. Air Force	Duke Engineering & Services, U.S. AF	Full	TCE	Surfactant	In Progress
2.10	Howard University- Pervaporation, Ultrafiltration Studies	Washington	DC	NA (Lab study)	Howard University	Lab/Bench	PCE, TCE	Surfactants	Completed
2.11	Ivey-Environmental Services- Clark Oil Site	Fredericton	NB, Canada	Clark Oil Co.	Ivey Environmental Services, Ltd.	Full	Diesel fuel oil	Ivey-sol (proprie-tary compound)	Completed

Case Study No.	Case Study Name	City	State/ Province	PRP/Site Owner	Primary Technical Team Member	Scale	Contaminants	Flushing Solution	Status (as of September 1999)
2.12	Ivey-Environmental Services- Commercial/ Residential Site	Fredericton	NB, Canada	not specified	Ivey Environmental Services, Ltd.	Full	Diesel fuel oil	Ivey-sol (proprietary compound)	Completed
2.13	McClellan AFB	McClellan AFB	CA	U.S. Air Force	Surbec	Pilot/Field	TCE	Surfactant	In Progress
2.14	OK Tool Area at Savage Well Site	Hillsborough County	NH	Superfund	INEEL, Duke Engineering & Services	Pilot/Field	PCE	Surfactants	In Progress
2.15	Pearl Harbor	Pearl Harbor	HI	U.S. Navy	Duke Engineering & Services	Pilot/Field	Petroleum Hydrocarbons (NFSO)	Thermal Surfactant	In Progress
2.16	SERDP project-Surfactant Enhancement of Dechlorination of PCBs	Atlanta	GA	NA (Lab study)	Georgia Institute of Technology	Lab/Bench	PCBs	Surfactants	In Progress
2.17	U.S. DOE Paducah Gaseous Diffusion Plant	Paducah	KY	U.S. DOE	Surbec	Lab/Bench	DNAPL	Surfactant/ Cosolvent	In Progress

Appendix C: Contact Information

Case Study	Contact Information	
2.1 Alameda Point Naval Air Station Site, Alameda, CA	Mark Hasegawa Surbec Environmental, L.L.C. 3200 Marshall Avenue, Suite 200 P.O. Box 1757 Norman, OK 73072 (405) 364-9726 markhase@aol.com	Ben Shiau Surbec Environmental, L.L.C. 3200 Marshall Avenue, Suite 200 P.O. Box 1757 Norman, OK 73072 (405) 364-9726 bshiau@msn.com
2.2 Bachman Road Residential Wells Remediation Project, Ann Arbor, Michigan	Linda M. Abriola Dept. of Civil and Env. Engineering University of Michigan Ann Arbor, MI 48109-2125 (734) 763-9964 abriola@engin.umich.edu	Kurt D. Pennell School of Civil and Env. Engineering Georgia Institute of Technology Atlanta, GA 30332 (404) 894-9365 kurt.pennell@ce.gatech.edu
2.3 Biosurfactant Flushing and Enhanced Remediation: In-situ biostimulation strategy for intractable shoreline sediment contaminated with diesel fuel, Australia	Bernard J. Peasley International Development Technologies Centre University of Melbourne c/-PO Box 827 Moonee Ponds 3039 Victoria, Australia 61-3-9375-7599 kimpan@connect.com.au	Turlough F. Guerin 14 Scotts Road Suite 19-06 Far East Plaza Singapore 228213 65-731-4426 turlough@singnet.com.sg
2.4 Boston Logan Airport Area, Boston, Massachusetts	James Kang Dames & Moore 6 Hutton Centre Dr., Suite 700 Santa Ana, CA 92707 (714) 433-2000 snajjk@dames.com	
2.5 Camp Lejeune Surfactant-Enhanced DNAPL Removal, Marine Corps Base Camp Lejeune, North Carolina	Laura Yeh Naval Facilities Engineering Service Center Code ESC 411 1100 23rd Ave. Port Hueneme, CA 93043-4370 (805) 982-1660 yehsl@nfesc.navy.mil	Fred Holzmeyer Duke Engineering & Services 9111 Research Blvd. Austin, TX 78758 (512) 425-2000 fjholzme@dukeengineering.com
2.6 Dover AFB, Test Cell 3-Cosolvent Solubilization, Dover, Delaware	Tim McHale ManTech Environmental Research Services Corp. Groundwater Remediation Field Lab P.O. Box 02063, Bldg. 909 Arnold Drive Ext. Dover AFB, DE 19902 (302) 677-4080 mchale@ad3100.ada.epa.gov	

Case Study	Contact Information
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2.8 Gulf Power, Lynn Haven, Florida	Jim Redwine Southern Company Services (205) 992-6075
2.9 Hill AFB Operable Unit (OU) 2 Full-Scale Surfactant Flood, Layton, Utah	Jon Gin U.S. Air Force Hill AFB Layton, UT (801) 775-6894 ginnj@hillwpos.hill.af.mil Dr. Richard Jackson Duke Engineering & Services 9111 Research Blvd. Austin, TX 78578 (512) 425-2000 rejacks@dukeengineering.com
2.10 Howard University: The Use of Pervaporation and Ultrafiltration Membranes for the Separation, Recovery, and Reuse of Surfactant Solutions, Washington, DC	Kimberly Jones Department of Civil Engineering Howard University 2300 Sixth Street NW Washington, DC 20059 (202) 806-4807 kjones@scs.howard.edu
2.11 Ivey Environmental Services- Clark Oil Company, Fredericton, New Brunswick, Canada	George Ivey Ivey Environmental Services PO Box 1103, Station A Fredericton, NB Canada E3B 5C2 (506) 451-8787 budivey@nb.sympatico.ca
2.12 Ivey Environmental Services- Commercial/ Residential Site, Fredericton, New Brunswick, Canada	George Ivey Ivey Environmental Services PO Box 1103, Station A Fredericton, NB Canada E3B 5C2 (506) 451-8787 budivey@nb.sympatico.ca
2.13 McClellan AFB: Surfactant/ Cosolvent Enhanced Subsurface Remediation of DNAPLs, McClellan AFB, California	David Rennie TRW, Support Contractor SM-ALC/EMRP 5050 Dudley Blvd, Suite 3 Building 269E McClellan AFB, CA 95652-1389 (916) 643-0830 ext. 410 rennie.david@email.mcclellan.af.mil Mark Hasegawa Surbec Environmental, L.L.C. 3200 Marshall Avenue, Suite 200 P.O. Box 1757 Norman, OK 73072 (405) 364-9726 markhase@aol.com

Case Study	Contact Information	
2.14 OK Tool Area at Savage Well Site, Hillsborough County, New Hampsire	John Londergan Duke Engineering & Services 9111 Research Blvd. Austin, TX 78758 (512) 425-2028 jtlonder@dukeengineering.com	Richard Goehlert U.S. EPA JFK Federal Building Boston, MA 02203-0001 (617) 918-1335 goehlert.dick@epa.gov
2.15 Millican Field, Pearl Harbor, Hawaii	Dr. Richard Jackson Duke Engineering & Services 9111 Research Blvd. Austin, TX 78758 (512) 425-2000 rejacks@dukeenginering.com	
2.16 Strategic Environment Research and Development Program (SERDP): Evaluation of Surfactants for the Enhancement of PCB Dechlorination in Soils and Sediments, Atlanta, Georgia	Kurt D. Pennell School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, GA 30332 (404) 894-9365 kurt.pennell@ce.gatech.edu	
2.17 U.S. Department of Energy (DOE) Paducah Gaseous Diffusion Plant, Paducah, Kentucky	Mark Hasegawa Surbec Environmental, L.L.C. 3200 Marshall Avenue, Suite 200 P.O. Box 1757 Norman, OK 73072 (405) 364-9726 markhase@aol.com	Ben Shiau Surbec Environmental, L.L.C. 3200 Marshall Avenue, Suite 200 P.O. Box 1757 Norman, OK 73072 (405) 364-9726 bshiau@msn.com

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