Technology
Status Report

GWRTAC
S
SERIES

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Technology Status Report
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 Concurrent Technologies Corporation (*CTC*) 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).

About "S" Series Reports

This report is one of the GWRTAC "S" Series of reports developed to provide a snapshot of the status of a given groundwater technology or topic, based on information compiled for GWRTAC's case study database. These reports are based on compiling readily available information from literature or from personal communications with involved parties. These reports are not intended as in-depth technical analyses and are not peer-reviewed.

Acknowledgements

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ABSTRACT

This technology status report provides a snapshot of the status of the *in situ* flushing remediation technology. The information provided herein is a reflection of the content of the Ground-Water Remediation Technologies Analysis Center's (GWRTAC's) case study database for innovative technologies. GWRTAC's case study database is not represented as being comprehensive, nor are the case studies included screened to verify their validity, quality, or "success" in remediation. Rather the case study database and resultant summaries are intended to provide members of the ground-water remediation community with basic information on activity in laboratory research, field demonstration, or full-scale application of innovative technologies in both the public and private sectors. The summaries are provided as a "snapshot" of the contents of GWRTAC's "living" case study database. Analysis of information present in GWRTAC's case study database and presented herein, is by GWRTAC.

In situ flushing is defined as 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. The majority of pilot-scale demonstrations of *in situ* flushing to date have involved the use of surfactants and co-solvents, while in the U.S., where full-scale site remedies have utilized *in situ* flushing, plain water is typically used as the flushing solution. GWRTAC is including plain water flushing solutions as *in situ* flusing cases, following the convention previously established by U.S. EPA. Halogenated VOCs are the most frequently targeted contaminant based on projects of all scales.

Some sources of information to GWRTAC have indicated a reluctance of regulatory personnel to the use of injectants for site remediation due to toxicity concerns. Research efforts underway at some institutions are focusing on the development of low toxicity, biodegradable, or U.S. Food and Drug Administration (FDA)-approved food additive flushing reagents to address this concern. In addition to toxicity concerns relative to injectants, persons responsible for implementing or regulating *in situ* flushing projects are concerned with containment, since the alteration of hydraulic and chemical properties, if uncontrolled, could exacerbate the contamination problem they are attempting to remediate. These two reasons are the most likely technical reasons for the small number of full-scale projects using surfactants, and why many of the enforcement sites flush within physically contained subsurface zones, such as sites first bound by slurry walls. Economically, recycling and reuse of surfactants or other flushing additives is also of concern, especially to site owners or potentially responsible parties (PRPs). Some research projects are specifically addressing recycling and reuse, as well as modeling of the flushing process.

This document was prepared for distribution by the Ground-Water Remediation Technologies Analysis Center (GWRTAC). GWRTAC is operated by Concurrent Technologies Corporation (*CTC*) 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 / PURPOSE OF STATUS REPORTS

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) continually compiles laboratory-, pilot- and full-scale case study information for a variety of innovative *in situ* technologies for ground-water and soil remediation. At this time, GWRTAC's case study database contains approximately 525 case studies. Periodically, GWRTAC will provide "S" Series Status reports based on information contained in the GWRTAC case study database for a selected technology.

GWRTAC's case study database is not represented as being comprehensive, nor are the case studies included screened to verify their validity, quality, or "success" in remediation. Rather the case study database and resultant status reports are intended to provide members of the ground-water remediation community with basic information on activity in laboratory research, field demonstration, or full-scale application of innovative technologies in both the public and private sectors. The GWRTAC database was designed in a manner to allow analysis of the use of each innovative technology monitored by GWRTAC, which is accomplished by the preparation of various tables and charts to reveal trends in technology application. This analysis, presented in the "S" Series Status reports, is by GWRTAC, and is based solely on the information in the GWRTAC database. The status reports are provided as a "snapshot" of the contents of GWRTAC's "living" case study database. As such, status reports for a given technology will be repeated in the future to reflect additional case study information compiled, and/or updates/revisions/additions to the database.

Submission of innovative technology case study information to GWRTAC via our on-line data submittal form (http://www.gwrtac.org) or by calling GWRTAC (1-800-373-1973) will allow GWRTAC to continue updating the database. Such notifications are appreciated, and may be followed with a request for additional information when GWRTAC focuses on the technology prior to preparation of an "S" Series report.

In addition to this Section 1.0, Introduction / Purpose of Status Reports, the remainder of this report is organized as follows. Section 2.0, *In Situ* Flushing Summary, reviews and shows trends related to general information such as the scale and status of the *in situ* flushing projects in the database, project objectives, contaminant source (whether existing or introduced), target media, and project locations. Section 3.0, Analysis of *In Situ* Flushing Technology, provides GWRTAC's analysis of trends in use of flushing solution, contaminant classes addressed, delivery and extraction and containment methods, project results and identified issues, and research needs. Section 4.0, Summary, provides a final overview of *in situ* flushing technology.

The Appendix contains the detailed project summaries for each of the 84 *in situ* flushing projects currently contained in the GWRTAC database, as well as GWRTAC's source(s) of information for the database, and also other external references, such as journal articles, pertaining to the project. It should be noted that the length and amount of detail in the project summaries varies greatly, depending upon whether published papers are available on the project, and/or the source material used by GWRTAC. For most enforcement sites, GWRTAC has not obtained copies of multiple documents submitted to regulatory agencies to gain a full and detailed picture of the project, but rather has relied upon telephone interviews with project managers to construct project summaries. For research sites where published papers or reports are readily available to summarize the *in situ* flushing project, executive summaries or project summaries were often provided to GWRTAC electronically for direct incorporation into the database. In still other cases, information found in the project summaries was provided by abstracts.

2.0 *IN SITU* FLUSHING SUMMARY

2.1 *In Situ* Flushing Definition / GWRTAC Report Availability

In situ flushing is defined as 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. Figure 1 is a schematic which illustrates a generalized *in situ* flushing process at a dense, non-aqueous phase liquid (DNAPL) contaminated site where a flushing solution is being injected into an unconfined aquifer. Additional information on *"In Situ* Flushing" may be found in a GWRTAC Technology Overview "O"-Series Report by the same title, (TO-97-02), and a Technology Evaluation "E"-Series Report (TE-96-02) entitled "Surfactants/Co-Solvents". In addition, two Technology Status "S"-Series Reports (EPA 542-K-94-003 entitled "Surfactants") and (EPA 542-K-94-006 entitled "Co-Solvents") were prepared by the U.S. Environmental Protection Agency (EPA) on the subject on *in situ* flushing, however, this information has been updated for this status report. A Featured Technology Summary Report for *in situ* flushing was also prepared based on the GWRTAC database as of August 7, 1998, however this information has also been further updated for this status report. All of these reports are available for downloading in *.PDF format from the GWRTAC website at http://www.gwrtac.org.

2.2 GWRTAC Database / Scale and Status of Projects

Currently, GWRTAC's case study database contains a total of 84 *in situ* flushing projects. It should be noted that by the above definition, GWRTAC has included case studies where plain water (usually treated groundwater) is used as the flushing solution. Undoubtedly, with this inclusion, hundreds of projects in which re-injection of treated groundwater occurs as an alternative to NPDES or POTW disposal routes would also be considered *in situ* flushing projects in the strictest sense. For the most part, these projects are not included in the database as *in situ* flushing remediation studies; the projects included have identified the flushing action of water or other flushing solution as an integral part of the cleanup process rather than as a disposition method. GWRTAC is including plain water flushing solutions as *in situ* flusing cases, following the convention previously established by U.S. EPA.

Table 1 provides a summary of pertinent information for the *in situ* flushing case studies which are currently part of the GWRTAC database. The case studies are listed in alphabetical order by project name, (which often indicates project location and/or site owner). Also listed for each site is a unique identification number assigned by GWRTAC; for reasons involved in development of the database, the GWRTAC ID numbers are not in consecutive order, and there may be gaps in the sequence. It should be noted that where several individual but unique pilot-scale demonstrations are planned or have occurred at the same location (ie., Dover Air Force Base, Dover, Delaware; Hill Air Force Base, Layton, Utah), these individual efforts are counted as separate pilot-scale case studies. However, for laboratory studies, a given laboratory research group is typically listed only once as a case study, although many different related efforts may have been conducted by that research group. Table 1 lists not only the GWRTAC ID and project name and location, but also lists selected primary organization points of contact for the categories of 1) Potentially Responsible Party (PRP)/Site Owner; 2) Funding Source/Sponsor; 3) Regulatory Agency; and 4) Technical Team Member. GWRTAC's actual database contains additional contacts as available in each category, including names, addresses and phone numbers for all points of contact. This information is available upon request from GWRTAC. Table 1 also includes information on the project scale, contaminants addressed, target media, flushing solution used, and the project status. It may be useful for the reader to refer to Table 1 while reviewing the remainder of this report.

In most cases, although supporting laboratory studies have taken place prior to pilot- or full-scale demonstrations, or pilot-scale tests may have been conducted prior to full-scale remediation, only the "most advanced" scale of the project is included in the GWRTAC case study database. That is, if a pilot-scale demonstration is listed, the supporting laboratory studies for the project are not separately listed as a laboratory-scale project. As illustrated by the pie chart in Figure 2, of the 84 *in situ* flushing case studies, 20 are laboratory studies, 42 are pilot-scale studies, and 22 are part or all of a full-scale site remediation. Figure 3 illustrates the status of the projects contained in the GWRTAC database. As seen from the figure, the vast majority of the projects have been completed (48 projects) or are in-progress (21 projects), and 15 of the projects GWRTAC has included are in either pre-design, design, or scheduled status. Table 1 lists the scale and status information for each individual project which is summarized in Figures 2 and 3.

2.3 Project Objectives / Contaminant Source / Target Media

Figure 4 depicts the project objectives typically inferred from GWRTAC's sources of information. More than one project objective may be included per project. (In this and other figures where more than one chart option is applicable, the chart indicates the total number of selections, or "responses", and thus the number upon which the chart's percentage labels are based, as well as the number of case studies containing the information charted.) This chart includes laboratory/bench-scale information, which often have a related research aspect, and some are actually testing proof of concept. The full-scale/commercial projects are intended for site remediation. Several of the pilot/field demonstrations are undertaken as feasibility studies for collection of economic/design data, and may have either a research or a remediation aspect to them. Thus, approximately 47 projects (39% of 120), were identified as having a research objective, and 28 projects (23% of 120) were identified as having proof of concept as an objective. Approximately 16 projects were inferred to have a feasibility aspect (collection of economic or design data). An additional 30 projects were planned or conducted as actual full or partial site remediation efforts.

For the 64 pilot/field demonstrations and full-scale commercial projects, Figure 5 shows whether the source of contamination was existing or the contaminant was introduced via a controlled release. As this figure indicates, 89%, or 57 of the 64 pilot/field demonstration and full-scale/commercial projects addressed existing contamination, while the remaining seven projects involved a controlled release. In the U.S., most pilot-scale demonstrations to date have occurred at sites with existing contamination. At the Groundwater Remediation Field Laboratory (GRFL) National Test Location at Dover Air Force Base, Dover, Delaware, a Contained Release Facility now allows research and development of detection, monitoring and remediation of dense, nonaqueous phase liquid (DNAPL) under controlled conditions where the source is emplaced. Five *in situ* flushing demonstrations are currently underway or planned at this facility, using surfactants and/or co-solvents and complexing sugars. Other pilot/field-scale studies where controlled releases have occurred have taken place in Canada. The first pilot/field-scale controlled release facility was constructed and operated at Canadian Forces Base Borden, near Alliston, Ontario, a field test facility operated by the University of Waterloo's Centre for Groundwater Research.

Figure 6 displays, for case studies of all scales, the environmental media targeted by the projects, as identified from GWRTAC's sources of information. More than one target medium may be indicated for an individual project. Typically, as in approximately 52 responses (42% of 123), both soil and groundwater are indicated as target media. There are about 23 responses where soil contamination only was targeted (where soil contamination is limited to the vadose zone well above the saturated zone or only soil is addressed in laboratory studies). A small number of projects (about five responses) primarily targeted the ground-water media. A total of 42 responses (34% of 123) target either light, nonaqueous phase liquid (LNAPL) or dense, nonaqueous phase liquid (DNAPL) (either product layers or free phase product entrained within the targeted treatment zone).

2.4 Project Locations

Figure 7 depicts the distribution of the locations by EPA Region of the *in situ* flushing projects in the GWRTAC database which have advanced to pilot-scale or full-scale, as well as the additional projects located outside the U. S., or which are at laboratory scale. EPA Regions II, III, IV, V, and VIII all contain from seven to 11 *in situ* flushing pilot- or full-scale projects. EPA Regions I, VI, VII, IX and X contain five or less projects. The map in Figure 8 graphically depicts the locations, per EPA Region in the U.S., of the 64 pilot- or full-scale studies in the GWRTAC database. For full-scale projects, based on the information collection process, it is likely that CERCLA sites are well-represented, and that RCRA Corrective Action Sites where *in situ* flushing is being utilized have not been identified. Also, relatively few sites outside the U.S. have been identified to date. The GWRTAC staff is actively seeking information on non-U.S. (to include Europe, Asia, South America) *in situ* projects to expand the current case study database.

Table 2 lists the U.S. state, Canadian province or other country locations of each of the pilot-scale or field-scale studies in the database. Utah and Delaware rank high on the list, respectively, due to the Hill Air Force Base and Dover Air Force Base projects. Excepting those, New Jersey (site of several full-scale flushing projects where treated site groundwater is used as the flushing agent), Florida, and Quebec are the states or provinces where activity is relatively high. A wide range of geologic settings and climatological conditions are represented by these diverse project locations.

3.0 ANALYSIS OF *IN SITU* FLUSHING TECHNOLOGY

3.1 Flushing Solutions

Figure 9 is a pie chart illustrating the types of flushing solutions being used in the various case studies of all scales. For this chart, if more than one type of flushing solution was used in a project, or if a flushing solution contained more than one type of flushing additive, both were counted (i.e. a project where both surfactants and co-solvents were used was counted as both a surfactant and a co-solvent project). The "other" category for this figure encompasses several different potential flushing additives (such as polymers, electolytes, complexing sugars, etc.), as indicated by the note on the figure, whether or not these additives are in use alone or combined with surfactant or other solutions. As shown, surfactants, plain water, other, and then co-solvents (in descending frequency of occurrence) are the top four categories of the known flushing solutions which have been used. It should be noted that, of the 22 full-scale studies, where known, the flushing solution used in the majority of the studies was plain water (or water with addition of nutrients), usually treated site groundwater. Exceptions are six sites located in Quebec, Canada, and three sites located in the U.S. GWRTAC ID FLSH0011 is the Estrie Region Machine Shop site in Quebec, Canada, in which a surfactant flushing solution was utilized at a site contaminated with LNAPL. GWRTAC ID FLSH0037 is a site in Drummondville, Quebec, where surfactants are used to remediate soil contaminated with benzene, toluene, ethylbenzene, and xylene (BTEX) and mineral oil and grease (MOG). GWRTAC ID FLSH0042 is the Thouin Sand Quarry Site in Quebec, Canada, where additives including surfactant were used to remediate DNAPL. GWRTAC ID FLSH0066 is an aluminum processing facility in Quebec where surfactants were used in the remediation of polychlorinated biphenyls (PCBs) and MOG. GWRTAC IDs FLSH0067 and FLSH0068 are two separate projects in Quebec where surfactants were used to treat soils contaminated with BTEX and MOG at or near petroleum sites. One of the sites in the U.S. thought to be the first to use a flushing additive other than nutrients at full-scale, is FLSH0050, located in Florida, where an arsenic plume in groundwater is being remediated using proprietary chemicals in the flushing solution. The remaining two U.S. projects are in planning stages or are confidential in nature.

Figure 10 is a bar chart depicting the flushing solution type used by project scale. As in Figure 9, more than one category of flushing solution per project may be included in this figure. As is apparent from this figure, while surfactants are used in many laboratory-scale studies and are being tested in the field at pilot-scale, only a small number of full-scale applications have occurred to date, and these are outside the U.S.; six Canadian projects are identified above. However, plans are currently underway to remediate at least a portion of Operable Unit 2 (OU2) at Hill Air Force Base using a surfactant flood. This is thought to be the first full-scale (currently funding for 1/5 of the full project is earmarked) application of surfactant flushing planned in the U.S., and may be underway within the next two years. Still, at least 14 full-scale *in situ* flushing case studies have been identified by GWRTAC where water (treated or untreated site groundwater, or potable water) with no additives other than nutrients is used as the flushing solution. Considering the laboratory- and pilot-scale studies, which are included in Figure 10, the majority of the research and demonstration projects have examined the use of surfactants. Only eight of the pilot-scale projects used co-solvents, compared to 30 which used surfactants. At the laboratory scale, 17 projects examined surfactants and one examined co-solvents. As mentioned above, the majority of the pilot-scale projects would have had laboratory work completed prior to the project. Figure 10 shows only laboratory/bench scale cases in which the given research group is doing laboratory work independently of a pilot-scale demonstration.

3.2 Contaminant Classes

Figure 11 is a bar chart depicting broad contaminant classes targeted in the studies included in the GWRTAC database, organized by project scale. Because many of the case studies targeted contaminants belonging to more than one class, several of the 84 case studies in the GWRTAC database are represented multiple times on Figure 11. At all scales, organic compounds are the most frequently targeted compounds, although the proportion of slightly more VOCs in comparison to non-VOCs for full-scale projects is not evident at the pilot- and laboratory-scales. Considering inorganics, proportionally more full-scale projects address inorganics than is evident at either the laboratory- or pilot-scales, although this may be incidental to targeting an organics contamination problem.

Figure 12 is a bar chart of all of the specific target contaminant classes, for all project scales. In the GWRTAC database, target contaminants are classified by choosing as many classes as applicable, using the most specific categorization possible based on the source information. From the 84 case studies included in this chart, the number of "responses" related to these projects is 188, because more than one contaminant class is applicable for many of the case studies. Based on Figure 12, halogenated VOCs are by far the most frequently targeted contaminant, being addressed in at least 41 of the case studies. DNAPL, BTEX, LNAPL, PCBs, and polynuclear aromatic hydrocarbons (PAHs) represent the next most frequently target contaminant classes. (Some of the not otherwise specified VOCs and semivolatile organic compounds (SVOCs) could potentially belong to these classes as well, either entirely or in part). Other organics frequently targeted include petroleum hydrocarbons and non-halogenated VOCs. Metals are frequently targeted as well; in a few cases solely, and in others, in addition to organic contamination. Further detail on the specific contaminants targeted by each *in situ* flushing project in the database is available from examination of Table 1.

A large number of demonstration projects have occurred at Hill Air Force Base using surfactants, co-solvents, and complexing sugars, where existing fuel contamination / LNAPL (OU1) or trichloroethene (TCE) / DNAPL (OU2) was targeted. At Dover Air Force Base again, surfactants, co-solvents, and sugars will be used, targeting TCE emplaced by Groundwater Remediation Field Laboratory personnel. Contaminants targeted by other surfactant/co-solvent projects (from Table 1) include BTEX, chlorinated volatile organic compounds (VOCs), PAHs, and PCBs. Full-scale/commercial projects where water is used as a flushing solution often address mixtures of organic and inorganic contaminants. One project, GWRTAC ID FLSH0043, addresses explosives, and two projects (FLSH0020 and FLSH0050) address arsenic ground-water contamination.

3.3 Delivery and Extraction / Containment Methods

While not listed separately here for each project, in general, delivery systems typically consist of vertical wells or infiltration galleries or pipes, constructed of PVC, polyethylene, or stainless steel. Extraction systems typically consist of vertical wells, although horizontal wells and vertical circulation wells are to be used or have been used at some sites. The number of wells at a site may range from one, to several hundred well points. Continuous flushing and correlation of results to the number of pore volumes flushed is typical for pilot-scale demonstrations. While most full-scale remediation projects utilized continuous flushing, in at least one case (FLSH0028), flushing occurs in a batch-type process using treated site groundwater. The project summaries in the Appendix indicate the type of delivery and extraction systems for each project, as well as details related to the delivery sequence of the flushing solutions used.

Figure 13 depicts the containment methods utilized for the case studies in the GWRTAC database for pilot/field and full-scale/commercial projects. Again, more than one containment method is often applicable; for the 84 case studies, there were 131 "responses" upon which Figure 13 was based. As expected, hydraulic containment is often practiced for a project (in at least 56 responses), but is often coupled with other either natural or constructed containment methods, such as a confining layer, or physical construct such as a slurry wall. Natural geologic barriers (typically low permeability confining layers) underlie approximately 36 of the pilot- to full-scale *in situ* flushing projects, based on the responses. Test cells have been constructed for approximately 14 pilot/field demonstrations, and several (approximately eight) full-scale projects are conducted with slurry walls keyed into confining layers, based on the responses.

3.4 Site Geologic Information

Figure 14 indicates the maximum depth of the treatment zone for all pilot/field to full-scale/commercial projects. Approximately 3/4 of the projects (47 of 64 projects) are included in the combined categories: "less than 10 feet below ground surface (bgs)"; "10 to 25 feet bgs"; or "25 to 50 feet bgs" maximum depth ranges Three projects targeted contaminants at depths from "50 to 100 feet bgs". Although hydraulic conductivity is a critical parameter in determining the potential likelihood of success of *in situ* flushing, a suprising number (35 out of 64) of project summaries did not specifically provide this information for the targeted zone of treatment. Figure 15 is a bar chart illustrating available hydraulic conductivity information (based on two order-of-magnitude ranges) for all pilot/field to full-scale/commercial projects. As would be expected, where the information is available, most of the projects are taking place in geologic units which have relatively high hydraulic conductivities (10^{-1} to 10^{-4} cm/sec).

Table 3 provides additional information on the geologic materials present at each of the pilot/field to full-scale/commercial projects in the GWRTAC database, where specified. Also listed is an indication of the size of the contaminant zone or project test area, where this information was available from project summaries. GWRTAC has inferred from available information that *in situ* flushing projects are primarily targeting geologic units which are either primarily coarse-grained sediments, either poorly or well sorted, or well sorted fine-grained sediments, as might be expected. Cases where contaminants located in bedrock are targeted include GWRTAC IDs FLSH0041 (fractured sandstone) and FLSH0058 (carbonate). Considering the volume of contaminated materials, the most readily comparable measure is the pore volume contained in the main ground-water plume, which is listed in Table 3. Where this information is available, the treatment zone pore volume given ranged between 580 to 15,000 gallons. The *in situ* flushing activities conducted typically involve sequential flushing of different flushing solutions (surfactants, cosolvents, water, or a combination thereof) in quantities related to this base pore volume.

Figure 16 shows the hydrogeologic setting of the target contaminants for pilot/field to full-scale/commercial projects; more than one setting may be indicated per project. As seen, 20 projects (27% of 75) target vadose zone contamination, while 49 projects (65% of 75) target contamination located within the saturated zone, but in an unconfined aquifer. Only one project was indicated as targeting contamination located in a confined aquifer.

3.5 Results and Economic Information

Table 4 lists results-oriented information available from project summaries, based on mass of contaminant removed or percentage of contaminant removed, and statements related to economics from project summaries. This information is not available from projects in design stages or scheduled projects, and is often not available for projects that are in progress, as noted on Table 4. Project performance may be measured through comparison of pre-flushing versus post-flushing soil and/or ground-water concentrations for selected contaminants, through analysis of soil cores before and after flushing, or through the use of partitioning interwell tracer tests (PITTs) or conservative interwell tracer tests (CITTs). In some research projects, results have been determined by more than one means. Table 4 indicates a variety of measures of results information, and is best understood by referring to the individual project summaries in the Appendix where Table 4 indicates that results are available. It can be generally stated that *in situ* flushing greatly accelerates the removal of contaminants relative to conventional pump and treat operations, based on information from individual project summaries and their conclusions. Economic information likewise, has not been condensed into readily analyzable information. Table 4 gives the reader an indication of the projects where economic factors are addressed in some manner in the project summaries contained in the Appendix.

4.0 SUMMARY / ISSUES IDENTIFIED / RESEARCH FOCUS

As noted in the previous sections of this report, the majority of pilot-scale demonstrations of *in situ* flushing to date known to GWRTAC have involved the use of surfactants and cosolvents. In the U.S., where full-scale site remedies have utilized *in situ* flushing, plain water has typically been used as the flushing solution. Halogenated VOCs are the most frequently targeted contaminant based on projects of all scales. Some sources of information to GWRTAC have indicated a reluctance of regulatory personnel to the use of injectants for site remediation due to toxicity concerns. Research efforts underway at some institutions are focusing on the development of low toxicity, biodegradable, or U.S. Food and Drug Administration (FDA)-approved food additive flushing reagents, to address this concern. In addition to toxicity concerns relative to injectants, persons responsible for implementing or regulating *in situ* flushing projects are concerned with containment, since the alteration of hydraulic and chemical properties, if uncontrolled, could exacerbate the contamination problem at a site. These two are the most likely technical reasons for the small number of full-scale projects using surfactants, and why many of the enforcement sites flush within physically contained subsurface zones, such as sites first bound by slurry walls. Economically, recycling and reuse of surfactants or other flushing additives is also of concern, especially to site owners or PRPs. At one site in Pennsylvania, although *in situ* flushing was identified as accelerating PCB removal from groundwater via a spring outfall from fractured sandstone, *in situ* flushing was discontinued after pilot testing largely due to the lack of focus on how to economically treat the elutriate. Some research projects are specifically addressing recycling and reuse, as well as modeling of the flushing process. At least one regulatory agency personnel expressed concern that commercially available models often failed to compensate for the narrow features of slurry walls and infiltration trenches, and it often can not be proven that all the water being infiltrated can indeed be captured.

Table 1. In Situ Flushing - Summary of Case Studies in the GWRTAC Database (Details for Each Project Included in Appendix)
Total Number of Case Studies = 84

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Flushing Solution	Status of Project
FLSH0066	Aluminum Company Site		QC	Not Specified	Not Specified	Not Specified	GSI Environnement	Full-Scale/Commercial	Transformer oil, PCBs, MOG	Soil, NAPL	Surfactants	Completed
FLSH0002	Bog Creek Farm, Howell Township, NJ	Howell Township	NJ	NA	U.S. EPA	U.S. EPA	U.S. Army Corps of Engineers	Full-Scale/Commercial	VOCs (toluene, benzene)	Groundwater	Treated Site Groundwater	In Progress
FLSH0039	Camp Lejeune Marine Corps Base	Camp Lejeune	NC	U.S. Marine Corps	NAVFAC ESTCP	NC DEHNR	Duke Engineering & Services (formerly INTERA)	Pilot/Field Demonstration	PCE (DNAPL) and Varsol R (LNAPL), the former dry cleaning solvent	Soil, Groundwater, NAPL	Surfactant	Scheduled
FLSH0003	Canadian AFB Borden, Alliston, Ontario, Canada	Alliston	ON	Canadian Air Force	NY Center for Haz Waste Mgmt	Not Specified	SUNY - Buffalo	Pilot/Field Demonstration	Tetrachloroethylene (also known as perchloroethylene or PCE), DNAPL	Groundwater, DNAPL	Surfactant (blend of 1% nonylphenol ethoxylate and 1% phosphate ester of nonylphenol ethoxylate)	Completed
FLSH0047	Cape Canaveral Lodge Complex 34	Cape Canaveral	FL	NASA	U.S. DOE/ORNL	State of Florida - RCRA	U.S. EPA ORD	Pilot/Field Demonstration	TCE	Soil, Groundwater, DNAPL	Surfactants or Cosolvents	In Design
FLSH0004	Chem-Dyne, Hamilton, OH	Hamilton	OH	Chem-Dyne	Chem-Dyne	U.S EPA	Conestoga Rovers Association	Full-Scale/Commercial	Arsenic, benzo(a)pyrene, chlordane, dieldrin, hexachlorobenzene, PCBs, priority pollutant acid compounds, VOCs	Groundwater	Treated Site Groundwater	Completed
FLSH0077	Coast Guard Facility, Elizabeth City, NC	Elizabeth City	NC	U.S. Coast Guard	U.S. EPA ORD	Not Specified	Surbec Environmental Services	Laboratory/Bench Scale	Chromium, Chlorinated Solvents	Soil, Groundwater	Surfactants	Completed
FLSH0020	Confidential		FL	Confidential	Confidential	Not Specified	Confidential	Full-Scale/Commercial	Arsenic	Soil, Groundwater	Proprietary Compound	In Progress
FLSH0005	Cornell University - Surfactant Enhance Biodegradation	Ithaca	NY	NA (Lab study)	Not Specified	NA (Lab study)	Cornell University	Laboratory/Bench Scale	Phenanthrene and biphenyl	Soil	Non-Ionic Surfactant	Completed
FLSH0006	Corpus Christi Dupont, Corpus Christi, TX	Corpus Christi	TX	Dupont	Dupont	Not Specified	SUNY - Buffalo	Pilot/Field Demonstration	DNAPL (Carbon Tetrachloride - CTET) (1.58 g/cm3 centipoise)	Soil, Groundwater, DNAPL	Biodegradable Surfactants Approved for use in Food Preparation (initially Witconol 2722 (Witco Corp.) then Tergitol 15-S012 (Union Carbide Corp.))	Completed
FLSH0007	Cross Brothers Pail, Pembroke, IL	Pembroke	IL	Sherwin Williams Paint Company	Sherwin Williams Pain Company	U.S. EPA	Sherwin Williams	Full-Scale/Commercial	VOCs (BTEX, PCE, TCE), and their breakdown products. (PCBs in soil previously excavated). As of 1998, influent (extracted groundwater contain only BTEX.	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0062	Dover AFB, Dover, DE (Cosolvent Mobilization)	Dover	DE	U.S. Air Force	SERDP	U.S. EPA	Mantech Environmental Clemson University	Pilot/Field Demonstration	DNAPL (PCE, or perchloroethylene)	Soil, Groundwater, DNAPL	Cosolvent (tert-butyl alcohol)	Scheduled
FLSH0063	Dover AFB, Dover, DE (Macromolecular Solubilization)	Dover	DE	U.S. Air Force	SERDP	U.S. EPA	Mantech Environmental University of Arizona	Pilot/Field Demonstration	DNAPL (PCE, or perchloroethylene)	Soil, Groundwater, DNAPL	Complexing Sugar	Scheduled
FLSH0064	Dover AFB, Dover, DE (Single-phase Microemulsion)	Dover	DE	U.S. Air Force	SERDP	U.S. EPA	Mantech Environmental University of Florida	Pilot/Field Demonstration	DNAPL (PCE, or perchloroethylene)	Soil, Groundwater, DNAPL	Cosolvent and Surfactant	Scheduled
FLSH0061	Dover AFB, Dover, DE (Test Cel 2, Surfactant Solubilization)	Dover	DE	U.S. Air Force	SERDP	U.S. EPA	Mantech Environmental University of Oklahoma	Pilot/Field Demonstration	DNAPL (PCE, or perchloroethylene)	Soil, Groundwater, DNAPL	Surfactant	Scheduled
FLSH0009	Dover AFB, Dover, DE (Test Cel 3, Cosolvent Solubilization)	Dover	DE	U.S. Air Force	SERDP	U.S. EPA	Mantech Environmental University of Florida	Pilot/Field Demonstration	DNAPL (PCE, or perchloroethylene)	Soil, Groundwater, DNAPL	Cosolvent (ethanol)	Scheduled
FLSH0010	Eckenfelder, Inc. - Surfactant Recycling	Nashville	TN	NA (Lab Study)	Not Specified	NA (Lab Study)	Eckenfelder, Inc.	Pilot/Field Demonstration	PCBs	Soil	Biodegradable, Nontoxic Anionic Surfactant (sodium dodecyl sulfate (SDS))	Completed
FLSH0073	Envirogen - Effects of Emulsion Viscosity	Lawrenceville	NJ	NA (Lab Study)	Not Specified	NA (Lab Study)	Envirogen, Inc.	Laboratory/Bench Scale	m-xylene	Soil	Surfactant foam (Witconol registered SN90)	Completed
FLSH0072	Envirogen - Surfactant Foam/Bioaugmentation	Lawrenceville	NJ	NA (Lab Study)	Not Specified	NA (Lab Study)	Envirogen, Inc.	Laboratory/Bench Scale	TCE, DNAPL	Soil	Surfactant foam (CS-330)	Completed
FLSH0011	Estrie Region Machine Shop, Quebec, CA	Quebec City	QC	Not Specified	Not Specified	Not Specified	GSI Environnement	Full-Scale/Commercial	Hydrocarbons, LNAPLs, "Mineral Cutting oil"	Soil, NAPL	Biodegradable, Nontoxic Surfactant	Completed
FLSH0021	Former Dry Cleaning Faciliy, Jacksonville, FL	Jacksonville	FL	Not Specified	U.S. EPA TIO	Florida DEP	Lavine Fricke Recon	Pilot/Field Demonstration	PCE (DNAPL)	Soil, Groundwater, NAPL	Cosolvent (90% ethanol and 5% water)	In Progress
FLSH0059	Fredricksburg, VA Wood Treating Site	Fredricksburg	VA	Owner of industrial site	Owner of industrial site	Not Specified	CH2M Hill	Pilot/Field Demonstration	Creosote-based wood treating oil (DNAPL)	Soil, DNAPL	Alkaline Agent, Surfactant, and Polyme (0.5 wt% Na2 CO3 plus 0.1 wt% Makon-10 (nonyl phenol with 10 moles ethylen oxide) and 1,500 mg/L xanthan gum)	Completed

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Total Number of Case Studies = 84

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Flushing Solution	Status of Project
FLSH0012	General Motors NAO Research & Development Center, Warren, MI	Warren	MI	General Motors	General Motors	Not Specified	General Motors	Pilot/Field Demonstration	PCBs, oils	Soil	0.75 wt% Surfactant (nonionic ethoxylated alcohol)	Completed
FLSH0084	Georessources - Aquifer Washing by Micellar Solutions	Sainte-Foy	QC	NA (Lab Study)	Not Specified	NA (Lab Study)	Georessources	Laboratory/Bench Scale	Mercier DNAPL (Mixture of heavy aliphatics, aromatics and chlorinated hydrocarbons)	Soil, NAPL	Alcohol-Surfactant-Solvent (n-butanol-SAS-toluene-D-limonene	Completed
FLSH0013	GHEA Associates, New Jersey Operating Facilty of Major U.S. Corporation		NJ	Unnamed	Unnamed	Not Specified	New Jersey Institute of Technology	Pilot/Field Demonstration	BTEX, VOCs, SVOCs	Soil	Nonionic Surfactant	In Design
FLSH0014	Goose Farm, Plumsted Twp, NJ	Plumsted Twp.	NJ	Morton International Inc.	Morton International, Inc.	U.S. EPA Region 02	Geomatrix Consultants	Full-Scale/Commercial	VOCs (benzene, toluene, ethylbenzene dichloromethane, TCE), SVOCs, PAHs	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0050	Gulf Power - Lynn Haven, FL	Lynn Haven	FL	Gulf Power Company	EPRI	Florida DEM	Southern Company Services, Inc.	Full-Scale/Commercial	Arsenic	Soil, Groundwater	Originally Citric acid; now a Proprietary Compound is Used	In Progress
FLSH0058	Hialeah County, FL		FL	Owner of industrial site	Owner of industrial site	Not Specified	CH2M Hill	Pilot/Field Demonstration	Hydraulic oil	Soil, Groundwater, LNAPL	Surfactant/Alkali (0.5 wt% Na2 CO3 plus 1.1 wt% NaHCO3, plus 0.5 wt% Na2O(Si02)3.22, plus 0.01 wt% Chloramine T plus 1000 mg/L xanthan gum)	Completed
FLSH0056	Hill Air Force Base (Cell 4, OU 1 Cyclodextrin Solubilization)	Layton	UT	U.S. Air Force	SERDP	U.S. EPA	U.S. Air Force University of Arizona	Pilot/Field Demonstration	Waste jet fuel and light lubricants mixed with chlorinated and nonchlorinated solvents	Soil, Groundwater, LNAPL	Sugar [hydroxypropyl-B-cyclodextrin (HPCD)]	In Progress
FLSH0055	Hill Air Force Base (OU 2 - Foan Flood)	Layton	UT	U.S. Air Force	AATDF	U.S. EPA	U.S. Air Force Duke Engineering & Services	Pilot/Field Demonstration	Chorinated solvents (TCE, TCA, PCE, and CTET) with petroleum hydrocarbons, DNAPL (DNAPL is approximately 70% TCE)	Soil, Groundwater, DNAPL	Foam/Surfactant	Completed
FLSH0057	Hill Air Force Base (OU2 1/5 Ful Scale Surfactant Flood)	Layton	UT	U.S. Air Force	U.S. Air Force	U.S. EPA	U.S. Air Force Duke Engineering & Services	Full-Scale/Commercial	TCE and DNAPL (DNAPL is 70% TCE)	Soil, Groundwater, DNAPL	Surfactant	Scheduled
FLSH0015	Hill Air Force Base, UT (Cell 3, OU1 - Cosolvent Mobilization)	Layton	UT	U.S. Air Force	SERDP	U.S. EPA	U.S. Air Force Clemson University	Pilot/Field Demonstration	LNAPL (JP-4 jet fuel, chlorinated and nonchlorinated solvents, PCBs) (Waste fuels and lubricants mixed with chlorinated solvents and PCBs)	Soil, Groundwater, LNAPL	Cosolvent (tert-butanol/hexanol)	Completed
FLSH0016	Hill Air Force Base, UT (Cell 5, OU1 - Surfactant Mobilization)	Layton	UT	U.S. AIr Force	SERDP	U.S. EPA	U.S. Air Force University of Oklahoma	Pilot/Field Demonstration	LNAPL (mixture of JP-4 jet fuel, chlorinated and nonchlorinated VOCs, naphthalene, pesticides, PCBs, dioxins) (Waste jet fuel and light lubricants mixed with chlorinated and nonchlorinated solvents)	Soil, Groundwater, LNAPL	Surfactant/Electrolyte (Aerosol OT/Tween w/ added CaCl2) (Most Tween surfactants have USDA food grade additive status)	Completed
FLSH0017	Hill Air Force Base, UT (Cell 6, OU1 - Surfactant Solubilization)	Layton	UT	U.S. Air Force	SERDP	U.S. EPA	U.S. Air Force University of Oklahoma	Pilot/Field Demonstration	LNAPL (Mixture of VOCs, naphthalene pesticides, PCBs, Dioxins, JP4) (Waste jet fuel and light lubricants mixed with chlorinated and nonchlorinated solvents)	Soil, Groundwater, LNAPL	Surfactant (Dowfax 8390)	Completed
FLSH0018	Hill Air Force Base, UT (Cell 8, OU1 - Surfactant/Cosolvent Solubilization)	Layton	UT	U.S. Air Force	SERDP	U.S. EPA	U.S. Air Force University of Florida	Pilot/Field Demonstration	LNAPL (JP-4 jet fuel, chlorinated and nonchlorinated solvents, PCBs)	Soil, Groundwater, LNAPL	Surfactant/Cosolvent (3.5 wt% Brij 91 [Polyoxyethylent (10) Oleyl Ether]) and 2.5 wt% n-pentanol)	Completed
FLSH0019	Hill Air Force Base, UT (OU2 - Micellar Flood)	Layton	UT	U.S. Air Force	AFCEE	U.S. EPA	U.S. Air Force Duke Engineering & Services	Pilot/Field Demonstration	Chlorinated solvents (TCE, TCA, PCE, and CTET), petroleum hydrocarbons, DNAPL (DNAPL is 70% TCE)	Soil, Groundwater, DNAPL	Surfactant/Cosolvent/Salinity (Electrolyte) (7.5 wt% sodium dihexyl sulfosuccinate, 3.75 wt% isopropyl alcohol, and 7,000 mg/L NaCl)	Completed
FLSH0022	Hill Air Force Base, UT (Test 1, OU 1 - Cosolvent Solubilization - Ethanol Flood)	Layton	UT	U.S. Air Force	U.S. EPA ORD	U.S. EPA	U.S. Air Force University of Florida	Pilot/Field Demonstration	LNAPL (BTEX , JP4, pesticides, VOCs SVOCs) (Waste jet fuel and light lubricants mixed with chlorinated and nonchlorinated solvents)	Soil, Groundwater, LNAPL	Cosolvents (70% ethanol, 12% n-pentanol)	Completed
FLSH0023	Hooker Chemical/Ruco Polymer NY	Hicksville	NY	Occidental Petroleum Corporation	Occidental Petroleum Corporation	U.S. EPA	Conestoga Rovers and Associates	Full-Scale/Commercial	VOCs (PCE, TCE, 1,2-DCE, vinyl chloride), phenol, and TICs (tentatively identified compounds)	Soil	Treated Site Groundwater	Pre-Design
FLSH0024	Howard University, Washington, DC - Treatment of PCBs with Surfactants	Washington	DC	NA (Lab Studies)	Gr Lakes/Mid-Atl Haz Sub Res Cntr	NA (Lab Studies)	Howard University	Laboratory/Bench Scale	PCBs	Soil	Surfactants	In Progress

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FLSH0025	JADCO-Hughes, Belmont, NC	Belmont	NC	King and Spalding (Law Firm)	King and Spalding (Law Firm)	U.S EPA	Constoga Rovers	Pilot/Field Demonstration	VOCs	Soil	Clean Water	Scheduled
FLSH0001	Koppers Co. Inc., Seaboard Plant, Kearny, NJ	Kearny	NJ	Beazer East, Inc.	Beazer East, Inc.	New Jersey Dept. of Environ. Protection	Key Environmental	Pilot/Field Demonstration	DNAPL (Creosote/Coal tar)	Groundwater, DNAPL	Site Groundwater After Oil/Water Separation	In Progress
FLSH0026	Laramie, WY, Private wood treating site	Laramie	WY	Not Specified	Union Pacific Railroad	Not Specified	CH2M Hill	Pilot/Field Demonstration	PAH, carrier oils, (DNAPL, LNAPL), DNAPL 1.04 g/cm2 density and 54 Cp viscosity	Soil, Groundwater	Alkaline Agents, Polymer, Surfactants Mixture	Completed
FLSH0027	Lee Chemical, Liberty, MO	Liberty	MO	City of Liberty, MO	City of Liberty, MO	Missouri Department of Natural Resources	City of Liberty, MO	Full-Scale/Commercial	PCE, TCE, chlorinated solvents	Soil	Untreated Site Groundwater	In Progress
FLSH0028	Lipari Landfill, Pitman, NJ	Pitman	NJ	U.S. EPA	U.S. EPA	U.S. EPA	CDM Federal Programs Corporation	Full-Scale/Commercial	VOCs (benzene, ethylbenzene, TCE), SVOCs, PAHs, chorinated ethers (bis-2 choroethyl ether) (Superfund URL) Methylene chloride, chloroform, benzene, 1,2-dichloroethane, 4-methyl-2-pentanone, toluene, chlorobenzene, total xylenes, phenol, bis(2-chloroeth	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0071	Louisiana State University - Colloidal Gas Aphron from Naturally-Derived Surfactant	Baton Rouge	LA	NA (Lab Study)	Not Specified	NA (Lab Study)	Louisiana State University	Laboratory/Bench Scale	Hexachlorobenzene	Soil	Surfactant (Natural, prepared from dry fruits of Sapindus mukorossi plants in India	Completed
FLSH0029	Michigan State University - Surfactant Research and Soils Modification with Surfactants	East Lansing	MI	NA (Lab Studies)	ERL-Athens	NA (Lab Studies)	Michigan State University	Laboratory/Bench Scale	DDT, PCBs, PAHs	Soil	Cationic Surfactants	In Progress
FLSH0030	Montana Pole & Treating, Butte, MT	Butte	MT	Montana DEQ	Montana DEQ	Montana DEQ	Camp, Dresser, and McKee, Inc.	Full-Scale/Commercial	Pentachlorophenol (PCP), PAHs, LNAPL (diesel fuel 5% PCP)	Soil, Groundwater, LNAPL	Nutrients (Organic Fertilizers) in Treated Site Groundwater	In Progress
FLSH0070	National Tsing Hua University - Effects of Surfactants of Sorption/Micellar Solubilization	Hsinchu	TAIWAN	NA (Lab Study)	Not Specified	NA (Lab Study)	National Tsing Hua University	Laboratory/Bench Scale	Benzene, chlorobenzene, and styrene (BCS), cadmium	Soil, Water	Anionic Surfactant (Sodium Dodecyl Sulfate - SDS), Nonionic Surfactant (Trtion X-100), Cetyltrimethylammoniu Bromide (CTAB)	Completed
FLSH0060	National Water Res Inst, Env Canada - Humic Acid Flushing	Burlington	ON	NA (Lab Studies)	Environment Canada	NA (Lab Studies)	Environment Canada	Laboratory/Bench Scale	Petroleum source of BTEX, TPH, and PAHs	Soil, Groundwater	Humic Acid	Completed
FLSH0031	Ninth Avenue Dump, Gary, IN	Gary	IN	Monsanto	Monsanto	U.S. EPA	Fluor Daniel GTI	Full-Scale/Commercial	VOCs (BTEX, TCE), COD	Soil, Groundwater, LNAPL	Treated Site Groundwater	Completed
FLSH0040	OK Tool Area at Savage Well Site		NH	U.S. EPA	U.S. EPA	U.S. EPA	INEEL Duke Engineering & Services (former INTERA)	Pilot/Field Demonstration	PCE	Groundwater, NAPL	Surfactant	Scheduled
FLSH0032	Ormet Corp., Hannibal, OH	Hannibal	OH	Ormet Corporation	Ormet Corporation	U.S. EPA	Dames & Moore	Full-Scale/Commercial	Tetrachloroethylene, cyanide, fluoride, As, Sb, Be, Mn	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0033	Patuxent Naval Air Test Center	Patuxent	MD	NA (Lab Studies)	U.S Navy	NA (Lab Studies)	Battelle Columbus Labs	Laboratory/Bench Scale	JP-5 jet fuel	Soil	Surfactants and Emulsifiers	Completed
FLSH0034	Peak Oil Co./Bay Drum Co., Tampa, FL	Tampa	FL	Unical Corporation	Unical Corporation	U.S. EPA	DeMaximus, Inc.	Full-Scale/Commercial	BTEX, PAHs, PCE, As, Cr, Pb	Soil, Groundwater	Treated Site Groundwater (nutrient addition under consideration)	In Design
FLSH0065	Pearl Harbor	Pearl Harbor	HI	Not Specified	Not Specified	Not Specified	Duke Engineering & Services	Pilot/Field Demonstration	Petroleum hydrocarbons (Navy Specia Fuel Oil (NFSO), a highly viscous (2,000 to 3,000 cp) fuel oil.	Soil, Groundwater, NAPL	Surfactant (developed specifcally for project)	Scheduled
FLSH0067	Petroleum Company (Bulk Plant)		QC	Not Specified	Not Specified	Not Specified	GSI Environnement	Full-Scale/Commercial	BTEX, MOG	Soil	Surfactants	Completed
FLSH0068	Petroleum Company (Residentia Site Contamination)		QC	Not Specified	Not Specified	Not Specified	GSI Environnement	Full-Scale/Commercial	BTEX, MOG	Soil, NAPL	Surfactant	Completed
FLSH0035	Picatinny Arsenal, NJ	Picatinny Arsenal	NJ	U.S. Army	U.S. EPA ORD	U.S. EPA	University of Virginia	Pilot/Field Demonstration	TCE	Soil, Groundwater	Surfactant (Triton X-100)	Completed
FLSH0078	PPG Plant, Lake Charles, LA	Lake Charles	LA	Not Specified	Not Specified	Not Specified	SUNY - University at Buffalo	Pilot/Field Demonstration	DNAPL (Primarily Dichloroethane - EDC)	Soil, Groundwater, NAPL	Surfactant (Linear Alkylbenzene Sulfonate)	Completed

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FLSH0046	Purdue University - Phototransformations of PCBs in Micellar Solutions	West Lafayette	IN	NA (Lab Study)	Not Specified	NA (Lab Study)	Purdue University	Laboratory/Bench Scale	PCBs (Arochlor 1254) and the specific congener 2,3,4,5-tetrachlorobiphenyl (2,3,4,5-TeCB)		Surfactants	Completed
FLSH0036	Rasmussen's Dump, Brighton, MI	Brighton	MI	Law Offices	Law Offices	U.S. EPA	DeMaximus Inc.	Full-Scale/Commercial	VOCs (benzene, TCE, toluene, xylene, ketones, chlorinated hydrocarbons, vinyl chloride)	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0069	SEAR for LNAPL Mitigation in Capillary Fringe			Not Specified	Not Specified	Not Specified	Groundwater & Environmental Services, Inc.	Pilot/Field Demonstration	LNAPL	Soil, Groundwater, NAPL	Surfactants	Completed
FLSH0037	Serrener/Varisco Consortium, Canada	Drummondville	QC	Not Specified	Environment Canada	Not Specified	GSI Environnement	Pilot/Field Demonstration	BTEX, aliphatic hydrocarbons, mineral oil and grease (MOG)	Soil	Surfactants	Completed
FLSH0038	Sindelfingen, Germany	Sindelfingen	GERMANY	Not Specified	Not Specified	Not Specified	Not Specified	Full-Scale/Commercial	TCE	Soil, Groundwater	Water	Completed
FLSH0074	SW Tank Farm, Tinker Air Force Base, OK	Midwest City	OK	U.S. Air Force	U.S. DOE/Lockheed/MSE	Not Specified	Surbec Environmental Services	Pilot/Field Demonstration	Aromatic Hydrocarbons (BTEX), TPH, NAPL	Soil, Groundwater, NAPL	Surfactant	Completed
FLSH0041	Texas Eastern Transmission Facil. Delmont, PA	Delmont	PA	Texas Eastern Transmission Corporation	Texas Eastern Transmission Corporation	Pennsylvania DEP	S.S. Papadopolous & Associates, Inc.	Pilot/Field Demonstration	PCBs	Fractured Rock, Groundwater	Surfactants [ethoxylated alcohols (Witconol SN-70) and cocamidopropyl betaine (Mirataine BET C-30)]	Completed
FLSH0042	Thouin Sand Quarry, Quebec, CA	L'Assomption	QC	Thouin Sand Quarry	Environment Canada	Not Specified	Laval University	Pilot/Field Demonstration	Oil waste and chlorinated solvents in th form of DNAPL, density = 1.02, viscosity = 18 cp	Soil, Groundwater, DNAPL	Surfactant/Cosolvent Mixture (n-butan hostapur (SAS), d-Limonene)	Completed
FLSH0053	U.S. Air Force, Plant 4, Fort Worth, TX	Fort Worth	TX	U.S. Air Force	U.S. Air Force	Not Specified	Duke Engineering & Services (formerly INTERA)	Pilot/Field Demonstration	TCE DNAPL	Soil, Groundwater, DNAPL	Surfactants	In Progress
FLSH0051	U.S. Coast Guard, Traverse City MI	Traverse City	MI	U.S. Coast Guard	U.S. EPA ORD	Not Specified	University of Oklahoma	Pilot/Field Demonstration	PCE, TCE and recalcitrant jet fuel components	Soil, Groundwater	Surfactant (Dowfax 8390)	Completed
FLSH0054	U.S. DOE Gaseous Diffusion Plnt, Paducah, KY	Paducah	KY	U.S. DOE	U.S. DOE	U.S. EPA	Duke Engineering & Services (formerly INTERA)	Pilot/Field Demonstration	TCE (DNAPL)	Soil, Groundwater, DNAPL	Surfactant (sorbitan monooleate approved for use as a food-grade additive by the U.S. FDA)	Completed
FLSH0075	U.S. DOE Paducah Gaseous Diffusion Plant	Paducah	KY	U.S. DOE	U.S. DOE/Lockheed/CH2M Hill	Not Specified	Surbec Environmental Services	Laboratory/Bench Scale	DNAPL		Surfactant and Surfactant/Cosolvent Screening	In Progress
FLSH0008	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, OH	Piketon	OH	U.S. DOE	U.S. DOE	Not Specified	Duke Engineering & Services (formerly INTERA)	Pilot/Field Demonstration	DNAPLs, TCE with some PCBs and other chlorinated solvents	Soil, Groundwater, DNAPL	Surfactant (4 wt% sodium dihexyl sulfosuccinate)/cosolvent (4 wt% isopropyl alcohol)/electrolyte (2 wt% 1: NaCl and CaCL2)	Completed
FLSH0043	Umatilla Army Depot (Lagoons), Hermiston, OR	Hermiston	OR	Umatilla Chemical Depot	Umatilla Chemical Depot	U.S. EPA	U.S. Army Corp of Engineers, Seattle Distric	Full-Scale/Commercial	Explosives- TNT, RDX, TNB, HMX	Soil, Groundwater	Treated Site Groundwater	In Progress
FLSH0044	United Chrome Products, Corvallis, OR	Corvallis	OR	United Chrome Products	United Chrome Products	Not Specified	CH2M Hill	Pilot/Field Demonstration	Hexavalent chromium (Cr+6)	Soil, Groundwater	City-Supplied Water	In Progress
FLSH0083	University of Arizona - HC Solubilzation and Mobilization by Biosurfactant	Tucson	AZ	NA (Lab Study)	Not Specified	NA (Lab Study)	University of Arizona	Laboratory/Bench Scale	Hexadecane	Soil, NAPL	Biosurfactant (rhamnolipid solution), with Na+, Mg2+, and Ca2+	Completed
FLSH0082	University of Florida - Two-Dimensional Flow Experiments and Simulations	Gainesville	FL	NA (Lab Study)	Not Specified	NA (Lab Study)	University of Florida	Laboratory/Bench Scale	None	Lab Study - Clean Soil	Cosolvent	Completed
FLSH0081	University of Illinois - Impact of Surfactant of Configuration of HC Lens	Carbondale	IL	NA (Lab Study)	Not Specified	NA (Lab Study)	University of Illinois at Carbondale	Laboratory/Bench Scale	Gasoline (BTEX, petroleum hydrocarbons)	Soil, Groundwater, NAPL	Surfactant	Completed
FLSH0052	University of Michigan - Partitioning Characteristics of PAHs	Ann Arbor	MI	NA (Lab Studies)	Not Specified	NA (Lab Studies)	Not Specified	Laboratory/Bench Scale	PAHs, such as phenanthrene	Soil	None	In Progress
FLSH0045	University of Michigan - Surfactant Remediation of NAPL-Contaminated Aquifers	Ann Arbor	MI	NA (Lab Studies)	Not Specified	NA (Lab Studies)	University of Michigan	Laboratory/Bench Scale	NAPLs (VOCs, dodecane, PCE, o-DCB)	Soil, Groundater, NAPL	Surfactants	In Progress
FLSH0079	University of North Carolina - Bank Formation in Surfactant Remediation of DNAPL	Chapel Hill	NC	Not Specified	Not Specified	Not Specified	University of North Carolina	Laboratory/Bench Scale	Tetrachloroethylene	NAPL	1:! Mixture of 2 Food-Grade Anionic Surfactants (Sodium Diamyl Sulfosuccinate (Aerosol AY) and Sodium Dioctyl Sulfosuccinate (Aeroso OT))	Completed
FLSH0080	University of Oklahoma - Remediation of Chlorinated Solvents Using Edible Surfactancts	Norman	OK	NA (Lab Study)	Not Specified	NA (Lab Study)	University of Oklahoma	Laboratory/Bench Scale	Chlorinated solvents (PCE, TCE, and trans 1,2-DCE)	Soil, Groundwater	FDA direct food additive status surfactants	Completed
FLSH0076	UST Site, Shawnee, OK	Shawnee	OK	National Science Foundation	NSF/SBIR	Not Specified	Surbec Environmental Services	Pilot/Field Demonstration	BTEX, TPH	Soil, Groundwater	Surfactant	Completed

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FLSH0048	Vineland Chemical, Vineland, NJ	Vineland	NJ	Vineland Chemical	Vineland Chemical	U.S. EPA	Not Specified	Full-Scale/Commercial	As, VOCs (dichloromethane)	Soil, Groundwater	Treated Site Groundwater	Scheduled
FLSH0049	Volk Air National Guard Base, WI	Camp Douglas	WI	Volk Air National Guard	U.S. Air Force	Not Specified	U.S EPA	Pilot/Field Demonstration	Hydrocarbons, chlorinated hydrocarbons (dichloromethane, chloroform, 1,1,1-trichloroethane (TCA), trichloroethylene (TCE))	Soil	Surfactants ((Adsee 799 and Hyonic PE-90)	Completed

Table 2. *In Situ* Flushing - Distribution of Case Studies by U.S. State, Canadian Province or Country (Pilot/Field and Full Scale/Commercial Projects Only; This Table Excludes Laboratory/Bench-Scale Projects) Total Number of Case Studies = 64

U.S. State, Canadian Province or Country	Number of Studies
Utah	9
New Jersey	7
Florida	6
Quebec	6
Delaware	5
Michigan	3
Ohio	3
North Carolina	2
Oklahoma	2
Oregon	2
Texas	2
Germany	1
Hawaii	1
Illinois	1
Indiana	1
Kentucky	1
Louisiana	1
Missouri	1
Montana	1
New Hampshire	1
NewYork	1
Ontario	1
Pennsylvania	1
Tennessee	1
Virginia	1
Wisconsin	1
Wyoming	1

Table 3 In Situ Flushing - Geology of Treatment Zone / Size of Contaminated Zone or Test Area Size (Pilot/Field Demos and Full-Scale/Commercial Projects Only; this Table Excludes Lab/Bench-Scale Projects)

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Geology of Main Target Treatment Zone	Geology of Target Treatment Zone Clarification	Volume of Contaminated Soil (Vadose Zone)	Maximum Areal Extent of Main Ground-water Contaminant Plume	Pore Volume Contained in Main Ground-water Contaminant Plume	Scale of Project
FLSH0066	Aluminum Company Site	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Heterogeneous, silty backfill	1,000 m3 (about 1,300 yd3)			Full-Scale/Commercial
FLSH0002	Bog Creek Farm, Howell Township, NJ	Unspecified					Full-Scale/Commercial
FLSH0039	Camp Lejeune	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Fine to very fine sand underlain by clay aquitard			4,800 gallon swept pore volume in test zone (contained 87 gal DNAPL before SEAR)	Pilot/Field Demonstration
FLSH0003	Canadian AFB Borden, Alliston, Ontario, Canada	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Unconsolidated sand aquifer, St. Lawrence Lowlands - beach sand deposit underlain by glacial till		9.8 x 9.8 foot (96 ft2) test cell	2,400 gallons	Pilot/Field Demonstration
FLSH0047	Cape Canaveral Lodge Complex 34	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Barrier island sediments		50 x 75 foot test area		Pilot/Field Demonstration
FLSH0004	Chem-Dyne, Hamilton, OH	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained					Full-Scale/Commercial
FLSH0077	Coast Guard Facility, Elizabeth City, NC	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0020	Confidential	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Coastal Plain - The Surfical Aquifer (silty fine sand)				Full-Scale/Commercial
FLSH0005	Cornell University - Surfactant Enhance Biodegradation	Unconsol. Seds. - Predom. Clay/Silt					Laboratory/Bench Scale
FLSH0006	Corpus Christi Dupont, Corpus Christi, TX	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Gulf Coast, well-sorted fine sand interbedded with clay		25 x 35 foot (875 ft2) test area		Pilot/Field Demonstration
FLSH0007	Cross Brothers Pail, Pembroke, IL	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Very well sorted fine-grained sand underlain by clay confining layer at 45-50 feet bgs	4 to 6 acre extent source area			Full-Scale/Commercial
FLSH0062	Dover AFB, Dover, DE (Cosolvent Mobilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Lynch Heights and Columbia Fms. unconfined aquifer - silty, poorly sorted sands, potential for discontinuous clay lenses and gravely sand lenses				Pilot/Field Demonstration
FLSH0063	Dover AFB, Dover, DE (Macromolecular Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Lynch Heights and Columbia Fms. unconfined aquifer - silty, poorly sorted sands, potential for discontinuous clay lenses and gravely sand lenses				Pilot/Field Demonstration
FLSH0064	Dover AFB, Dover, DE (Single-phase Microemulsion)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Lynch Heights and Columbia Fms. unconfined aquifer - silty, poorly sorted sands, potential for discontinuous clay lenses and gravely sand lenses				Pilot/Field Demonstration
FLSH0061	Dover AFB, Dover, DE (Test Cell 2, Surfactant Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Lynch Heights and Columbia Fms. unconfined aquifer - silty, poorly sorted sands, potential for discontinuous clay lenses and gravely sand lenses				Pilot/Field Demonstration

Table 3 In Situ Flushing - Geology of Treatment Zone / Size of Contaminated Zone or Test Area Size (Pilot/Field Demos and Full-Scale/Commercial Projects Only; this Table Excludes Lab/Bench-Scale Projects)

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Geology of Main Target Treatment Zone	Geology of Target Treatment Zone Clarification	Volume of Contaminated Soil (Vadose Zone)	Maximum Areal Extent of Main Ground-water Contaminant Plume	Pore Volume Contained in Main Ground-water Contaminant Plume	Scale of Project
FLSH0009	Dover AFB, Dover, DE (Test Cell 3, Cosolvent Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Lynch Heights and Columbia Fms. unconfined aquifer - silty, poorly sorted sands, potential for discontinuous clay lenses and gravely sand lenses				Pilot/Field Demonstration
FLSH0010	Eckenfelder, Inc. - Surfactant Recycling	Unspecified	Lab study - soil test bed				Pilot/Field Demonstration
FLSH0073	Envirogen - Effects of Emulsion Viscosity	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0072	Envirogen - Surfactant Foam/Bioaugmentation	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0011	Estrie Region Machine Shop, Quebec, CA	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	St. Lawrence Lowlands - Fine sand with 10-12% silt	1,800 m3 (about 63,575 ft2)			Full-Scale/Commercial
FLSH0021	Former Dry Cleaning Facilty, Jacksonville, FL	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Sandy alluvium				Pilot/Field Demonstration
FLSH0059	Fredricksburg, VA Wood Treating SIte	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Clay-silt alluvium, cresote perched on clay lenses				Pilot/Field Demonstration
FLSH0012	General Motors NAO Research & Development Center, Warren, MI	Unconsol. Seds. - Interbedded Sediments	Central Glaciated Plains - 10 to 13 feet of sandy fill overlying fine-grained alluvial and sandy glacial outwash	10 foot diameter x 5 foot deep test plot			Pilot/Field Demonstration
FLSH0084	Georessources - Aquifer Washing by Micellar Solutions	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0013	GHEA Associates, New Jersey Operating Facilty of Major U.S. Corporation	Unconsol. Seds. - Predom. Clay/Silt	Clayey soils				Pilot/Field Demonstration
FLSH0014	Goose Farm, Plumsted Twp, NJ	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Coastal Plain - Kirkwood Aquifer				Full-Scale/Commercial
FLSH0050	Gulf Power - Lynn Haven, FL	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Coastal Plain - The Surfical Aquifer (silty fine sand)				Full-Scale/Commercial
FLSH0058	Hialeah County, FL	Bedrock - Carbonate - Karst	SE Coastal Plain Cly org rich sand over solution cavity limestone				Pilot/Field Demonstration
FLSH0056	Hill Air Force Base (Cell 4, OU 1 - Cyclodextrin Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft) or about 160 ft2 test cell	1,000 to 2,500 gallons	Pilot/Field Demonstration
FLSH0055	Hill Air Force Base (OU 2 - Foam Flood)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay				Pilot/Field Demonstration
FLSH0057	Hill Air Force Base (OU2 1/5 Full Scale Surfactant Flood)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay				Full-Scale/Commercial
FLSH0015	Hill Air Force Base, UT (Cell 3, OU1 - Cosolvent Mobilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin- Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft or about 160 ft2) test cell	1,500 gallons	Pilot/Field Demonstration
FLSH0016	Hill Air Force Base, UT (Cell 5, OU1 - Surfactant Mobilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft or about 160 ft2) test cell	1,500 to 2,500 gallons	Pilot/Field Demonstration
FLSH0017	Hill Air Force Base, UT (Cell 6, OU1 - Surfactant Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft or about 160 ft2) test cell		Pilot/Field Demonstration

Table 3 In Situ Flushing - Geology of Treatment Zone / Size of Contaminated Zone or Test Area Size (Pilot/Field Demos and Full-Scale/Commercial Projects Only; this Table Excludes Lab/Bench-Scale Projects)

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Geology of Main Target Treatment Zone	Geology of Target Treatment Zone Clarification	Volume of Contaminated Soil (Vadose Zone)	Maximum Areal Extent of Main Ground-water Contaminant Plume	Pore Volume Contained in Main Ground-water Contaminant Plume	Scale of Project
FLSH0018	Hill Air Force Base, UT (Cell 8, OU1 - Surfactant/Cosolvent Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft or about 160 ft2) test cell	1,000 to 2,500 gallons	Pilot/Field Demonstration
FLSH0019	Hill Air Force Base, UT (OU2 - Micellar Flood)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		6 x 9 m (19.7 x 29.5 ft o about 580 ft2) test area	15,000 gallons	Pilot/Field Demonstration
FLSH0022	Hill Air Force Base, UT (Test1, OU1 - Cosolvent Solubilization)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Great Basin - Poorly sorted alluvial sand and gravel underlain by lacustrian clay		3 x 5 m (9.8 x 16.4 ft or about 160 ft2) test cell	4,000 L (about 1,057 gal)	Pilot/Field Demonstration
FLSH0023	Hooker Chemical/Ruco Polymer, NY	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Upper Glacial Formation				Full-Scale/Commercial
FLSH0024	Howard University, Washington, DC - Treatment of PCBs with Surfactants	Unspecified	Lab study				Laboratory/Bench Scale
FLSH0025	JADCO-Hughes, Belmont, NC	Unspecified					Pilot/Field Demonstration
FLSH0001	Koppers Co. Inc., Seaboard Plant, Kearny, NJ	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Fill unit				Pilot/Field Demonstration
FLSH0026	Laramie, WY, Private wood treating site	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Graduated from fine sands, silts and clays at surface to coarse sands and fine gravels at base	>500,000 yd3 total (27 x 27 f test cell and 130 x 130 ft test cell)	(27 x 27 ft (729 ft2) test cell and 130 x 130 ft (16,900 ft2) test cell)	5,000 gallons within 27 x 27 ft test cell	Pilot/Field Demonstration
FLSH0027	Lee Chemical, Liberty, MO	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Missouri River bottom alluvial sediments				Full-Scale/Commercial
FLSH0028	Lipari Landfill, Pitman, NJ	Unspecified	Cohansey Aquifer				Full-Scale/Commercial
FLSH0071	Louisiana State University - Colloidal Gas Aphron from Naturally-Derived Surfactant	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0029	Michigan State University - Surfactant Research and Soils Modification with Surfactants	Unspecified	Lab studies				Laboratory/Bench Scale
FLSH0030	Montana Pole & Treating, Butte MT	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Sandy alluvial material	200,000 yd3 total site (50,000 to 60,000 yd3 may be remediated via in situ flushing)			Full-Scale/Commercial
FLSH0070	National Tsing Hua University - Effects of Surfactants of Sorption/Micellar Solubilization	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0060	National Water Res Inst, Env Canada - Humic Acid Flushing	Unspecified	Medium to coarse-grained sand				Laboratory/Bench Scale
FLSH0031	Ninth Avenue Dump, Gary, IN	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Sand/waste (Mostly sand but mixed with debris (timbers, etc.). Originally was wetland (Dune and Swale) formation particular to northern Indiana				Full-Scale/Commercial

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FLSH0040	OK Tool Area at Savage Well Site	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Outwash plain overlying metamorphic bedrock (at 100 foot depth) No true confining layer present.		Dissolved plume is approx. 1 mile in length		Pilot/Field Demonstration
FLSH0032	Ormet Corp., Hannibal, OH	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Fairly porous, well-sorted sand with some silt.				Full-Scale/Commercial
FLSH0033	Patuxent Naval Air Test Center	Unspecified	Lab study				Laboratory/Bench Scale
FLSH0034	Peak Oil Co./Bay Drum Co., Tampa, FL	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Silty sand				Full-Scale/Commercial
FLSH0065	Pearl Harbor	Unspecified				Est. 580 gallons	Pilot/Field Demonstration
FLSH0067	Petroleium Company (Bulk Plant)	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Sand with boulders	9,000 m3 (about 11,800 yd3)			Full-Scale/Commercial
FLSH0068	Petroleum Company (Residential Site Contamination)	Unconsol. Seds. - Predom. Clay/Silt	Organic soil (peat moss)	1,000 m3 (about 1,300 yd3)			Full-Scale/Commercial
FLSH0035	Picatinny Arsenal, NJ	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Atlantic Coastal Plain - Sand and gravel aquifer, confining later at 60 feet bgs		20 x 60 feet (1200 ft2) treatment area		Pilot/Field Demonstration
FLSH0078	PPG Plant, Lake Charles, LA	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	"10 ft sand" - within Interbedded Clays and Thin Sands (Beaumont or Prarie Formation)			1,250 gallons = two "effective pore volumes"	Pilot/Field Demonstration
FLSH0046	Purdue University - Phototransformations of PCBs in Micellar Solutions	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0036	Rasmussen's Dump, Brighton, MI	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Sand and gravel		Areal extent of infiltration galleries two acres		Full-Scale/Commercial
FLSH0069	SEAR for LNAPL Mitigation in Capillary Fringe	Unspecified					Pilot/Field Demonstration
FLSH0037	Serrener/Varisco Consortium, CA	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Low permeability till covered with a 1 m (about 3.3 ft) thick layer of fill (granular material in silty matrix). Bedrock is about 3 m (about 9.8 ft) deep.		Study area 520 m3 (approx. 680 yd3)		Pilot/Field Demonstration
FLSH0038	Sindelfingen, Germany	Unspecified					Full-Scale/Commercial
FLSH0074	SW Tank Farm, Tinker Air Force Base, OK	Unspecified					Pilot/Field Demonstration
FLSH0041	Texas Eastern Transmission Facility, Delmont, PA	Bedrock - Sandstone - Highly Fractured	Fractured and weathered bedrock. (Interbedded sandstone, shale, clay, limestone, and coal of the Pennsylvanian age Conemaugh Group)				Pilot/Field Demonstration
FLSH0042	Thouin Sand Quarry, Quebec, CA	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	St. Lawrence Lowlands - 2 m silty sand over 30 m clay			6 m3 (212 ft3 or 1585 gal)	Pilot/Field Demonstration
FLSH0053	U.S. Air Force Plant 4, Fort Worth, TX		Central nonglaciated plains				Pilot/Field Demonstration
FLSH0051	U.S. Coast Guard, Traverse City, MI	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel					Pilot/Field Demonstration

Table 3 In Situ Flushing - Geology of Treatment Zone / Size of Contaminated Zone or Test Area Size (Pilot/Field Demos and Full-Scale/Commercial Projects Only; this Table Excludes Lab/Bench-Scale Projects)

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Geology of Main Target Treatment Zone	Geology of Target Treatment Zone Clarification	Volume of Contaminated Soil (Vadose Zone)	Maximum Areal Extent of Main Ground-water Contaminant Plume	Pore Volume Contained in Main Ground-water Contaminant Plume	Scale of Project
FLSH0054	U.S. DOE Gaseous Diffusion Plnt, Paducah, KY	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Appalachian Plateau Gravelly Fine to Medium Sand				Pilot/Field Demonstration
FLSH0075	U.S. DOE Paducah Gaseous Diffusion Plant	Unspecified					Laboratory/Bench Scale
FLSH0008	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, OH	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Nonglaciated Central Plain - Basal alluvial gravel (Gallia Formation)		16.4 x 6.6 feet (108 ft2)	3,700 gallons	Pilot/Field Demonstration
FLSH0043	Umatilla Army Depot (Lagoons), Hermiston, OR	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Sandy alluvium w/ low organic content overlying solid basalt confining layer	48,400 yd3	350 acres		Full-Scale/Commercial
FLSH0044	United Chrome Products, Corvallis, OR	Unconsol. Seds. - Predom. Clay/Silt	Upper water-bear zone (silt), over silty clay			2.6 MM gallons	Pilot/Field Demonstration
FLSH0083	University of Arizona - HC Solubilzation and Mobilization by Biosurfactant	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0082	University of Florida - Two-Dimensional Flow Experiments and Simulations	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0081	University of Illinois - Impact of Surfactant of Configuration of HC Lens	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0052	University of Michigan	Unspecified					Laboratory/Bench Scale
FLSH0045	University of Michigan - Surfactant Remediation of NAPL-Contaminated Aquifers	Unspecified					Laboratory/Bench Scale
FLSH0079	University of North Carolina - Bank Formation in Surfactant Remediation of DNAPL	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0080	University of Oklahoma - Remediation of Chlorinated Solvents Using Edible Surfactancts	Unspecified	NA (Lab Study)				Laboratory/Bench Scale
FLSH0076	UST Site, Shawnee, OK	Unspecified					Pilot/Field Demonstration
FLSH0048	Vineland Chemical, Vineland, NJ	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Medium to fine sand with low organic content	126,000 yd3			Full-Scale/Commercial
FLSH0049	Volk Air National Guard Base, WI	Unspecified	Sand (Soil beneath fire training pit)				Pilot/Field Demonstration

Table 4 In Situ Flushing - Recovered Contaminant Mass / Economic Information Available
Total Number of Case Studies = 84

GWRTAC ID	Project Name	Reported Contaminant Mass Recovered	Reported Fraction of Inital Mass Recovered	Economic Information	Scale of Project
FLSH0066	Aluminum Company Site			Total project cost +/- $300,000. (Canadian) over one year duration.	Full-Scale/Commercial
FLSH0002	Bog Creek Farm, Howell Township, NJ	Project is in Progress; Mass Removed not yet Evaluated Though Groundwater Contaminant Concentrations are Decreasing.	Project is in Progress		Full-Scale/Commercial
FLSH0039	Camp Lejeune	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0003	Canadian AFB Borden, Alliston, Ontario, Canada	Well Purging = 47 L (~12.4 gal), Waterflooding = 2.3 L (~0.6 gal), Chemical Flood = 63.43 L (~16.8 gal), Post-Waterflood = 3.44 L (~0.9 gal)	Well Purging and Waterflooding 31%, Purging, Waterflooding plus Chemical Flood 72%, Fraction of Post-Waterflood Residual 40%	No estimated full-scale cost was developed.	Pilot/Field Demonstration
FLSH0047	Cape Canaveral Lodge Complex 34	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0004	Chem-Dyne, Hamilton, OH			Re-injection was discontinued due to the high cost of filtering groundwater prior to re-injection.	Full-Scale/Commercial
FLSH0077	Coast Guard Facility, Elizabeth City, NC				Laboratory/Bench Scale
FLSH0020	Confidential	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0005	Cornell University - Surfactant Enhance Biodegradation				Laboratory/Bench Scale
FLSH0006	Corpus Christi Dupont, Corpus Christi, TX	283 L (Approximately 75 Gallons) Carbon Tetrachloride (CTET)	No Estimates of Initial Mass Available.	DNAPL removal progressed at a rate more rapid than would be expected with standard pump and treat technology, based on analysis of three monitoring well nests within the DNAPL source area. It was concluded that although initial capital costs would be gre	Pilot/Field Demonstration
FLSH0007	Cross Brothers Pail, Pembroke, IL	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0062	Dover AFB, Dover, DE (Cosolvent Mobilization)	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0063	Dover AFB, Dover, DE (Macromolecular Solubilization)	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0064	Dover AFB, Dover, DE (Single-phase Microemulsion)	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0061	Dover AFB, Dover, DE (Test Cell 2, Surfactant Solubilization)	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration

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GWRTAC ID	Project Name	Reported Contaminant Mass Recovered	Reported Fraction of Inital Mass Recovered	Economic Information	Scale of Project
FLSH0009	Dover AFB, Dover, DE (Test Cell 3, Cosolvent Solubilization)	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0010	Eckenfelder, Inc. - Surfactant Recycling	92 mg/Kg Reduced to 1 mg/Kg Biphenyl	90% Volume Reduction Even Without System Optimization		Pilot/Field Demonstration
FLSH0073	Envirogen - Effects of Emulsion Viscosity				Laboratory/Bench Scale
FLSH0072	Envirogen - Surfactant Foam/Bioaugmentation		Foam Injection Flushed 75% of TCE Through Sand Column; Microbe Addition Resulted in 95-99% Degradation of Residual TCE.		Laboratory/Bench Scale
FLSH0011	Estrie Region Machine Shop, Quebec, CA	Combined Water and Chemical Flood = 160,000 Kg	Estimate of Intital Mass not Available	Total project cost +/- $1,200,000. (Canadian) over one year duration.	Full-Scale/Commercial
FLSH0021	Former Dry Cleaning Facilty, Jacksonville, FL	Project is in Progress	Project is in Progress		Pilot/Field Demonstration
FLSH0059	Fredricksburg, VA Wood Treating SIte	Significant Volumes of Fluid were not Produced	Slow Injection Limiited Delivery Resulting in Test Discontinuation		Pilot/Field Demonstration
FLSH0012	General Motors NAO Research & Development Center, Warren, MI	1.6 Kg PCB and 16.9 Kg "Oil"	11% PCB and 11% "Oil"	Estimated full-scale cost not available.	Pilot/Field Demonstration
FLSH0084	Georessources - Aquifer Washing by Micellar Solutions		Up to 95% of Mercier DNAPL recovered in laboratory sand columns		Laboratory/Bench Scale
FLSH0013	GHEA Associates, New Jersey Operating Facilty of Major U.S. Corporation	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0014	Goose Farm, Plumsted Twp, NJ	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0050	Gulf Power - Lynn Haven, FL	Project is in Progress; Minimum 42 Pounds Arsenic Removed	Project is in Progress		Full-Scale/Commercial
FLSH0058	Hialeah County, FL	Waterflooding = 240 L (Approximately 63 Gallons), Chemical Floods = 550 L (Approximately 145 Gallons)	20% Waterflooding, Additional 45% Chemical Flooding	The pilot was not expanded to the entire 40,000 ft3 area for a variety of reasons. A management change, a cost and benefit analysis to remove a nonhazardous oil, and the location of the contaminate under a functioning structure made expansion difficult.	Pilot/Field Demonstration
FLSH0056	Hill Air Force Base (Cell 4, OU 1 - Cyclodextrin Solubilization)	Project is in Progress	Project is in Progress		Pilot/Field Demonstration
FLSH0055	Hill Air Force Base (OU 2 - Foam Flood)	36.5 Gallons DNAPL (An Amount Greater than Initial Volume Estimate; Concluded Additional DNAPL Entered Test Area)	89% Reduction in DNAPL		Pilot/Field Demonstration
FLSH0057	Hill Air Force Base (OU2 1/5 Full Scale Surfactant Flood)	Project not yet Begun	Project not yet Begun		Full-Scale/Commercial

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FLSH0015	Hill Air Force Base, UT (Cell 3, OU1 - Cosolvent Mobilization)		80% Total NAPL Content Removed from Test Cell (>90% of More Soluble Contaminants and 70-80% of Less Soluble Compounds		Pilot/Field Demonstration
FLSH0016	Hill Air Force Base, UT (Cell 5, OU1 - Surfactant Mobilization)				Pilot/Field Demonstration
FLSH0017	Hill Air Force Base, UT (Cell 6, OU1 - Surfactant Solubilization)				Pilot/Field Demonstration
FLSH0018	Hill Air Force Base, UT (Cell 8, OU1 - Surfactant/Cosolvent Solubilization)	Approximately 350 L (92 gallons)	72% NAPL (Based on Tracer Test), 64-96% (Based on Core Estimates), 62-82% (Based on Mass Balance)		Pilot/Field Demonstration
FLSH0019	Hill Air Force Base, UT (OU2 - Micellar Flood)	341 Gallons, Based on PITT	99%	Thus, over the course of a few months, at a cost of about $3,000/gallon, 98.5% of the residual DNAPL was removed. This can be compared with the original USAF estimate for cleanup of the DNAPL that used the traditional time frame of 30 years with a cost o	Pilot/Field Demonstration
FLSH0022	Hill Air Force Base, UT (Test1, OU1 - Cosolvent Solubilization)	Approximately 350 L (92 Gallons) NAPL	>85% Cell-Wide Basis, >95% in Central Flood Zone, >75% in Bottom 0.5 m		Pilot/Field Demonstration
FLSH0023	Hooker Chemical/Ruco Polymer, NY	Project not yet Begun	Project not yet Begun		Full-Scale/Commercial
FLSH0024	Howard University, Washington, DC - Treatment of PCBs with Surfactants	Project is in Progress	Project is in Progress		Laboratory/Bench Scale
FLSH0025	JADCO-Hughes, Belmont, NC	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0001	Koppers Co. Inc., Seaboard Plant, Kearny, NJ	Project is in Progress; During First 3 Months of Operation, Over 11,000 Gallons DNAPL Collected	Project is in Progress		Pilot/Field Demonstration
FLSH0026	Laramie, WY, Private wood treating site	1,900 Gallons PAH-Contaminated Oil Removed from 27x27' Test Cell; 23,600 Gallons Oil were Produced from 130x130' Test Cell	94% Reduction in Oil Concentration (27x27' Test Cell)	Full-scale applications of the chemically enhanced recovery technique would require an extensive piping network and large amounts of fluids and chemicals. Based on extrapolation from the 1989 pilot test, full-scale in situ soil flushing would require more	Pilot/Field Demonstration
FLSH0027	Lee Chemical, Liberty, MO	Project is in Progress; Performance Results not yet Available	Project is in Progress; Performance Results not yet Available		Full-Scale/Commercial
FLSH0028	Lipari Landfill, Pitman, NJ	Project is in Progress; Performance Results not yet Available	Project is in Progress; Performance Results not yet Available		Full-Scale/Commercial

Table 4 In Situ Flushing - Recovered Contaminant Mass / Economic Information Available
Total Number of Case Studies = 84

GWRTAC ID	Project Name	Reported Contaminant Mass Recovered	Reported Fraction of Inital Mass Recovered	Economic Information	Scale of Project
FLSH0071	Louisiana State University - Colloidal Gas Aphron from Naturally-Derived Surfactant		Desorption of up to 90% total hexachlorobenzene		Laboratory/Bench Scale
FLSH0029	Michigan State University - Surfactant Research and Soils Modification with Surfactants	Project is in Progress	Project is in Progress		Laboratory/Bench Scale
FLSH0030	Montana Pole & Treating, Butte, MT	Project is in Progress; Performance Results not yet Available	Project is in Progress; Performance Results not yet Available		Full-Scale/Commercial
FLSH0070	National Tsing Hua University - Effects of Surfactants of Sorption/Micellar Solubilization				Laboratory/Bench Scale
FLSH0060	National Water Res Inst, Env Canada - Humic Acid Flushing				Laboratory/Bench Scale
FLSH0031	Ninth Avenue Dump, Gary, IN				Full-Scale/Commercial
FLSH0040	OK Tool Area at Savage Well Site	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0032	Ormet Corp., Hannibal, OH	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0033	Patuxent Naval Air Test Center				Laboratory/Bench Scale
FLSH0034	Peak Oil Co./Bay Drum Co., Tampa, FL	Project not yet Begun	Project not yet Begun		Full-Scale/Commercial
FLSH0065	Pearl Harbor	Project not yet Begun	Project not yet Begun		Pilot/Field Demonstration
FLSH0067	Petroleium Company (Bulk Plant)			Total project cost +/- $300,000. (Canadian) over four month duration.	Full-Scale/Commercial
FLSH0068	Petroleum Company (Residential Site Contamination)			Total project cost +/- $300,000. (Canadian) over one year duration.	Full-Scale/Commercial
FLSH0035	Picatinny Arsenal, NJ				Pilot/Field Demonstration
FLSH0078	PPG Plant, Lake Charles, LA				Pilot/Field Demonstration
FLSH0046	Purdue University - Phototransformations of PCBs in Micellar Solutions				Laboratory/Bench Scale
FLSH0036	Rasmussen's Dump, Brighton, MI	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0069	SEAR for LNAPL Mitigation in Capillary Fringe				Pilot/Field Demonstration
FLSH0037	Serrener/Varisco Consortium, CA			Total project cost +/- $1,073,736. (Canadian).	Pilot/Field Demonstration

Table 4 In Situ Flushing - Recovered Contaminant Mass / Economic Information Available
Total Number of Case Studies = 84

GWRTAC ID	Project Name	Reported Contaminant Mass Recovered	Reported Fraction of Inital Mass Recovered	Economic Information	Scale of Project
FLSH0038	Sindelfingen, Germany	Within 18 Months After TCE Spill, 17 Metric Tons of Chlorinated Hydrocarbons were Recovered	Initial Mass Estimates not Available from Source		Full-Scale/Commercial
FLSH0074	SW Tank Farm, Tinker Air Force Base, OK				Pilot/Field Demonstration
FLSH0041	Texas Eastern Transmission Facility, Delmont, PA	0.32 Kg PCBs	Unknown	At present, no plans exist for further surfactant flushing at the site. Instead, recovery and treatment of PCBs at the spring is planned. The limiting factor controlling the duration of the surfactant injections presented above was the ability to effect	Pilot/Field Demonstration
FLSH0042	Thouin Sand Quarry, Quebec, CA	992 Kg DNAPL	86% Residual DNAPL		Pilot/Field Demonstration
FLSH0053	U.S. Air Force Plant 4, Fort Worth, TX	Project is in Progress; Surfactants may or may not be Applicable	Project is in Progress; Surfactants may or may not be Applicable		Pilot/Field Demonstration
FLSH0051	U.S. Coast Guard, Traverse City, MI	3.354 gm PCE Total, 2.757 gm PCE Through Surfactant-Enhanced Solubilization	Intial Mass not Known		Pilot/Field Demonstration
FLSH0054	U.S. DOE Gaseous Diffusion Plnt, Paducah, KY	No Increase in TCE Concentration was Achieved	No Increase in TCE Concentration was Achieved		Pilot/Field Demonstration
FLSH0075	U.S. DOE Paducah Gaseous Diffusion Plant				Laboratory/Bench Scale
FLSH0008	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, OH	20 to 40 L (Approximately 5.to 10 Gallons) DNAPL	Approximately 50% of Original DNAPL	No estimated full-scale cost was available.	Pilot/Field Demonstration
FLSH0043	Umatilla Army Depot (Lagoons), Hermiston, OR	Project is in Progress	Project is in Progress		Full-Scale/Commercial
FLSH0044	United Chrome Products, Corvallis, OR	Project is in Progress; Over 3 Years, 9.7 MM Gallons of Impacted Groundwater Containing 26,732 lbs. of Cr+6 have been Removed	Project is in Progress	Cost estimates indicate that treatment costs were estimated at $40/lb of Cr+6 removed for the first 25,000 lbs. As Cr+6 concentrations drop in later phases of operation, it is estimated that costs will double to $80/lb of Cr+6 removed.	Pilot/Field Demonstration
FLSH0083	University of Arizona - HC Solubilzation and Mobilization by Biosurfactant		58% of Residual NAPL (Hexadecane) Removed Within Three Pore Volumes From Laboratory Sand Columns		Laboratory/Bench Scale
FLSH0082	University of Florida - Two-Dimensional Flow Experiments and Simulations				Laboratory/Bench Scale
FLSH0081	University of Illinois - Impact of Surfactant of Configuration of HC Lens				Laboratory/Bench Scale
FLSH0052	University of Michigan	Project is in Progress	Project is in Progress		Laboratory/Bench Scale

Table 4 In Situ Flushing - Recovered Contaminant Mass / Economic Information Available
Total Number of Case Studies = 84

GWRTAC ID	Project Name	Reported Contaminant Mass Recovered	Reported Fraction of Inital Mass Recovered	Economic Information	Scale of Project
FLSH0045	University of Michigan - Surfactant Remediation of NAPL-Contaminated Aquifers	Project is in Progress	Project is in Progress		Laboratory/Bench Scale
FLSH0079	University of North Carolina - Bank Formation in Surfactant Remediation of DNAPL				Laboratory/Bench Scale
FLSH0080	University of Oklahoma - Remediation of Chlorinated Solvents Using Edible Surfactancts				Laboratory/Bench Scale
FLSH0076	UST Site, Shawnee, OK				Pilot/Field Demonstration
FLSH0048	Vineland Chemical, Vineland, NJ	Project not yet Begun	Project not yet Begun		Full-Scale/Commercial
FLSH0049	Volk Air National Guard Base, WI				Pilot/Field Demonstration

Figure 1. Schematic of In-Situ Flushing System

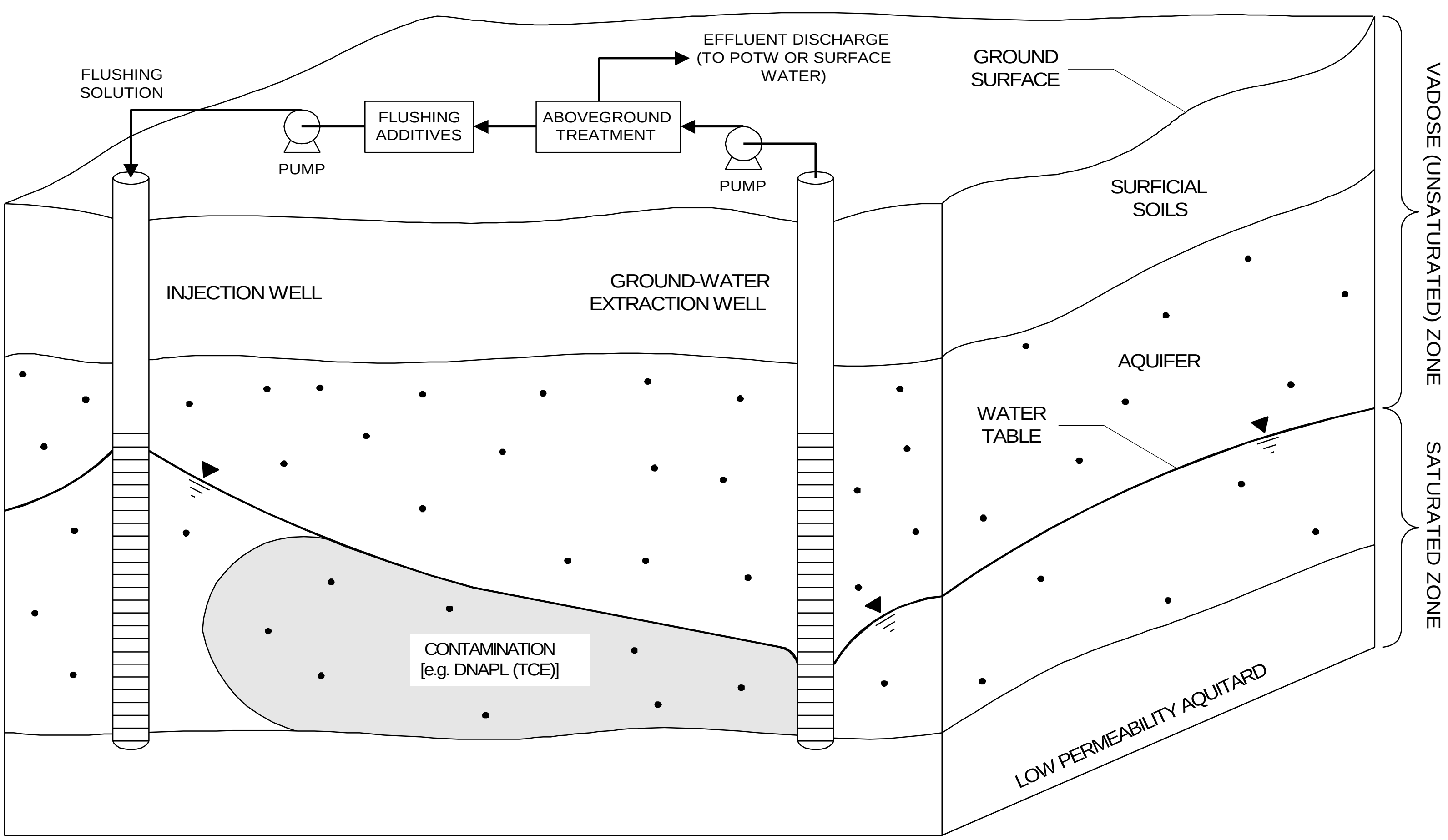
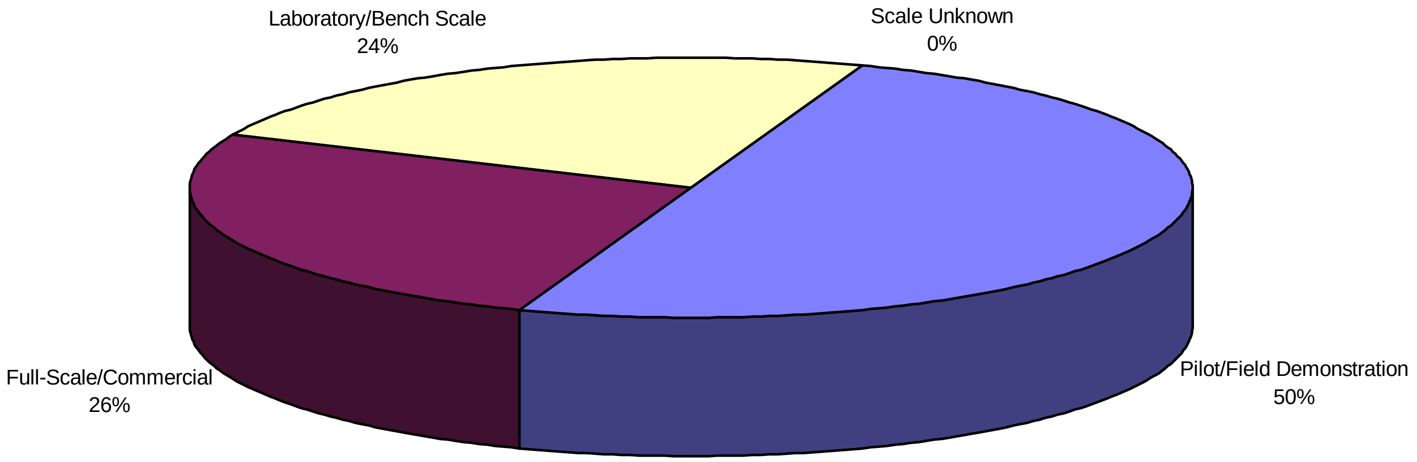


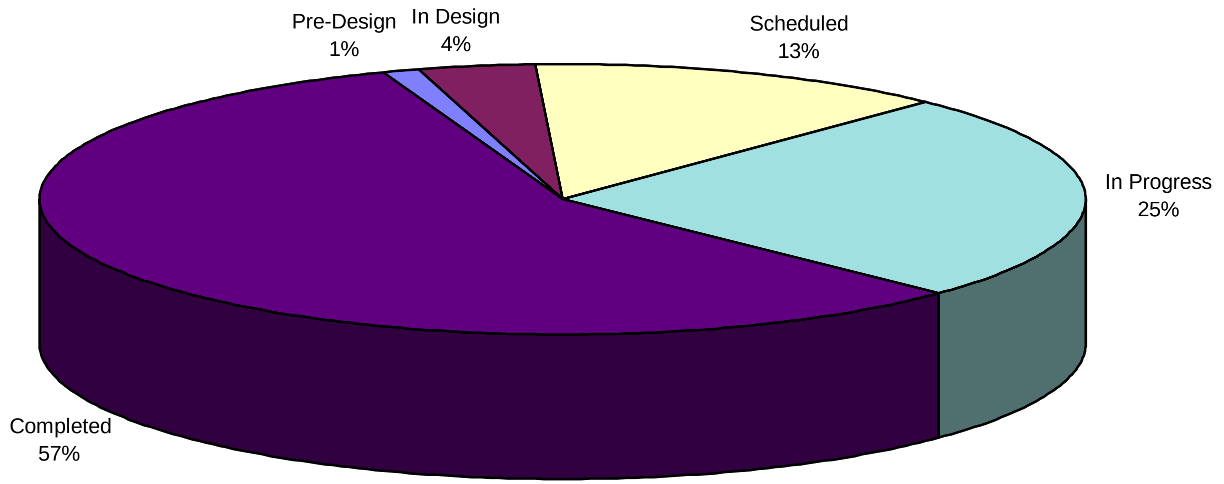
Figure 2. *In Situ* Flushing - Project Scale

(Only Includes "Most Advanced" Scale for Each Project)



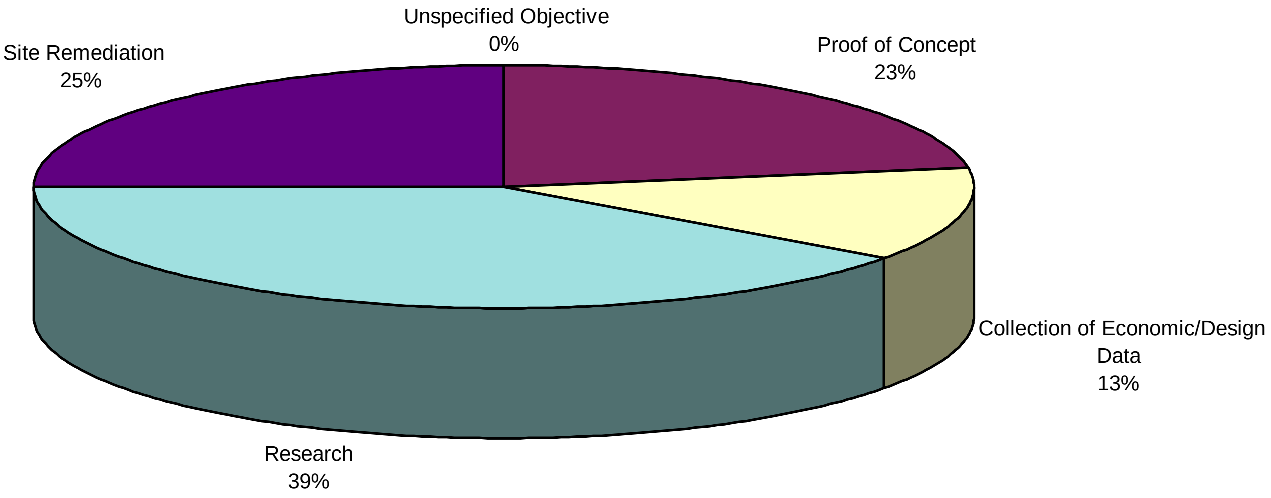
Total Number of Case Studies = 84

Figure 3. *In Situ* Flushing - Project Status



Total Number of Case Studies = 84

Figure 4. *In Situ* Flushing - Project Objectives

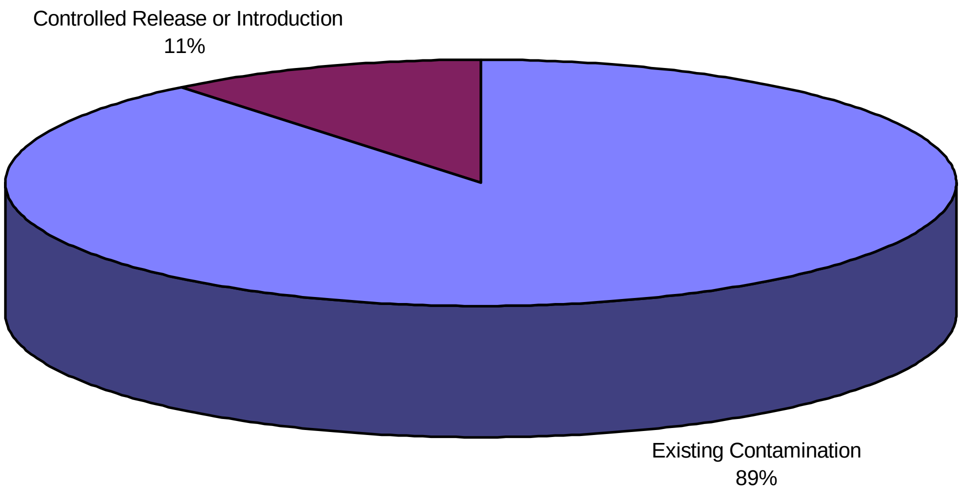


Total Number of Case Studies = 84

Number of Responses on which Percentage Labels is Based = 120

Figure 5. *In Situ* Flushing - Contaminant Source

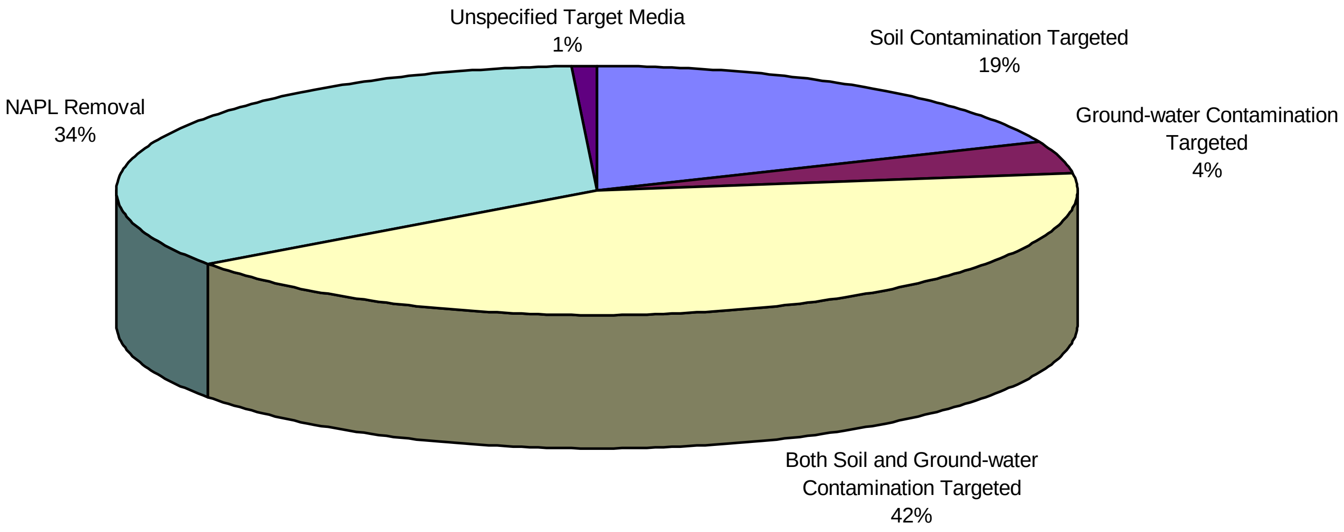
(Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only;
This Figure Excludes Laboratory/Bench Scale Projects)



Total Number of Case Studies = 64

Figure 6. In Situ Flushing - Environmental Media Targeted

(May Include More than one Target Medium per Case Study)



Total Number of Case Studies = 84

Number of Responses on which Percentage Labels is Based = 123

Figure 7. ***In-Situ*** **Flushing - Distribution of Case Studies by EPA Region**
(EPA Region is given for Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only)

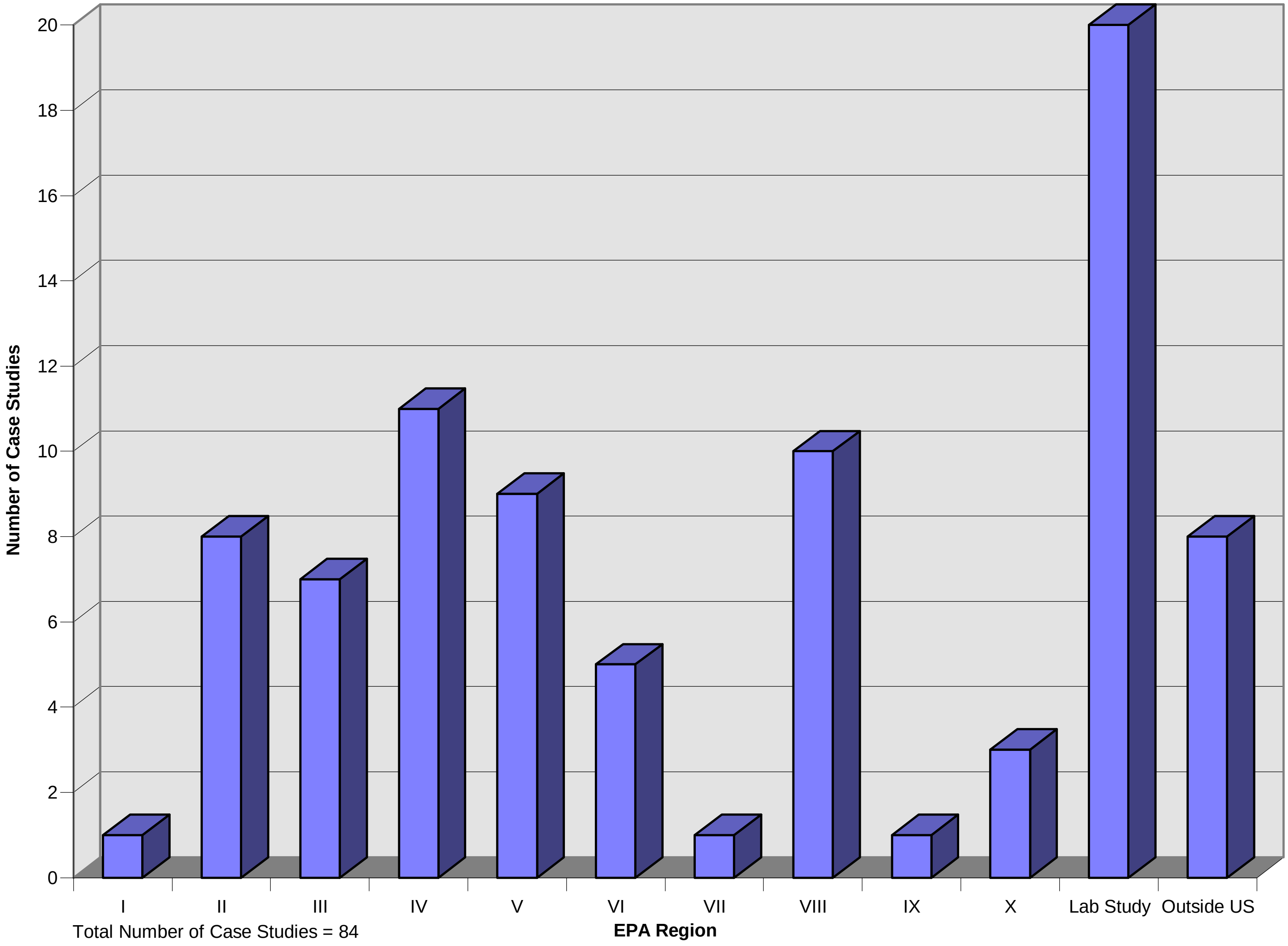


Figure 8. *In Situ* Flushing - Distribution of Case Studies By EPA Region
(EPA Region is given for Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only)

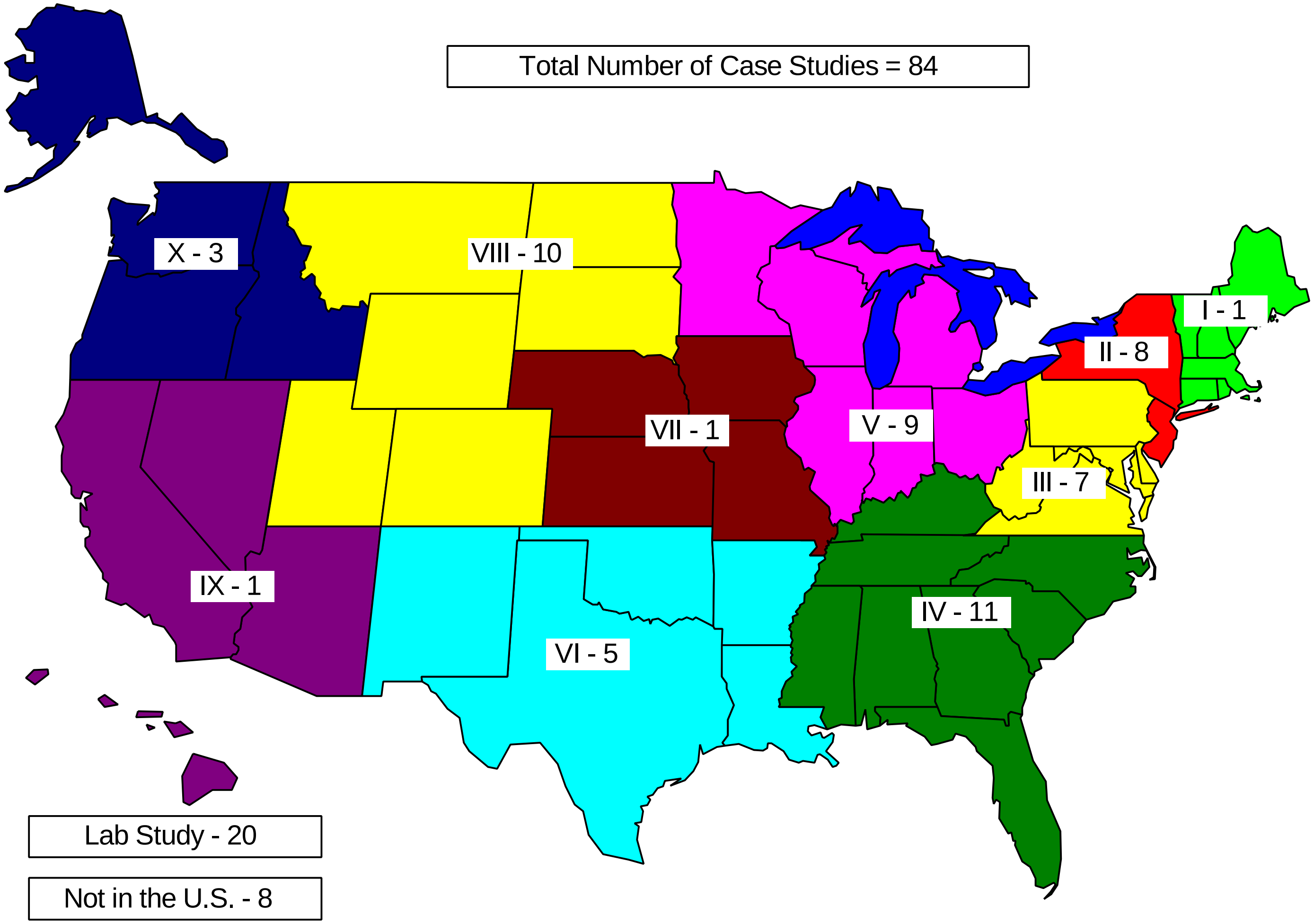
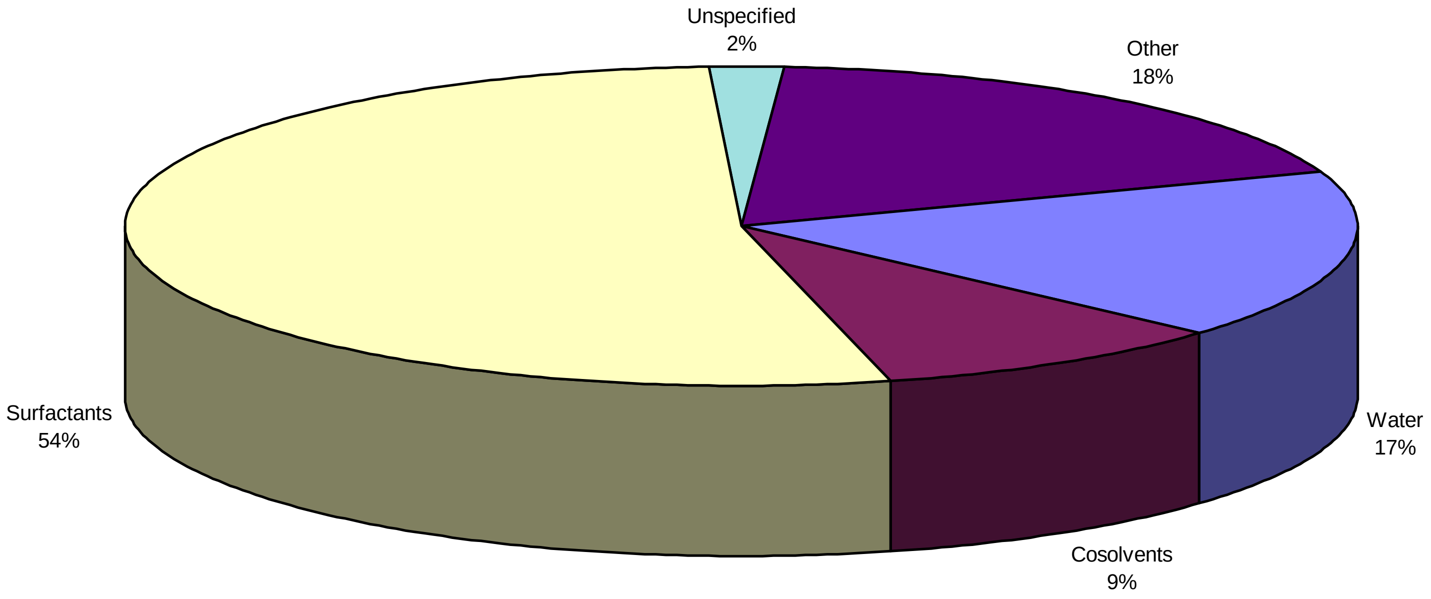


Figure 9. *In Situ* Flushing - Flushing Solution Type Used

(May Include More than one Flushing Solution Type per Case Study
Some Case Studies Did Not Report Solution Type)

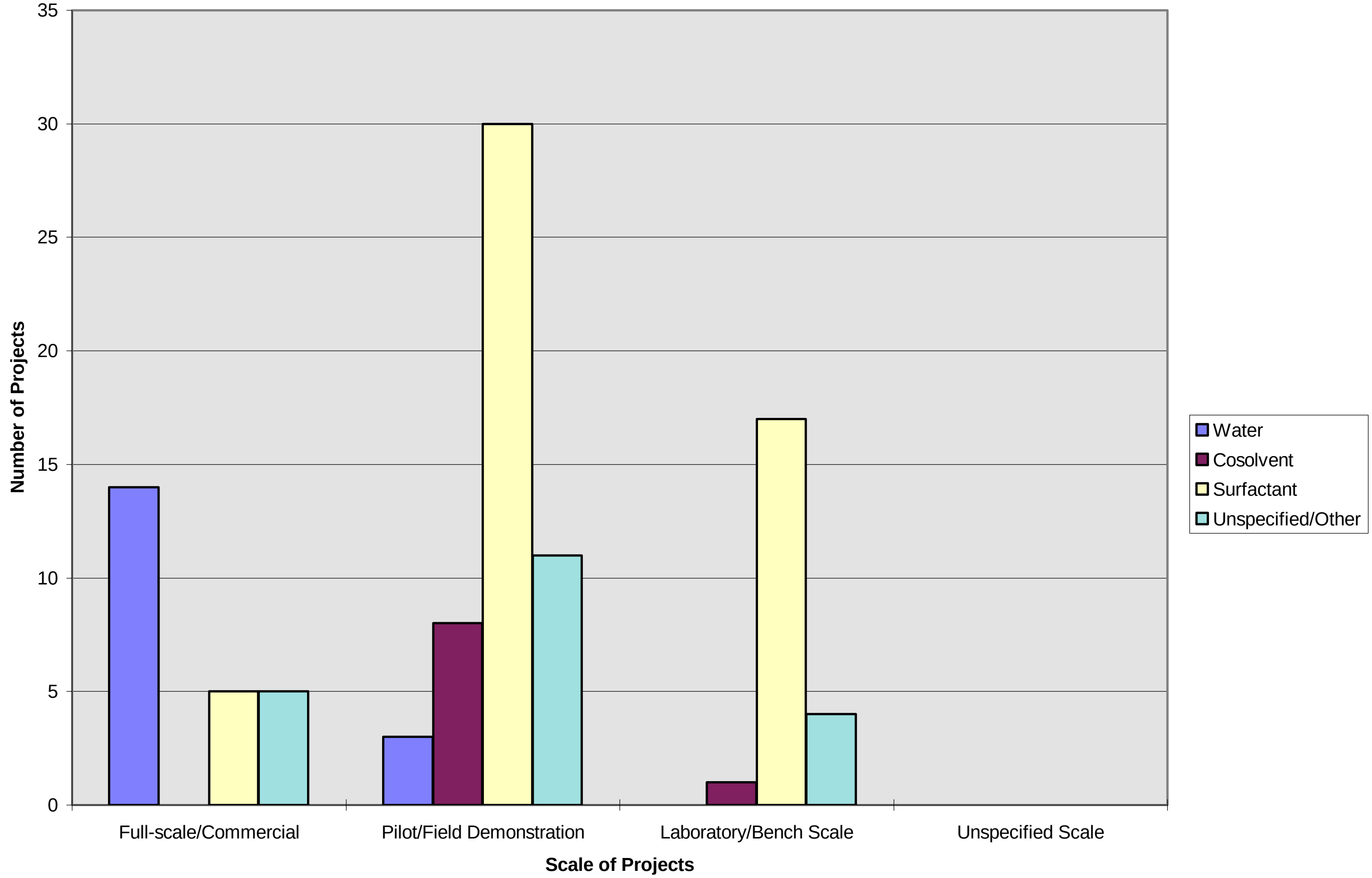


Total Number of Case Studies = 84

Number of Responses on which Percentage Labels is Based = 98

Note: For this figure, the "Other" category includes projects where complexing sugars, proprietary compounds, ploymers, humic acid, and/or electrolytes (alone or in addition to other compounds) were used in flushing solutions.

Figure 10. *In Situ* Flushing - Flushing Solution Type by Project Scale
(May Include More than one Flushing Solution Type per Case Study)

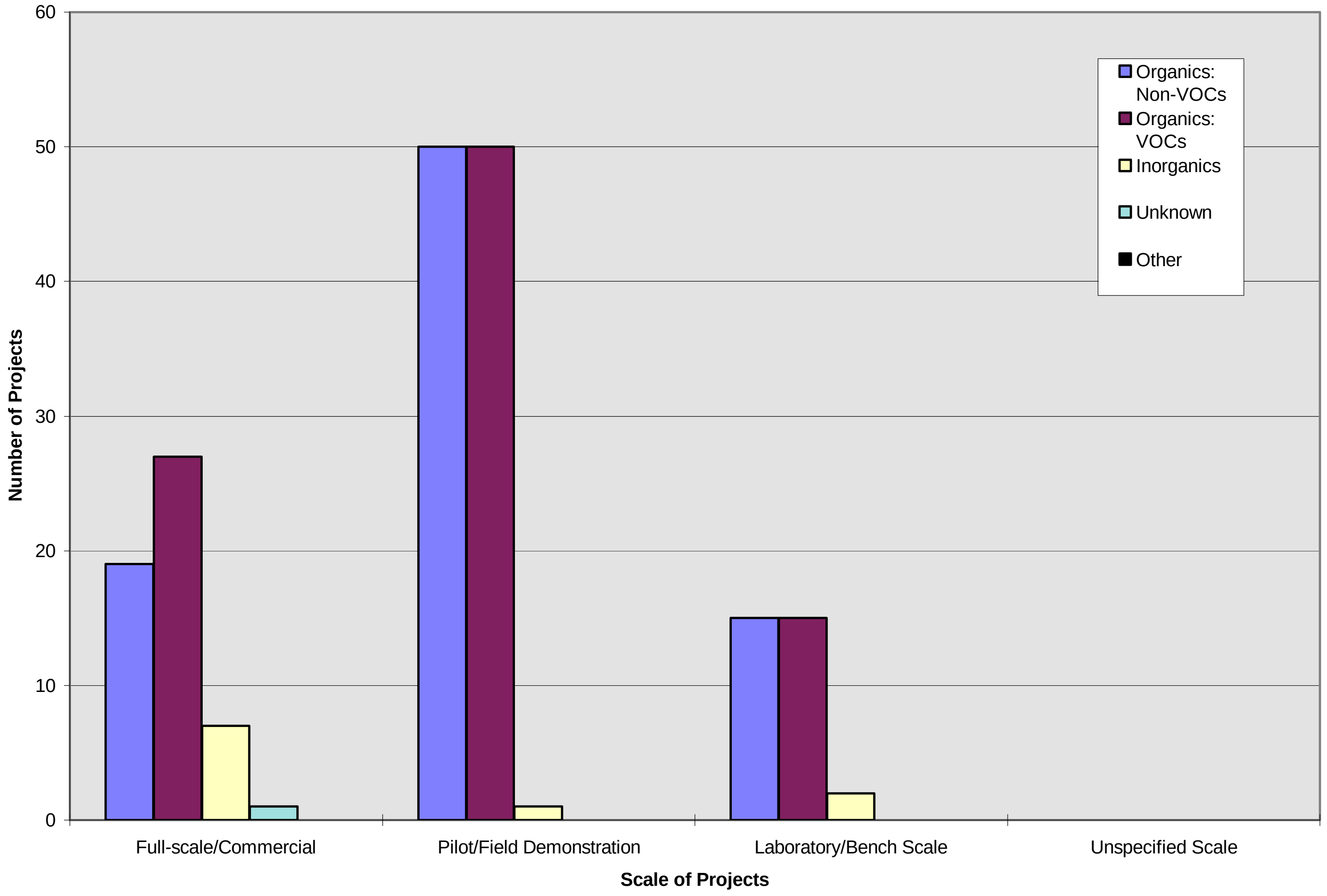


Total Number of Case Studies = 84

Number of Responses = 98

Note: For this figure, the "Other" category includes "Unspeicified" projects and projects where complexing sugars, proprietary compounds, ploymers, humic acid, and/or electrolytes (alone or in addition to other compounds) were used in flushing solutions.

Figure 11. *In Situ* Flushing - Contaminant Class by Project Scale
(May Include More than one Contaminant Class per Case Study)

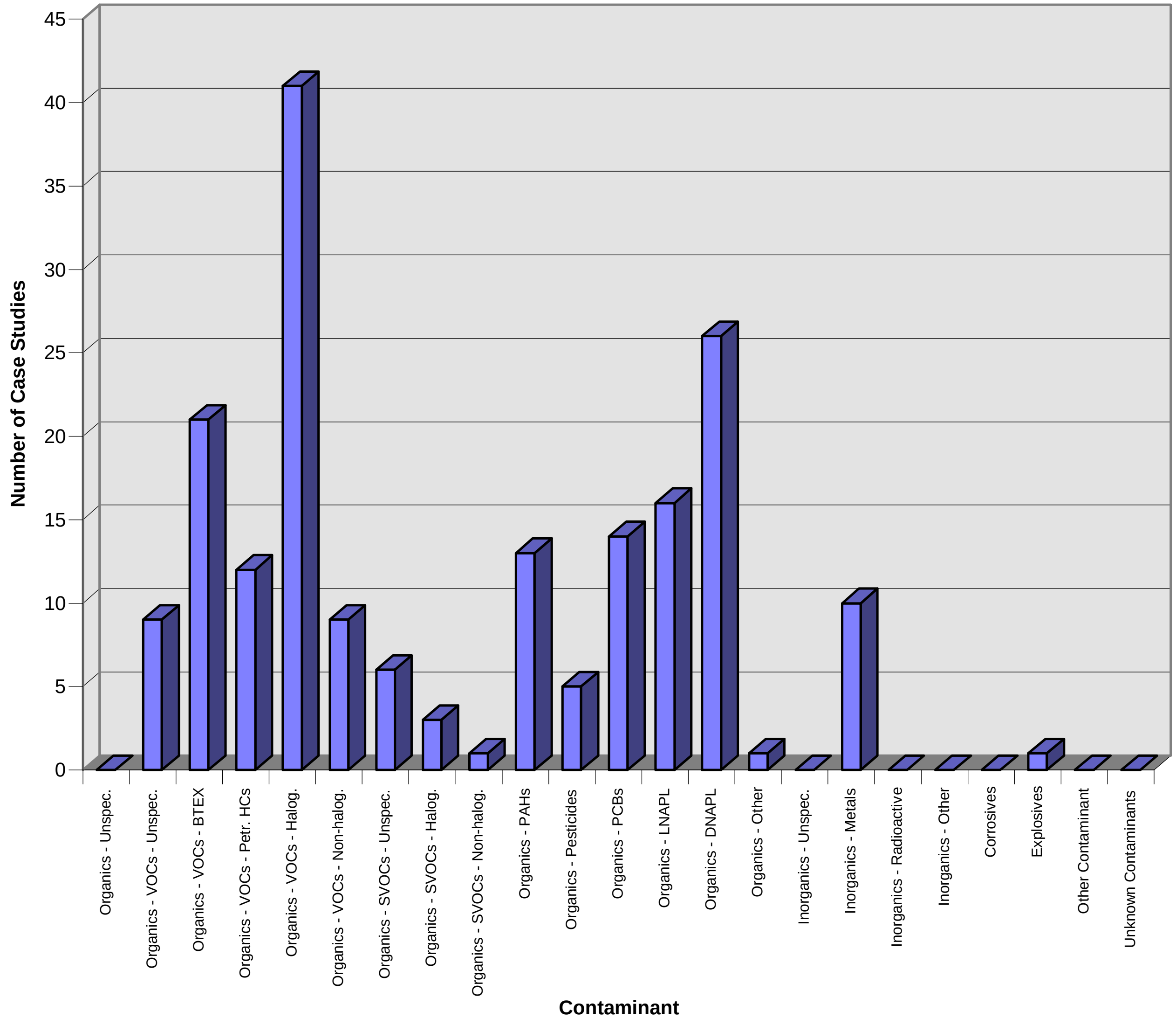


Total Number of Case Studies = 84

Number of Responses = 187

Figure 12. ***In Situ*** **Flushing - Contaminant Class**

(May Include More than one Contaminant Class per Case Study)

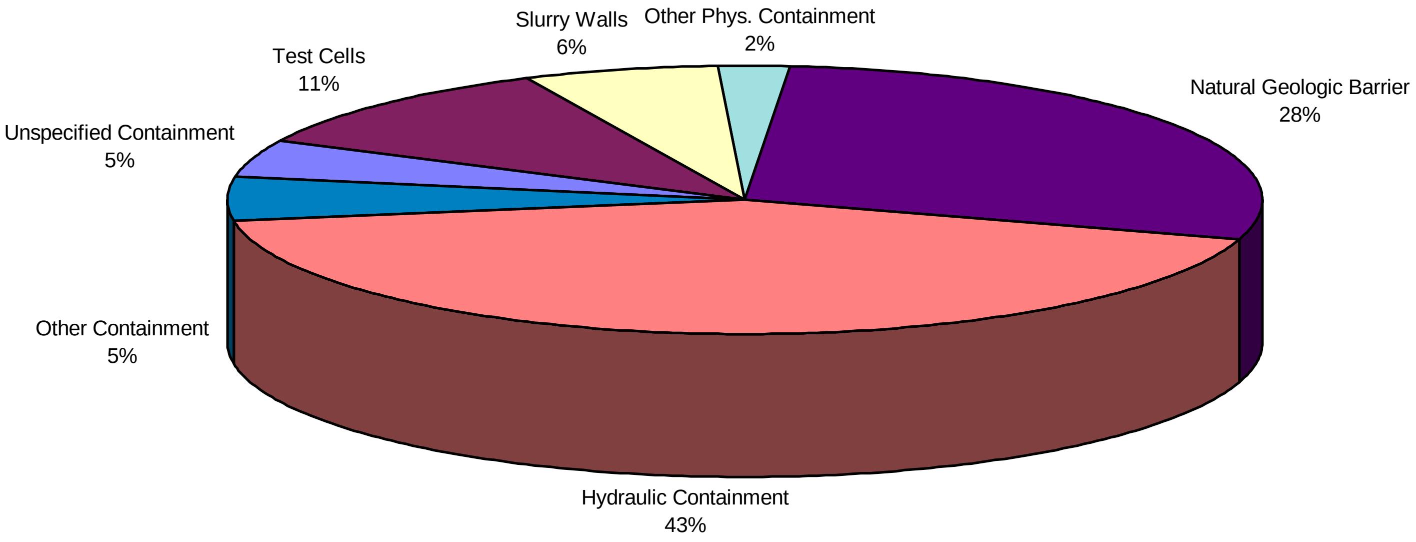


Total Number of Case Studies = 84

Number of Responses = 188

Figure 13. *In Situ* Flushing - Containment Method

(Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only;
This Figure Excludes Laboratory/Bench Scale Projects)
(May Include More than one Containment Method per Case Study)

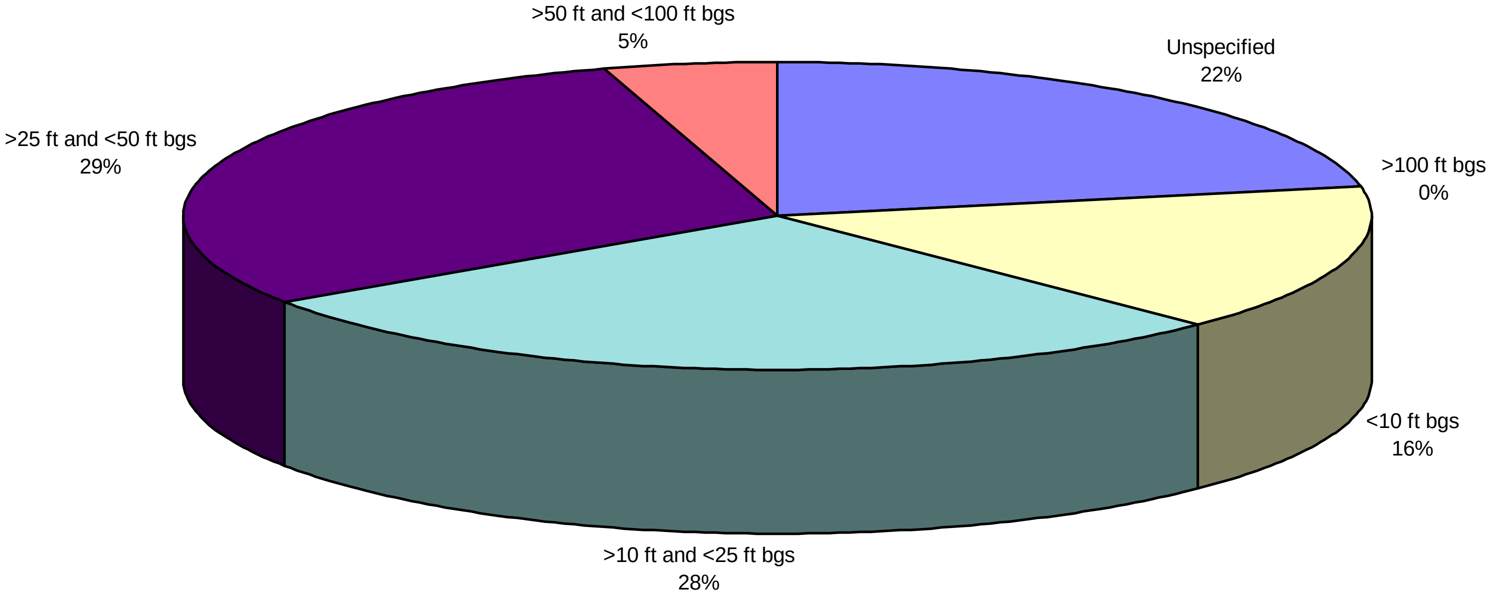


Total Number of Case Studies = 84

Number of Responses on which Percentage Labels is Based = 131

Figure 14. *In Situ* Flushing - Maximum Depth of Treatment Zone

(Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only;
This Figure Excludes Laboratory/Bench Scale Projects)



Total Number of Case Studies = 64

Figure 15. *In Situ* Flushing - Average Hydraulic Conductivity of Treatment Zone
(Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only;
This Figure Excludes Laboratory/Bench Scale Projects)

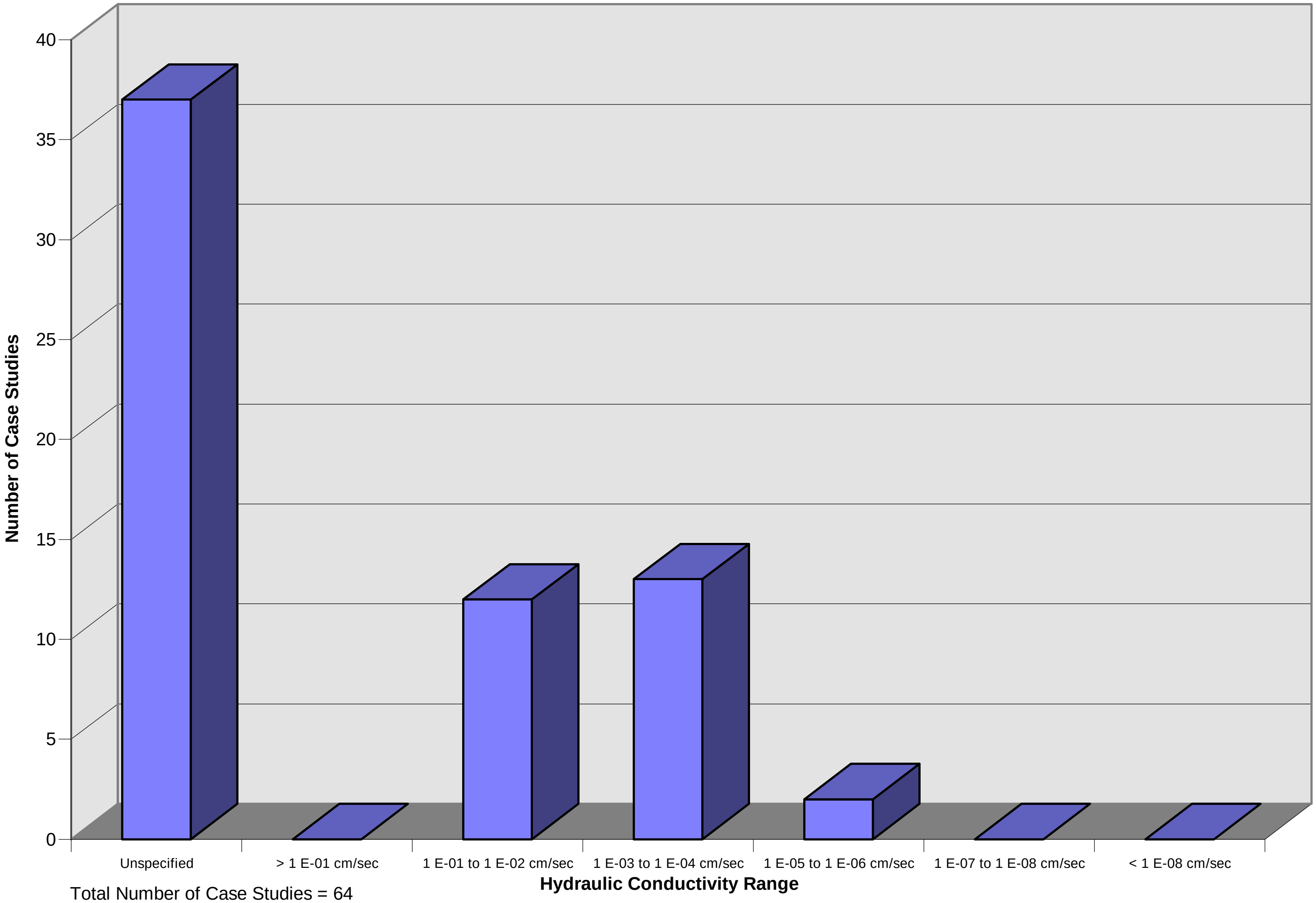
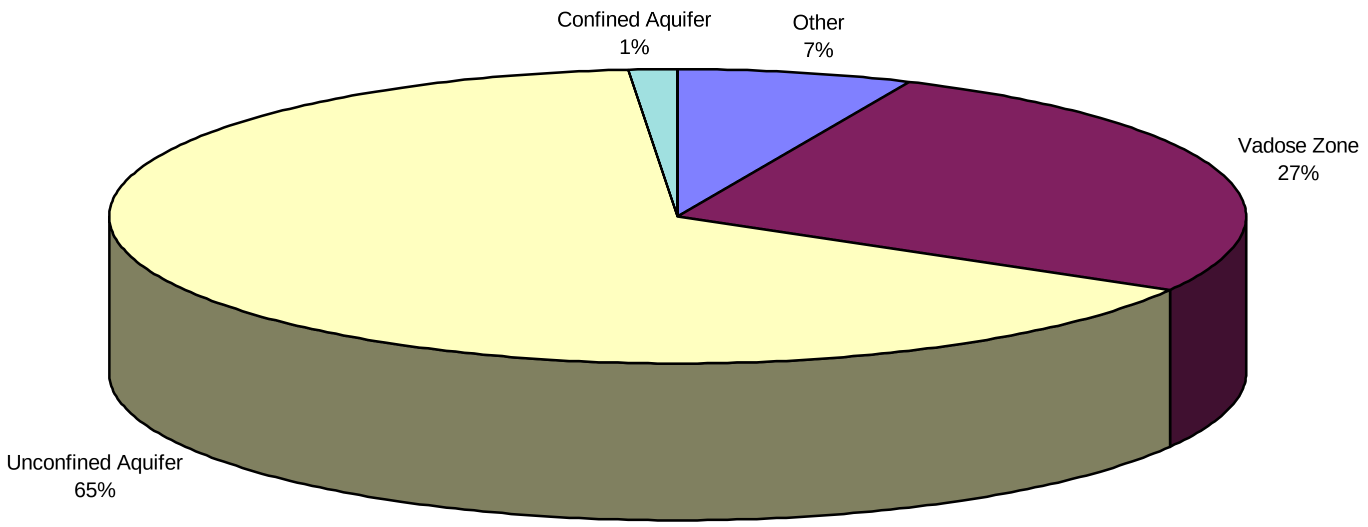


Figure 16. *In Situ* Flushing - Hydrogeologic Setting of Target Contaminants

(Pilot/Field Demonstrations and Full-Scale/Commercial Projects;
Figure Excludes Laboratory/Bench-Scale Projects)
(May Include More than one Hydrogeologic Setting per Case Study)



Total Number of Case Studies = 64

Number of Responses on which Percentage Labels is Based = 75

APPENDIX

GWRTAC INFORMATION SOURCES, PROJECT SUMMARIES, AND ADDITIONAL REFERENCES

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0001

Project Name: Koppers Co. Inc., Seaboard Plant, Kearny, NJ

City: Kearny **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Sawchuck, P.E., et al. "DNAPL Recovery at a Former Coke and By-Products Facility in New Jersey"

Project Summary:

The following was excerpted from Sawchuck, P.E., et al. "DNAPL Recovery at a Former Coke and By-Products Facility in New Jersey":

An Interim Remedial Measures (IRM) pilot project was completed at a former coke and by-products facility in New Jersey, bordering the Hackensack River. The pilot project was developed to evaluate the most effective method of DNAPL (coal tar/creosote) recovery, and to provide design data for a full-scale IRM. The pilot system used two DNAPL recovery wells and two DNAPL recovery trenches. The wells and trenches were operated in two phases under a variety of scenarios to determine the effectiveness of simultaneous groundwater extraction and upgradient groundwater distribution on hydraulic gradients and DNAPL extraction. After above-ground separation of DNAPL, site groundwater was re-injected upgradient of the collection trenches to recirculate, and provide hydraulic push to mobilize DNAPL toward collection trenches.

The DNAPL recovery and groundwater extraction systems included two recovery trenches and two recovery wells installed parallel to the river. The two recovery trenches were located downgradient of the former coal tar area. The two recovery wells were located west of the recovery trenches and downgradient of the former pitch processing area. The eastern recovery trench was approximately 180 feet in length, while the mid recovery trench was about 80 feet in length. Each trench was excavated to the top of the confining unit. Two horizontal perforated polyethylene recovery pipes were installed in each trench. One pipe was installed at the bottom invert of the trench to facilitate DNAPL recovery, while the second pipe was installed at about one-half the depth of the saturated zone to facilitate groundwater extraction. A 24-inch diameter recovery sump was installed in each trench. The design allowed simulation of about 150 foot sump spacings with the shorter trench, and 350 foot sump spacings for the longer trench. The two recovery wells were installed using conventional drilling techniques, and constructed of six-inch diameter stainless steel casings and screens. The screens were ten feet in length with slot sizes of 0.010 inches. Separate, dedicated DNAPL pumps and groundwater extraction pumps were installed in each trench and well. Submersible air powered piston driven DNAPL recovery pumps with conductivity sensor controls were used, together with aboveground air powered double diaphragm groundwater pumps. This allowed evaluation of DNAPL recovery rates over a wide range of groundwater flow rates, from zero to greater than eight gallons per minute.

From top to bottom, the site is underlain by 4 to 21 feet of fill, 0 to 8 feet of "meadow mat" (a peat unit containing some silt and clay), 0 to 45 feet of organic clay and silt containing varying amounts of find sand, plant material and shell fragments, 0 to 20 feet of sand and sandy silt, 0 to 60 feet of clay, 0 to 40 feet of till, and bedrock at a depth of 50 to 90 feet.

The site is located along the tidally influence Hackensack River in northeast New Jersey. The river bounds the 160-acre site on its northern and eastern edges. The site is part of the 100-year floodplain and is generally flat, although there are a number of mounds that rise three to seven feet above grade. A pilot Interim Remedial Measures (IRM) system was designed to mitgate the DNAPL seeps that occur in the coal tar plant area along the northern border of the river. These seeps occur at an elevation of about two to four feet below sea level, which is the topmost elevation of the DNAPL confining layer, which crops out in the river.

The vertical migration of DNAPL is impeded by the meadow mat and by the organic clay and silt unit. DNAPL that can not flow vertically is driven horizontally toward the river by gravity and potentiometric gradients. In the coal tar plant area along the northern dike walls bordering the river, the fill unit is eight to 12 feet thick, and the meadow mat is about four feet thick. DNAPL measurements in temporary piezometers and monitoring wells range up to six feet in thickness.

The water table is about two to four feet below the ground surface. Groundwater in the fill unit flows toward the river with a gradient of 0.002 ft/ft to 0.006 ft/ft. Slug tests conducted in the fill unit indicate a hydraulic conductivity of the fill unit ranges between 7.5 x 10-4 cm/sec and 1.8 x 10-2 cm/sec.

During the first three months of operation, over 11,000 gallons of DNAPL with less than 3% moisture were collected. The study demonstrated that recovery wells were more effective in recovering DNAPL with limited groundwater extraction than recovery trenches at the site. It was also concluded that groundwater distribution upgradient of the recovery points did not significantly affect recovery rates. Groundwater extraction was shown to be effective in increasing DNAPL recovery rates due to the ability to produce large hydraulic gradients in the immediate vicinity of the DNAPL recovery system. However, the percentage of DNAPL recovered decreased significantly with increased groundwater extraction.

As of July 1998, because other remedial measures will be taken, the IRM is expected to continue in operation for approximately two more years, then will be discontinued.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

Sawchuck, P.E., et al. "DNAPL Recovery at a Former Coke and By-Products Facility in New Jersey"

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0002

Project Name: Bog Creek Farm, Howell Township, NJ

City: Howell Township **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): Ed Finity
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following notes were recorded from April 1997 and July 1998 conversations with the EPA RPM:

Aproximately 30 extraction wells spaced every 25 feet along a brook extract a total of 30 gpm of groundwater from water table aquifer, prior to groundwater discharge into brook. The extraction wells are approximately 15 feet deep and are terminated small distance into lower, uncontaminated aquifer underlying the water table aquifer of concern. Water is treated aboveground, and re-injected at 30 gpm rate. Water is re-injected upgradient of contaminated zone via a trench that is approximately 200 to 250 feet long. The flushing project is being conducted within a slurry wall barrier, which is keyed into a confining clay layer less than 25 feet deep.

RPM indicates a ten year operation was estimated; project is now in third year of operation. (Since this is a fund-lead site, EPA will operate the site for ten years, after which time, it will be turned over to the state of New Jersey.) Results have been variable, though a general trend of decreasing concentrations of toluene and benzene in groundwater is noted; a five year review will be performed which will review results of the project after five years of operation. In the coming year, U.S. EPA and the U.S. Army Corps of Engineers will begin to attempt to modulate the use of the extraction wells; they may only pump the most contaminated wells for example, or otherwise modify operation to increase efficiency.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0003

Project Name: Canadian AFB Borden, Alliston, Ontario, Canada

City: Alliston **State/Province:** ON

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Fountain, J.C. and D.S. Hodge, February 1992: "Extraction of Organic Pollutants Using Enhanced Surfactant Flushing - Initial Field Test (Part 1), New York State Center for Hazardous Waste Management, State University of New York at Buffalo, Jarvis Hall 207, Buffalo, New York

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was excerpted from GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue University, available at www.gwrtac.org and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, and Fountain, 1992: Direct quotes are from Fountain, 1992. Fountain, et. al. 1996 present a comprehensive review of this project.

The study area was a clean surficial sand aquifer with < 1% clay, and < 0.1% organic carbon in a 3x3x3 m3 cell. The test cell was constructed by driving sheet piling walls into the underlying clay aquitard. A second sheet-piling wall was installed 1 m outside the inner wall for containment. Five injection wells and five extraction wells (5 cm PVC) were installed parallel to each other on opposite sides of the 9 m2 cell. Multi-level monitoring wells were also installed. The upper PCE zone (0 to 1 m BGS) was perched on a layer within the sand less than 2 cm in thickness. The lower pool was located on the clay aquitard at the base of the cell. A 2% surfactant solution was pumped through the cell. The PCE in the extracted solution was air stripped and the surfactant solution was recycled through the cell for 14 PVs.

"in a field test conducted at Canadian Forces Base Borden in collaboration with the Waterloo Center for Groundwater Research, a 3-meter by 3-meter test cell was constructed by driving sheet piling walls into a 4-meter-thick unconsolidated sand aquifer. Approximately 231 liters of tetrachloroethylene was added in a controlled release by B. Kueper, who then excavated the top meter to study the DNAPL flow. The ceil was then refilled with clean sand and a blend of I percent nonyl-phenol ethoxylate, and I percent phosphate ester of nonylphenol ethoxylate was pumped through the 3-meter-thick contaminated section of the cell to evaluate surfactant-enhanced remediation."

"The surfactant was injected in five wells on one side of the cell and extracted from five wells on the other side. The wells were screened over the entire contaminated zone, which was kept saturated throughout the experiment. The concentration of tetrachloroethylene (PCE) in the effluent increased from its aqueous solubility of about 150 parts per million (ppm) to over 4,000 ppm when the surfactant was added. The increase in concentration illustrates the efficiency of the surfactant process. The surfactant solution used provides a solubility of PCE of about 12,000 ppm; values in excess of 11,500 ppm were observed in several sampling points on the five multilevel monitoring wells in the cell. This illustrates that the surfactants provided the same solubilization power in the field as predicted in the laboratory."

"The system performed as expected, solubilization was high, surfactant breakthrough was indistinguishable from that of a conservative tracer indicating sorption was veny low (the aquifer has no significant clay or organic content) and the air stripper separation was effective. Several modifications had to be made to the air stripper, however, to prevent foaming; very low air velocities were eventually employed."

The DNAPL concentration was rapidly reduced in the cell in areas of high hydraulic conductivity. The residual PCE in the top 1 m was reduced from an initial value of 10% to a value of 1% after 14.4 PVs. At a depth of 2.5 to 3 m, where the ground was either saturated or at 20% saturation with PCE initially, the PCE saturation was reduced to 3% after 14.4 PVs. Approximately 80% of the total material was recovered, with the remaining material lost to volatilization or remaining in dead zones within the formation. The surfactant solution was initially injected into the wells with a constant-head system on each well; this later was changed to peristaltic pumps due to plugging of the injection wells.

"The concentration of PCE in the multilevels dropped to a few ppm within 14 pore volumes, except for the multilevel ports right on the aquitard. These data indicated that the DNAPL had been removed over nearly the entire aquifer. This was confirmed by analysis of cores taken prior to the start of the experiment, after seven pore volumes had been circulated, and after 14 pore volumes had been circulated. These analyses showed that:

I. Nearly all the PCE was removed by 14 pore volumes.

2.The layers of high PCE concentration, which represent perched lenses of PCE, remained at the same height throughout the experiment indicating the lenses did not drop due to vertical mobilization.

3.The persistence of PCE along the aquitard indicates that complete removal would require an extended treatment time.

After having circulated almost 20 pore volumes of solution, and elevated concentrations of PCE still occurred in the multilevel at the top of the aquitard.

The base of the aquifer has slightly dipping layers of sand and silt. The PCE is apparently concentrated in the sand layers. Cleaning of the layers is retarded by low horizontal flow rates resulting from the low hydraulic conductivity of the silt layers. Similar hard-to-clean low-flow zones can be expected in any aquifer."

Scale-up plans not applicable, as this research activity was conducted in response to a planned release.

Report(s)/Publication(s) (Additional Information Sources):

Fountain, J.C. and D.S. Hodge, February 1992: "Extraction of Organic Pollutants Using Enhanced Surfactant Flushing - Initial Field Test (Part 1), New York State Center for Hazardous Waste Management, State University of New York at Buffalo, Jarvis Hall 207, Buffalo, New York

Fountain, John; Waddell-Sheets, Carol ; Lagowski, Alison; Taylor, Craig; Frazier, Dave; Byrne, Michael. Chapter 13: Enhanced removal of dense nonaqueous-phase liquids using surfactants, in Surfactant-Enhanced Subsurface Remediation: Emerging Technologies, ACS Symposium Series 594, Dave A. Sabatini, Robert C. Knox, and Jeffrey H. Harwell, eds., 1995.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

GWRTAC ID: FLSH0004

Project Name: Chem-Dyne, Hamilton, OH

City: Hamilton **State/Province:** OH

Primary GWRTAC Personal Communication Source (Name/Organization): Larry Schmidt
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm.

Project Summary:

The following text is from notes taken from May 1997 conversation with EPA RPM:

The 20-acre site is located adjacent to the Great Miami River. The constituent plume was present in an alluvial water table aquifer; the depth of the water table is approximately 20 to 30 feet below the ground surface (bgs). The valley floor, at 200 feet bgs, formed the confining layer, however the contaminants were present at 80 feet bgs and shallower. No physical containment, such as a slurry wall, was constructed at the site. A total of 25 shallow (30 feet bgs) and deep (80 feet bgs) wells were utilized for groundwater extraction. Re-injection of the treated groundwater was accomplished through approximately eight shallow (20 feet bgs) wells. A total of 859 gpm groundwater is pumped and treated. Some treated groundwater is re-injected, while a percentage is discharged via an NPDES permit. Re-injection was discontinued due to the high cost of filtering groundwater prior to re-injection.

Results and cost information were not available from GWRTAC source.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm.

GWRTAC ID: FLSH0005

Project Name: Cornell University - Surfactant Enhance Biodegradation

City: Ithaca **State/Province:** NY

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org:

A study was conducted to determine whether a non-ionic surfactant added to the surface of Lima silt loam would enhance the biodegradation of phenanthrene and biphenyl. Researchers concluded that surfactants at low concentrations may be useful for in situ bioremediation of sites contaminated with hydrophobic pollutants without causing movement of the parent compounds to groundwater. Dr. Alexander will continue with this work but has no plans to conduct field studies.

Report(s)/Publication(s) (Additional Information Sources):

Aronstein, B.N. and Alexander, M., 1992: "Surfactants at Low Level Concentrations Simulate Biodegradation of Sorbed Hydrocarbons in Samples of Aquifer Sand and Soil Slurries" in Environmental Toxicology and Chemistry, 11, pp. 1227-1231.

Aronstein, B.N. and Alexander, M., 1993: "Effect of a Non-Ionic Surfactant Added to the Soil Surface on the Biodegradation of Aromatic Hydrocarbons within the Soil" in Applied Microbiology and Biotechnology, Vol. 39, pp. 386-390.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

GWRTAC ID: FLSH0006

Project Name: Corpus Christi Dupont, Corpus Christi, TX

City: Corpus Christi **State/Province:** TX

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Fountain, John., 1993: Project summary: Extraction of organic pollutants using enhanced surfactant flushing, part II, NY State Center for Hazardous Waste Management, Buffalo, NY, November 1993.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC and GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue University, available at www.gwrtac.org:

Low toxicity, biodegradable surfactant flushing solution was used for remediation of carbon tetrachloride (CTET) contamination. Site was used for manufacture of chlorocarbons. The site was selected for the pilot test because DNAPL was present in a shallow zone, there was adequate hydraulic conductivity of contaminated zone for flushing, and the target zone is underlain by a thick clay unit forming a barrier to further vertical migration. The test area was 25 x 35 feet in area. The target zone was comprised of a 12 foot sand lens within a thick regional clay unit. The sand lens extends from approximately 12 to 24 feet below the ground surface, and is comprised of a very well-sorted fine sand with variable amounts of smectitie clays and a low carbon content.

CTET was present at shallow depths, underlain by a thick clay aquitard (barrier to vertical migration). The target zone was a 12 ft fine grain sand lens with variable smectitic clay content (1 to 15%), 0.025 to 0.031% organic carbon, and 12,000 mg / L total dissolved solids at 12 to 24 ft below ground level, making the overall test area 25 by 35 ft. The formation had moderate hydraulic conductivity (>= 10-3 cmsec). An array of 6 injection wells and one central extraction well were used. This project was completed in four phases. In the first phase a 1% surfactant solution was pumped to the injection wells with the extraction solution air stripped to remove the

PCE. The surfactant solution was recycled. Phase II was similar with one well being replaced. In Phase III a new surfactant was used. In Phase IV a smaller area was tested.

Surfactant was added to the extracted groundwater at the surface, injected through an array of distribution wells, and then removed via extraction wells. The contaminants were separated by air stripping, and the stripped solution mixed with surfactant. The surfactant solution was then re-injected; the concentration of surfactant used was 1% in this pilot test. The surfactant was not a food-grade additive, but is approved for use in "food preparation procedures", has low toxicity, and is readily biodegradable under both aerobic and anaerobic conditions. The cycle of extraction, aboveground treatment and mixing of surfactant and re-injection of surfactant was repeated throughout the test.

The project was conducted in four separate phases. In Phase I (June 1991 to August 1991), a 1% surfactant solution was delivered through six distribution wells, and removed via one central extraction well. In Phase II (March 1992 to June 1992) a new extraction well was utilized as one original extraction well was rendered unusable by sanding. During Phase II, the original surfactant was subjected to a high sorption rate, and biofouling of surface tanks and delivery wells occurred. In Phase III (June 1992 to October 1992), because of the issues encountered in Phase II, the surfactant was changed. In Phase IV (January 1993 to February 1993), a smaller area comprising the northern half of the original test area was utilized, due to low flow rates due to a depressed regional water table.

In the first two phases, completed in 6/91-8/91 and 3/92-6/92, respectively, the surfactant was found to sorb considerably and biofouling of the above ground tanks occurred resulting in the change of surfactant. The initial concentrations in monitoring wells were 200-300 mgL with concentrations jumping to 800-900 mg / L at the point that the surfactant reached 0.5% in the monitoring wells (i.e., about 1 PV). The average concentration of CTET in the solution recovered was 790 and 219 mg / L for Phases I and II, respectively. After 12.5 pore volumes, a total of 73 gallons of CTET were removed.

Prior to the test, CTET was found at >1,000 ppm in both soil core and water samples from the test zone. During the in situ flushing test, the average effluent concentration of CTET decreased from 790 ppm (Phase I) to 219 ppm (Phase IV). A total of approximately 73 gallons of CTET was removed during the project, after injection of 12.5 pore volumes of flushing solution. DNAPL removal progressed at a rate more rapid than would be expected with standard pump and treat technology, based on analysis of three monitoring well nests within the DNAPL source area. It was concluded that although initial capital costs would be greater than pump and treat, the reduction in time required to complete remediation greatly reduces the O&M costs.

Report(s)/Publication(s) (Additional Information Sources):

Fountain, John; Hodge, D., Project summary: Extraction of organic pollutants using enhanced surfactant flushing: Initial field tests, Part I, NY State Center for Hazardous Waste Management, February, 1992.

Fountain, J. C. “A pilot scale test of surfactant enhanced pump and treat, in Proceedings of Air and Waste Management Association’s 86th Annual Meeting, Denver, Colorado, June 13-18, 1993.

Fountain, J. C.; Waddell-Sheets, C., A pilot field test of surfactant enhanced aquifer remediation:

Corpus Christi, Texas, Extended Abstract from ACS symposium in Atlanta Georgia, September 27-29, 1993.

Fountain, John., 1993: Project summary: Extraction of organic pollutants using enhanced surfactant flushing, part II, NY State Center for Hazardous Waste Management, Buffalo, NY, November 1993.

Fountain, John; Waddell-Sheets, Carol ; Lagowski, Alison; Taylor, Craig; Frazier, Dave; Byrne, Michael. Chapter 13: Enhanced removal of dense nonaqueous-phase liquids using surfactants, in Surfactant-Enhanced Subsurface Remediation: Emerging Technologies, ACS Symposium Series 594, Dave A. Sabatini, Robert C. Knox, and Jeffrey H. Harwell, Eds., 1995.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency, 1995: "In Situ Remediation Technology Status Report: Surfactant-Enhancements”, EPA 542-K-94-003, Office of Solid Waste and Emergency Response (5102W), Washington, DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0007

Project Name: Cross Brothers Pail, Pembroke, IL

City: Pembroke **State/Province:** IL

Primary GWRTAC Personal Communication Source (Name/Organization): Sherry Biachin
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following text is from notes taken from Internet URL http://www.epa.gov/superfund/index.htm, May 1997 and July 1998 conversations with the U.S. EPA RPM, and from July 1998 conversations with the PRP spokesperson, and a technical team member.

Site is located approximately 14 miles east of the town of Kankakee, IL, within Pembroke Twp., Kankakee County. Site consists of a 20-acre parcel of land. Cross Brothers operated a drum and pail reclaiming operation at the site from 1961 until 1980. The operation employes a crude process to incinerate the residue material contained in drums and pails received for reconditioning. Essentially, the operation consisted of inverting the containers to allow the residue material to drain out onto the ground. Then solvent would be added to the containers to dissolve any remaining residue. Throughout the process, the operation was haphazard, allowing indiscriminant dumping of great quantities of residues (largely dyes, pigments, inks, and solvents). PCB-contaminated soil was excavated.

Wells are pumped to remove ground-water, and treatment occurs above-ground. Re-injection of treated groundwater for flushing of source area vadose zone contamination occurs via a sprayfield, with sprinklers, and for flushing the saturated portion of the aquifer, occurs though injection wells downgradient of the source area. Extraction and injection wells are also utilized to maintain hydraulic control at the downgradient edge of the contaminant plume. The source area is approximately four to six acres in extent. areal extent. A confining clay layer is present at 45 to 50 feet below the ground surface, and the water table is variable with season, from four to eight feet below the ground surface. There is not a slurry wall or other physical construct present at the site acting as an engineered barrier. Injection and extraction wells immediately downgradient of the source area, and injection and extraction wells immediately downgradient of the downgradient (leading) edge of the contaminant plume are installed to a depth one foot above the confining clay layer. The targeted unconfined aquifer consists of very well sorted, fine-grained sand. Standard MCLs are the treatment goal.

Project designed for 100% re-injection of treated ground-water, however, problems with plugging had occurred. Project duration was projected for 15 to 20 years. Performance data is presented in quarterly reports to U.S EPA, results are generally good. Only standard difficulties occurred during implementation.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

GWRTAC ID: FLSH0008

Project Name: U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, OH

City: Piketon **State/Province:** OH

Primary GWRTAC Personal Communication Source (Name/Organization): Jacqui Avvadoumides
Duke Engineering & Services

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following is excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC and GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue University, available at www.gwrtac.org, Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, and INTERA, 1997 update. Direct quotes from INTERA, 1997 update on DOE PORTS project, revised by Duke Engineering & Services (DE&S), July 1998:

The contamination occurs in the Gallia sand and gravel aquifer at the X701B area at the DOE Portsmouth Plant. The hydraulic conductivity of the DNAPL-contaminated zone is approximately 10-2 cm/sec. Two existing wells, spaced 15 ft apart and 20 ft deep have produced free phase NAPL in this area.

"A test of the efficacy of surfactants to solubilize multi-component DNAPLs in alluvium and the use of partitioning tracers to determine the spatial distribution and total volume of DNAPL. Surfactants were screened and tested at the State University of New York at Buffalo (SUNY), while tracers were chosen and tested at the University of Texas at Austin (UT). INTERA (Austin, TX), now part of DE&S, was the prime contractor with DOE's Morgantown Energy Technology Center and was responsible for project management, hydraulic testing, test zone preparation, predictive numerical simulation, and the execution of before and after partitioning interwell tracer tests and the solubilization test conducted in September 1996 at DOE's Portsmouth Gaseous Diffusion Plant, Piketon, Ohio.

Hydraulic testing of the Gallia alluvium (27-34 ft bgs) conducted in March of 1996, indicated that the sustainable injection and extraction rates for both tracer and solubilization tests would be 0.2

L/s (3 gpm) and 0.3 L/s (5 gpm), respectively. The initial PITT conducted in July of 1996 indicated that there was approximately 20-40 liters (5-10 gallons) of DNAPL trapped by capillary forces in the basal gravel layer of the Gallia alluvium between two existing wells just west of the former X701B pond. Using this information the solubilization test was designed to inject an aqueous surfactant solution containing 4 percent sodium dihexyl sulfosuccinate, 4 percent isopropyl alcohol and 0.2 percent electrolyte (NaCL and CaCL2) for a period of 1.5 days. The second PITT, conducted immediately following the solubilization test in late September, measured only 8 liters (approximately 2.1 gallons) of DNAPL remaining in the alluvium between the injection and extraction wells. This indicated that approximately 50 percent of the DNAPL had been removed by solubilization, however not all of the solubilized DNAPL was recovered at the extraction well because of hydraulic interferences recorded by pressure transducers throughout the site. The swept pore volume of the final PITT was 3,400 gallons (13,000 liters), yielding an average final DNAPL saturation of 0.06 percent.

A comparison of the PORTS and Hill AFB results, both of which projects were conducted by the same team of INTERA and UT during the summer of 1996, indicates that the necessary conditions for successful employment (i.e. greater than 90% DNAPL recovery) of surfactant-enhanced aquifer remediation (SEAR) are:

1) the DNAPL zone is well characterized in terms of the spatial distribution and total volume of DNAPL and the hydraulic and capillary properties of the alluvium trapping the DNAPL, and

2) Such characterization is incorporated into a robust design of the solubilization using predictive numerical simulation and laboratory experimentation which results in efficient sweeping of the DNAPL zone by the surfactant flood."

As of February 1997, data analysis and reporting were in progress. Plans for scale-up are uncertain.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Intera, Inc. and State University of New York (SUNY) at Buffalo. 1995. "The In-Situ Decontamination of Sand and Gravel Aquifers by Chemically Enhanced Solubilization of Multiple-Component DNAPLs with Surfactant Solutions. Phase I Final Topical Report: Laboratory and Pilot Field-Scale Testing." Submitted to Morgantown Energy Technology Center, U.S. Department of Energy.

Jackson, R.E., and Pickens, J.F. "Determining Location and Composition of Liquid Contaminants in Geologic Formations," U.S. Patent No. 5,319,966.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0009

Project Name: Dover AFB, Dover, DE (Test Cell 3, Cosolvent Solubilization)

City: Dover **State/Province:** DE

Primary GWRTAC Personal Communication Source (Name/Organization): Tim McHale
Mantech Environmental

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes taken during May 1997 and July 1998 conversations with personnel stationed at Air Force Laboratory, Dover Air Force Base, Delaware, and additional information provided to GWRTAC.

A series of demonstrations will be conducted at the Groundwater Remdiation Field Laboratory (GRFL) site at Dover Air Force Base, Delaware, located three miles southeast of the city of Dover. The GRFL site was established in 1996 to test and evaluate innovative remediation technologies geared towards the cleanup or containment of soil and groundwater contamination, specifically from chlorinated solvents. The GRFL site is funded by the Strategic Environmental Research and Development Program (SERDP) established to develop innovative technologies for the cleanup of soil and groundwater contamination. SERDP was developed as a partnership between the EPA, DoD, and the DOE to support these environmental efforts.

The Dover National Test Site (DNTS) was designed to allow safe conduct of environmental remediation technologies research; in situ technologies which address fuels and solvents and associated DNAPLs are the primary focus. Dover Air Force Base is immediately underlain by sediments of Cretaceous to Recent age. The uppermost water-bearing zone is comprised of the Pleistocene Lynch Heights and underlying Columbia Formations, which together form a water table aquifer which extends from the ground surface to an approximate 40 foot depth below the ground surface (bgs). In general, these formations are composed of medium to fine sands with gravely sand, silt, and clay lenses. The upper unit of the Miocene Calvert Formation underlies the Coumbia Formation, and consists of gray, firm, dense marine clays with thin laminations of silt and fine sand. This upper portion of the Calvert Formation acts as a confining layer, and ranges in thickness from 20 to 28 feet. The Frederica aquifer is a 22 foot thick upper sand unit within the Calvert Formation, and is located from approximately 66 to 88 feet bgs. The Frederica aquifer is underlain by a middle silt and clay unit which is greater than 80 feet thick in the area of Dover Air Force Base.

At DNTS, three in-ground 3 meter by 5 meter test cells with sheet metal framing have been constructed. The test cells are keyed into a clay unit present at 40 feet below the ground surface. A secondary containment cell is also present around the test cells. Test cells 2 and 3 will be used for the enhanced source removal (ESR) project demonstrations. A total of 12 injection/extraction wells were to be installed in an array to provide hydraulic containment.

Six different pilot tests will be conducted at Dover AFB, beginning in August 1998; five of the six tests will be in situ flushing demonstrations, with the sixth being an air sparging/SVE demonstration. Each test will be run for approximately seven months, including phases for tracer studies, demonstration, and post-tracer studies for delineation of residual contamination.

Each in situ flushing technology tested will consist of flushing the test cell with a remedial fluid to remove PCE. Researchers know only that the permit allowed for the release of up to 100 liters, or 26 gallons, of PCE, thus simulating a 1/2 barrel spill. Recovered PCE/remedial fluids will be extracted from the test cell and treated at the surface or at an off-site facility. After each demonstration, the test cell will be flushed again with clean water to remove any remaining remedial fluids.

The first in situ flushing project will be conducted in test cell 3 at Dover AFB, and is scheduled to begin in mid August, 1998. University of Florida researchers will conduct a partioning interwell tracer test (PITT) to identify the volume of PCE released into the test cell. They will then use ethanol for remedial in situ flushing testing cosolvent solubilization as the removal mechanism.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0010

Project Name: Eckenfelder, Inc. - Surfactant Recycling

City: Nashville **State/Province:** TN

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), Technology Innovation Office, Washington, DC, available at www.gwrtac.org

Project Summary:

The following is excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org:

Researchers from Eckenfelder, Inc., and Vanderbilt University have successfully tested a pilot-scale system for recycle and reuse of spent surfactant solution from organics-contaminated soil washing. The research involved testing of the integrated pilot-scale unit on the removal of biphenyl from a soil test bed (152 pounds) spiked with biphenyl as a representative nonvolatile contaminant and the continued treatment of the soil with the recycled surfactant solution. Not only was 99% of the biphenyl removed from the soil, but there was no decrease in the effectiveness of the recycled surfactant solution in removing the biphenyl compared to the virgin solution.

This work was conducted under a U.S. EPA Small Business Innovative Research Phase II (SBIR-II) research grant. Since it had been determined in earlier Phase I research that the surfactant can remove high levels of biphenyl (1000 mg/kg) from soil, the Phase II research simulates the polishing of the removal of biphenyl. Soil with an initial biphenyl concentration of 92 mg/kg was cleaned to approximately 1 mg/kg using 7.7 pore volumes of a 2.5% surfactant solution. A conservative estimate of 20 to 40 pore volumes of water would be required to reach the same degree of biphenyl removal. The process achieved a 90% volume reduction of waste even without optimization of the system.

Researchers also have developed a mathematical model to assess relative cleanup times as a function of the location of the recovery and injection wells, surfactant concentration, solution flow rates, and soil particle size. The model also has been used to estimate preliminary full-scale costs for PCB removal.

The surfactant selected by Eckenfelder, Inc. for testing is sodium dodecyl sulfate (SDS). It is biodegradable, relatively nontoxic, and commercially available. The anionic character of SDS permits its recovery and reuse by solvent extraction and also reduces its tendency to sorb to negatively charged soils, such as clays.

Researchers have proposals in to DOE and DOD for further tests of both in situ and ex situ systems.

Report(s)/Publication(s) (Additional Information Sources):

Clarke, Ann N., Oma, Kenton H., Megehee, Maria M., and Wilson, David J. "Soil Cleanup by Surfactant Recycle Washing II." Separation Science and Technology 28 (13-14) October 1993, p 2103-2135.

Oma, K.H., Clarke, A.N., Megehee, M.M., Mutch, R.D. and Wilson, D.J. "Pilot-Scale Surfactant Flushing Test Results with PCB-Contaminated Soil" Proceedings of an ACS Conference on Emerging Technologies for Hazardous Waste Management, Atlanta, GA, September 21-23, 1992.

Oma, Kenton H., Clarke, Ann N., Megehee, Maria M., and Wilson, David J. "Soil Cleanup by Surfactant Washing III." Separation Science and Technology 28 (15-16) November 1993, p. 2319-2349.

Underwood, Julie L., Debelak, Kenneth A., Wilson, David J., and Means, Jennifer M. "Soil Cleanup by In Situ Surfactant Flushing V. "Separation Science and Technology 28 (8), May 1993, p. 1527-1537.

Underwood, Julie L., Debelak, Kenneth A., and Wilson, David J. "Soil Cleanup by Surfactant Washing VI. "Separation Science and Technology 28 (9), July 1993, p. 1647-1669

U.S. Enivronmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), Technology Innovation Office, Washington, DC, available at www.gwrtac.org.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0011

Project Name: Estrie Region Machine Shop, Quebec, CA

City: Quebec City **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): Charles Boulanger
GSI Environnement

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Project Summary:

The following was excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org, and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, which cites Ross, et al., 1996:

"During the fall and winter of 1993-94, Ecosites Inc. in Quebec City started the in situ restoration of contaminated soil under a machine shop building. The contamination was cutting oil extended from 6 to 14 feet (1.83-4.27 m) beneath the concrete slab. This represents a volume of 2350 cu. yd. (1,800 m3) of oil laden soils with concentrations reaching 200,000 ppm (mg/kg). Moreover, a free-floating product phase of hydrocarbon reaching 3 feet (~ 1 m) in free thickness was observed."

The watertable was at approximately 3 m BGS. The hydraulic conductivity was 10-4 cm/sec. 400 injection-extraction wells were installed in 3 distinct zones: A peripheral network to hydraulically isolate the contamination, a second zone used only to extract the oils and washing solutions, and a third zone which was used both to inject and extract material. The extract was processed on-site in a wastewater treatment system. Laboratory feasibility trials were performed to: select the surfactant, evaluate biodegradability and toxicity of wash solutions, and plan hydraulic controls. A computerized system for data acquisition was installed to monitor ground-water movement.

"A total of 157.5 metric tons (160,000 kg) of oil has been extracted from the subsoil in less than 110 days of operation. During 20 days in the fall 1993 and another 30 days during the winter 1994, 8,270 gallons (37,600 liters) of free oil were recovered. and the sludge in the water treatment system trapped the equivalent of 2,090 gallons (9,500 liters) of oil. The second cycle consisted of applying eight cycles of washing operations underneath the building using biodegradable, nontoxic surfactant solutions. These operations extended over 60 days.

The results show that a total of 353,000 lb (160,000 kg) of hydrocarbon were extracted from the soil in order to decontaminate the site to a level tolerable to the authorities. Daily recovery rates varied between 880 and 5,500 Ib/day (400 and 2,500 kg)." The watertable within the contaminated area was raised 2 m by injecting washing solution using the injection/extraction wells. Most of the recovered fluids were emulsified oil. After extraction, high microbial levels of hydrocarbon degraders were found in the soil. The duration of the project was 12 months, and was completed at a cost of +/- $1,200,000. (Canadian).

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Ross, A., Boulanger, C., and Tremblay, C. 1996. "In Situ Remediation of Hydrocarbon Contamination Using an Injection-Extraction Process," Remediation Management, March/April, pp. 42-45.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0012

Project Name: General Motors NAO Research & Development Center, Warre

City: Warren **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, and GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue U, avail. at www.gwrtac.org:

Following laboratory evaluations of a surfactant washing technique, researchers conducted a two-phase field test of an in situ surfactant washing method at a site contaminated with polychlorinated biphenyls (PCBs) and oils. Feasibility studies were also conducted on the use of ultrafiltration to recover surfactant from aqueous waste streams generated from the in situ surfactant washing. The field test site was used to store unused machinery and the contamination is confined to the upper 15 feet of the subsurface fill material. A containment wall of clay and cement was previously installed around the five-acre site. This wall extends to a depth of 60 feet below the surface. A surfactant solution was applied via vertical infiltration to a test plot 10 feet in diameter and five feet deep, for 70 days. The leachate was collected with a recovery well installed through the center of the plot. The leachate pumped to the surface was biotreated to degrade the oils and surfactant while the PCBs were recovered from the leachate by an activated carbon system. Soil cores from the site showed initial concentrations of up to 6,000 ppm PCBs and 67,000 ppm oils. In separate tests, leachate from the surfactant washing demonstration was collected in a process tankand pumped into a Romicon Model HF-Lab-5 ultrafiltration unit equipped with either of two membranes (XM50 and PM500) to evaluate the recovery of the surfactant from the leachate for possible reuse.

About 10% of the contaminants were recovered after 5.7 pore volume washings during the phase 1 field test. During a similar phase 2 test the following year, an additional 14% was recovered after 2.3 pore volumes. The results from the second phase of the field study surpassed the prediction of the long-term perfomance of this technology based on the phase 1 results and confirmed the technical viability of the process.

In the ultrafiltration experiments, 67% of the surfactant mass was recovered with the PM500 membrane, with 90 and 83% of the PCBs and oils being retained, respectively. The XM50 membrane did not capture the surfactant quite as efficiently (46%), however retained approximately the same fraction of PCB and oil (94% and 89%, respectively).

Report(s)/Publication(s) (Additional Information Sources):

Abdul, A.S., Gibson, T.L., and Rai, D.N. 1990. "Selection of Surfactants for Removal of Petroleum Products from Shallow Sandy Aquifers," Ground Water, Vol. 28, No. 6, pp. 920-926.

Abdul, S.A., and Gibson, T.L. 1991. "Laboratory Studies of Surfactant-Enhanced Washing of Polychlorinated Biphenyl from Sandy Materials," Environmental Science & Technology, Vol. 25, No. 4, pp. 665-671.

Abdul, A.S., Gibson, T.L., Ang, C.C., Smith, J.C., and Sobczynski, R.E. 1992. "In-Situ Surfactant Washing of Polychlorinated Biphenyls and Oils from a Contaminated Aquifer," Ground Water, Vol. 30, No. 2, pp. 219-231.

Abdul, A.S., and Ang, C.C. 1994. "In-Situ Surfactant Washing of Polychlorinated Biphenyls and Oils from a Contaminated Field Site: Phase II Pilot Study," Ground Water, Vol. 32, No. 5, pp. 727-734.

Ang, C.C., and Abdul, A.S. 1991a. "Aqueous Surfactant Washing of Residual Oil Contamination from Sandy Soil," Ground Water Monitoring Review, Vol. 11, No. 2, pp. 121-127.

Ang, C.C., and Adbul, A.S. 1991b. "A Laboratory Study of the Biodegradation of an Alcohol Ethyoxylate Surfactant by Native Soil Microbes," Journal of Hydrology, Vol. 138, pp. 191-209.

Ang, C.C., and Adbul, A.S. 1994. "Evaluation of an Ultrafiltration Method for Surfactant Recovery and Reuse During In Situ Washing of Contaminated Sites: Laboratory and Field Studies," Ground Water Monitoring and Remediation.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency, 1995: "In Situ Remediation Technology Status Report: Surfactant-Enhancements", EPA 542-K-94-003, Office of Solid Waste and Emergency Response (5102W), Washington, DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0013

Project Name: GHEA Associates, New Jersey Operating Facilty of Major U.S.

City: **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, and GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue University, available at www.gwrtac.org:

Nonionic surfactant to be used as flushing solution to treat VOCs, SVOCs and BTEX. (Project was started, but put on hold as of April 1995). On-site system for cleaning leachates and reconstituting surfactants. Site is actively used for machining operations. Soils underlying the site are very clayey, and are contaminated with a mixture of chlorinated organic solvents and BTEX at levels of 1,000 to 2,000 ppm. The water table is located approximately ten feet below the ground surface. There is a clay barrier about ten feet below the ground surface. The treatment zone will be isolated with slurry walls. Due to relatively low permeability of the soil, a dense network of feed trenches alternated with extraction wells will be used to contact the flushing solution within this zone.

This project had been on hold since 1995. There were no plans to restart the project at that time.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency, 1995: "In Situ Remediation Technology Status Report: Surfactant-Enhancements”, EPA 542-K-94-003, Office of Solid Waste and Emergency Response (5102W), Washington, DC

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0014

Project Name: Goose Farm, Plumsted Twp, NJ

City: Plumsted Twp. **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): Farnaz Sargazzi
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following text is from notes from April 1997 conversation with EPA RPM, July 1998 conversation with former EPA site hydrogeologiest, and from Internet (EPA.gov):

Site is located approximately two miles northeast of New Egypt, New Jersey. Majority of waste materials (lab packs, 55-gallon drums, bulk liquids) from manufacture of polysulfide rubber and solid rocket fuel propellant were place into 100 x 300 x 15 foot pit dug through fine sand. ROD (9/27/85) states groundwater will be extracted via a wellpoint system, treated on site, and re-injected into the soil. It was estimated that ten pore volumes would be required to remove the mobile contaminants from the soil and groundwater. Pilot studies were planned during the design phase to optimize the treatment system components.

RPM (4/25/97) indicates that flushing occurs on a continuous basis. A total of 41 extraction wells are utilized, pumping an average of 80 gpm. The water is treated aboveground and approximately 85 to 90% of the water is re-injected. The contaminated zone is within the Cohansey Aquifer, and is contained within a slurry wall, which is approximately 40 feet deep, and keyed into a semi-confining layer underlying the treatment zone. The confining layer has a vertical hydraulic conductivity of 10-5 cm/sec. order of magnitude. Two re-injection trenches are located within the slurry wall, and flush the contaminated zone. Two additional trenches are located outside of the slurry wall in uncontaminated areas, are are used to control hydraulic gradient only. All trenches are shallow, and are of variable lengths.

As of July 1998, former site hydrogeologist indicated that approximately two years prior, problems with the in situ flushing operation occurred at the site. Groundwater samples from wells completed in the lower aquifer beneath the confining layer began to exhibit high concentrations of benzene. At this time, all of the groundwater being infiltrated was being directed into the shorter trench within the slurry wall, due to malfunctioning equipment in the longer trench. It was speculated that the hydraulic heads in the upper Kirkwood Aquifer, which was the aquifer being targeted for flushing, had become too high, thus causing downward leakage through the confining layer. Around this time, water was re-diverted into the longer trench, and into the trenches located outside the slurry wall. In the opinion of this EPA representative, there may be innate problems using commercially available software to model in situ flushing operations. The narrow features of slurry walls and infiltration trenches are often not compensated for during the modeling efforts, and it often can not be proven that all the water being infiltrated can indeed be captured.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm;

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0015

Project Name: Hill Air Force Base, UT (Cell 3, OU1 - Cosolvent Mobilization)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Falta, et. al., 1997: Abstract "Field Evaluation of Cosolvent-Enhanced In-Situ Remediation", CRADA CR-821992-01-0 between R.S. Kerr Environmental Research Lab and Clemson University, July 28, 1997.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following is excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org, Falta, et. al., 1997: Abstract "Field Evaluation of Cosolvent-Enhanced In-Situ Remediation", CRADA CR-821992-01-0 between R.S. Kerr Environmental Research Lab and Clemson University, July 28, 1997, and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The saturated zone pore volume (PV) within each cell is variable from 1,000 to

2,500 gallons per cell. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For the test at Cell 3, OU 1, tert-butanol mixed with n-hexanol was used as the flushing solution. The 3 m x 5 m test cell contains approximately 1,500 gallons of water (i.e., the PV). A partitioning tracer test was performed on the cell with bromide, ethanol, methanol, tert-butanol, methyl-hexanol, and dimethyl pentanol as tracers. From this test, the estimated amount of NAPL in the cell is 60 gal. The LNAPL originated from petroleum hydrocarbons and spent solvents, and is a complex mixture of aromatic and aliphatic hydrocarbons, chlorinated solvents, and other compounds. The bulk of the NAPL composition consists of low solubility, low vapor pressure compounds, and the NAPL not soluble in pure methanol, ethanol, acetone, or isopropanol.

The test involved the injection and extraction of 7,000 gallons of a mixture of tert-butanol and n-hexanol. Specifically, the following chemical system was delivered in sequence:

0.85 pore volume of 95 vol% tert-butanol/hexanol (1 pore volume is approximately 1,500 gal)

1.33 pore volumes of 81 vol% tert-butanol/hexanol, 16 vol% n-hexanol

2.33 pore volumes of 95 vol% tert-butanol

0.33 pore volume of 47.5 vol% tert-butanol

30 pore volumes of waterflood

It was anticipated that most of the NAPL will be removed before the total volume of alcohol is pumped. The earlier cosolvent test at Hill AFB performed by The University of Florida group (Test 1, Operational Unit 1) was designed to solubilize the NAPL. The intent in this test is to mobilize the NAPL to basically remove it in a plug. Formulating a cosolvent mixture that will mobilize this specific complex NAPL has required extensive laboratory work. Fluids produced during the effort were stored on site with plans for eventual discharge to the onsite wastewater treatment plant.

The results of post flood soil coring indicate better than 90% removal of the more soluble contaminants (TCA, toluene, ethylbenzene, xylenes, trimethylbenzene, naphthalene) and 70% to 80% removal of less soluble compounds such as decane and undecane. The results of pre-flood and post-flood NAPL partitioning tracer tests show about 80% removal of the total NAPL content from the test cell.

Report(s)/Publication(s) (Additional Information Sources):

Falta, et. al., 1997: Abstract "Field Evaluation of Cosolvent-Enhanced In-Situ Remediation", CRADA CR-821992-01-0 between R.S. Kerr Environmental Research Lab and Clemson University, July 28, 1997.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

GWRTAC ID: FLSH0016

Project Name: Hill Air Force Base, UT (Cell 5, OU1 - Surfactant Mobilization)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following is excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The saturated zone pore volume (PV) within each cell is variable from 1,000 to 2,500 gallons per cell. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For the test at Cell 5, OU 1 performed in the summer of 1996, an Aerosol OT/Tween series surfactant mixture with added $CaCl_2$ was used as the surfactant. Many (if not all) Tween series surfactants have U.S.D.A. food grade additive status. The intent is to mobilize the NAPL with a middle phase microemulsion. Initial partitioning tracer tests were performed. Specifically, 6.6 pore volumes of a 2.2 wt% Aerosol OT and 2.1wt% TWEEN 80 solution were injected through the 3 x 5 m test cell. During treatment 3,000 to 4,000 samples were to be collected from the extraction and multiport sampling wells for chemical and surfactant analysis. Fluids produced were stored on site with plans for eventual discharge to the Hill AFB wastewater treatment plant.

As of February 1997, analysis of the collected data was ongoing. Formal documentation of results was anticipated in 1997.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0017

Project Name: Hill Air Force Base, UT (Cell 6, OU1 - Surfactant Solubilizatio

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following is excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The saturated zone pore volume (PV) within each cell is variable from 1,000 to 2,500 gallons per cell. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For the test at Cell 6, OU 1 an initial partitioning tracer test was first performed. Then in the summer of 1996, an overall 4.3 wt% solution of Dowfax 8390 was used as the surfactant for remedial flushing. This is a solubilizing (micelle forming) diphenyloxide disulfonate surfactant mixture; the same one used at the Traverse City site. The intent is to solubilize the NAPL within surfactant micelles. The specific Dowfax surfactant was chosen largely because of its low sorption potential in the subsurface due to the dual negative charges on each monomer. Specifically, 10 pore volumes of the Dowfax solution were injected through the 3 x 5 m test cell. It is anticipated that this system will be less efficient than the mobilizing system used in Cell 5: Ten pore volumes may not be sufficient to reduce the residual NAPL concentration to below 10% of the original value. During treatment 3,000 to 4,000 samples were to be collected from the extraction and multiport sampling wells for chemical and surfactant analysis. Fluids produced during the effort were stored on site with plans for eventual discharge to the Hill AFB wastewater treatment plant.

As of February 1997, data analysis was ongoing. Formal documentation of results was anticipated in 1997.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, GWRTAC, 320 William Pitt Way, Pittsburgh, PA, available at www.gwrtac.org

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

GWRTAC ID: FLSH0018

Project Name: Hill Air Force Base, UT (Cell 8, OU1 - Surfactant/Cosolvent S

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

AATDF Spring 1998 Newsletter: Summary "Lab and Field Evaluation of Single-Phase Microemulsions for Enhanced In-Situ Remediation of Contaminated Aquifers".

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Jawitz, J.W., R.D. Rhue, M.D. Annable, and P.S.C. Rao, 1997: Executive Summarry of "Laboratory and Field Evalution of Single-Phase Microemulsions (SPME) ffor Enhanced In-situ Remediation of Contaminated Aquifers" Final Report, Nov. 28, 1997, Submitted to: DoD/AATDF, Rice University, Houston, TX

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following is excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org, ,AATDF Spring 1998 Newsletter: Summary "Lab and Field Evaluation of Single-Phase Microemulsions for Enhanced In-Situ Remediation of Contaminated Aquifers", and Jawitz, J.W., R.D. Rhue, M.D. Annable, and P.S.C. Rao, 1997: Executive Summarry of "Laboratory and Field Evalution of Single-Phase Microemulsions (SPME) ffor Enhanced In-situ Remediation of Contaminated Aquifers" Final Report, Nov. 28, 1997, Submitted to: DoD/AATDF, Rice University, Houston, TX:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The saturated zone pore volume (PV) within each cell is variable from 1,000 to 2,500 gallons per cell. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For the test at Cell 8, OU 1, conducted in the summer of 1996, a field trial involving flushing with a microemulsion precursor (a mixture of a nonionic surfactant and alcohol) was conducted. A mixuture of 3.5 wt% Brij 91 [Polyoxyethylent (10) Oleyl Ether]) and 2.5 wt% n-pentanol was used to generate a stable, single-phase microemulsion (SPME) of LNAPL in the aqueous solution. In the single-phase microemulsion SPME process, a surfactant and co-surfactant (alcohol) mixture is added to the subsurface, where a water-continuous, low-viscosity, oil-in-water microemulsion forms on contact with residual NAPL. This Winsor Type I microemulsion can be diluted in water and transported through porous media as a single-phase, low-viscosity fluid. In contrast with micellar solubilization, which typically requires 10 - 20 pore volumes of flushing and selectively solubilizes NAPL components, fewer pore volumes of the surfactant/alcohol mixture are needed to microemulsify all NAPL components uniformly. The SPME study was divided into three separate phases: Laboratory Precursor Selection, Field Implementation, and Numerical Simulations.

The first phase of this study was to select a surfactant and cosurfactant which together form the microemulsion precursor, which would produce a low-viscosity, single-phase microemulsion on contact with the complex, multi-component NAPL found at the field site. Eighty-six surfactants and a number of alcohols were screened, with enhanced NAPL solubilization and low-viscosity (<2 cp) as the main acceptance criteria. The viscosity of the precursor solution was limited to preclude large hydraulic gradients across the test cell and excessive drawdown around the extraction wells. The precursor solution selected was the surfactant Brij 97® (polyoxyethylene (10) oleyl ether) at 3% by weight and n-pentanol at 2.5% by weight in water. This mixture was evaluated in the laboratory in both column and two-dimensional aquifer models using contaminated and uncontaminated media from the field site at Hill AFB.

The second phase of this study was field implementation of the SPME flushing technology in a test cell constructed at Hill AFB Utah. Field testing of the SPME technology was part of a larger study coordinated by researchers at the USEPA National Risk Management Laboratory in Ada, Oklahoma. The study was funded through the Strategic Environmental Research and Development Program (SERDP) to conduct side-by-side testing of a total of nine technologies. Each test was conducted in isolation test cells using evaluation methods that provided consistency among the results. The final comparison of the effectiveness of each technology will follow completion of the studies.

The SPME flushing field study was conducted in a test cell that isolated a section of the surficial aquifer by penetrating a thick clay aquitard at a depth of eight meters (26.2 feet) below ground surface (bgs). At Hill AFB, OU1, the LNAPL has over 200 identified components. The major constituents of the Hill OU1 LNAPL on a mass basis are decane, 1,3,5-trimethyl benzene and undecane. Seasonal fluctuations in the water table smeared the LNAPL over the interval 5 m (16.4 feet) bgs to 8 m (26.2 feet) bgs. The sheet pile-enclosed cell measured 2.8 m x 4.6 m (9.2 x 15.1 feet) and penetrated 3.7 m (12.1 feet) into the clay confining unit. Leak testing of the sheet pile cell confirmed that leakage of the sheet pile cell was insignificant. The water table within the test cell was maintained at 4.9 m bgs. The test cell held fifteen multilevel samplers, three extraction wells and four injection wells. The injection wells and extraction wells were screened from 4.9 m to 7.9 m (16.1 to 25.9 feet) bgs. At each of the fifteen multilevel sampler locations, from five to eight individual samplers were bundled to yield a total of 96 multilevel sampling points. Peristaltic pumps maintained a flow rate of approximately one pore volume per day.

The extent of contamination within the test cell was assessed by collecting soil samples during well installation and analyzing for a selected group of target analytes present in the NAPL. The test cell contamination was also characterized by conducting a 10-pore volume tracer test with a group of partitioning and non-partitioning tracers. The test cell had an average NAPL saturation of about 0.06 prior to SPME flushing. Water samples were also collected and analyzed for the target analytes, however, nearly all the contaminants were below detection limits. Finally, before the SPME flood, contamination in the test cell was characterized using interfacial tracers. The method estimates the contact area between NAPL and water in the test cell. The interfacial tracer method, developed at the University of Florida, was tested for the first time in the SPME test cell at Hill AFB. The result indicated that the NAPL-water contact area can vary more than one order of magnitude within the test cell. This variability in NAPL-water contact area could have significant impacts on in-situ flushing extraction efficiency. If there are mass transfer limitations that are magnified with low NAPL-water contact area this will reduce flushing efficiency, or if the NAPL is simply non-uniformly distributed, as evidenced by a low NAPL-water contact area, this can lead to inefficiencies.

The SPME flood was conducted over a 18-day period by pumping nine pore volumes of the precursor solution with some flow interruption periods. In the field test, a non-reactive tracer test was conducted first to determine the hydrodynamic performance of the cell and then set the flow rate for the rest of the flushing test. Next, a 0.16 pore volume pulse of partitioning tracers, methanol (2700 mg/L) and 2, 2-dimethyl 3-pentanol (930 mg/L), flowed through the sheet pile-enclosed cell before the SPME test. The distribution and morphology of NAPL in the test cell was also characterized with interfacial tracers that were first developed and tested during this project. After the pre-flood tracer tests, 3.5 pore volumes of water were flowed through the test cell. Nine pore volumes of the surfactant and alcohol mixture (3% Brij 97 (polyoxyethylene (10) oleyl ether) and 2.5% n-pentanol) were perfused through the test cell. The viscosity of the surfactant + alcohol mixture, measured in the field, was 1.66 centipoise. The surfactant/alcohol mixture was followed by surfactant alone, a water flood, and a final partitioning tracer test.

To assess NAPL removal, the investigators collected soil cores before and after the addition of the surfactant and alcohol mixture; they also conducted pre- and post-flush NAPL partitioning tracer tests. Fluid samples were collected from the extraction wells (540 total) and multilevel samplers (6500 total). Eighty-five pre-flush soil core samples and 40 post flush soil core samples were collected from the test cell. Soil cores were sub-sampled and immediately extracted in the field. Soil core and fluid samples were analyzed for target LNAPL components (p-xylene, n-decane, n-undecane, n-dodecane, n-tridecane, 1, 2 - dichlorobenzene, 1, 2, 4 - trimethylbenzene, naphthalene, trichlorobenzene).

The use of multiple methods of evaluation provides a more comprehensive assessment of the technology and therefore better comparison with other technologies tested in the SERDP project. During the SPME flushing study, samples of effluent (combined from the three extraction wells) were collected for a laboratory investigation of methods to minimize and reduce cost of waste management. The use of salt to separate the waste into oil and water rich phases for more economic disposal was investigated at a small pilot scale.

Following the SPME flood, a post-flushing partitioning tracer test was conducted. The method and tracers used were the same as the pre-flushing test. The average NAPL saturation in the test cell following the SPME flood was 0.018, producing a NAPL reduction of about 72%. After the tracer test was completed, post-flushing core samples were collected. The core samples were compared to average values obtained during the pre-flush sampling to estimate mass removal for each target analyte. The mass removal based on core estimates ranged from 64 to 96%, but the three largest constituents present in the NA.PL, n-undecane, n-decane, and 1,3,5-trimethylbenzene, were removed more than 90%.

The final method used to evaluate the SPME effectiveness was a mass balance on the target analytes. Using estimates of initial mass from the core data and partitioning tracers, the mass recoveries were calculated. Using the partitioning tracers to estimate initial mass, the mass removal estimates ranged from 62 to 82%. When the core data are used to estimate the initial mass only two constituents, n-decane and n-undecane, can be compared for removal effectiveness and the removals for these were 93 and 105%, respectively. Once again, an apparent difference in the effectiveness is seen between the results based on tracers and soil cores. A pitch fraction model of the NAPL is proposed as a likely explanation for the differences observed. The methods outlined above demonstrate that the SPME process was capable of affecting significant mass removal of the complex multi-component NAPL.

Simulations of the SPME flushing study were conducted following the experiment. In this effort both the tracer tests and the SPME flushing results were used. The simulator UTCHEM was used. The model was capable of simulating the processes observed in the experimental data. It was evident that the model required the use of a mass transfer term to capture the observed behavior. While the model simulation may have limited use in helping to design experiments conducted in a controlled test cell, they can be very important for designing hydraulically controlled systems. Of greater utility are simulations to assess cost and efficiencies of the SPME process at larger scales than the test cell.

Report(s)/Publication(s) (Additional Information Sources):

AATDF Spring 1998 Newsletter: Summary "Lab and Field Evaluation of Single-Phase Microemulsions for Enhanced In-Situ Remediation of Contaminated Aquifers".

Annable, M.D., Jawitz, J.W., Rao, P.S.C., and Rhue, R.D. 1996c. "Field Testing of a Surfactant-Alcohol Mixture for In-Situ NAPL Solubilization as a Microemulsion." Presented at the 2nd Annual Conference on Remediation, Houston, Texas, pp. 75-77.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr.

Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Jawitz, J.W., R.D. Rhue, M.D. Annable, and P.S.C. Rao, 1997: Executive Summarry of "Laboratory and Field Evalution of Single-Phase Microemulsions (SPME) ffor Enhanced In-situ Remediation of Contaminated Aquifers" Final Report, Nov. 28, 1997, Submitted to: DoD/AATDF, Rice University, Houston, TX

Jawitz, J.W., M.D. Annable, P.S.C. Rao, and D. Rhue. 1997. "Field Testing of a Surfactant-Alcohol Mixture For In-Situ NAPL Solubilization As A Single-Phase Microemulsion," Extended Abstract. To be presented at the ACS annual meeting in San Francisco, April 1997.

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Monthly Progress Reports are available from the Advanced Applied Technology Demonstration Facility for Environmental Technology, at DOD/AATDF, Rice University, Energy & Environmental Systems Institute, M.S. 316, P.O. Box 1892 (or 6100 S. Main St.), Houston, Texas 77251 (or 77005).

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0019

Project Name: Hill Air Force Base, UT (OU2 - Micellar Flood)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

Project Summary:

The following was excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org, Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, and Executive Summary of Demonstration of Surfactant-Enhanced Aquifer Remediation of Chlorinated Solvent DNAPL at Operable Unit 2, Hill AFB, UT, INTERA (a Duke Engineering & Services Company). Direct quotes are from Rice University, 1997:

During the summer of 1996, INTERA conducted a successful demonstration of surfactant-enhanced aquifer remediation (SEAR) in collaboration with the Center for Petroleum and Geosystems Engineering at the University of Texas at Austin (UT) and with Radian International. The US Air Force Center for Environmental Excellence (AFCEE) funded the necessary DNAPL-zone characterization and surfactant-flood demonstration. The Center for Petroleum and Geosystems Engineering at UT funded the design of the surfactant floods, and Hill AFB near Ogden, Utah provided extensive logistical support. The University of Texas performed the design of the surfactant flood and a partitioning tracer test, and RADIAN International performed the treatment engineering. INTERA, Inc. was the principle contractor and performed all field injection-extraction operations and applied for all permits. As is documented in this report, SEAR meets the requirements set down by the Defense Department's DNAPL Integrated Product Team (IPT) for cost-effective detection and remediation of chlorinated-solvent DNAPL zones.

The demonstration was conducted at Operable Unit 2 (OU2) at Hill AFB, which had received large volumes of chlorinated solvents from degreasing operations conducted at the base. OU2 is a closed chemical disposal area underlain by an alluvial sand aquifer confined on its sides and below by thick clay deposits that form a capillary barrier to DNAPL migration. The hydraulic conductivity of this alluvium is in the range of 10-2 to 10-3 cm/s. This aquifer contains tens of thousands of gallons of DNAPL, seventy percent of which is TCE.

Based on extensive laboratory testing, a chemical system including sodium dihexyl sulfosuccinate (8 wt%), isopropyl alcohol (8 wt%) and sodium chloride was selected for the field study. Laboratory work indicates that this system generates a micellar solution that can effectively carry 600,000 mg of TCE per liter and reduces interfacial tension by approximately two orders of magnitude. Laboratory work also was conducted to select tracers to be used in Partitioning Interwell Tracer Tests (PITTs), which were conducted prior to Phase I chemical delivery (May), prior to Phase II chemical delivery (August), and after Phase II delivery.

A demonstration area was developed during the Spring of 1996 by installing a set of three injection wells (SB-2, SB-3 and SB-4) and three extraction wells (U2-1, SB-1 and SB-5) in a 3 x 3 line-drive geometry. This well field also contained one hydraulic control (injection) well (SB-8) to prevent the upgradient flow of tracers and surfactant, and one interwell monitor well. The distance between injectors and extractors was 20 ft; the distance between individual injectors and individual extractors was 10 ft; the water table depth was approximately 25 ft below ground surface; and there was a 4-ft thick zone of free-phase and residual DNAPL approximately 45 ft below ground surface. The screened intervals of the injectors and extractors were completed in this DNAPL zone and extended some distance above it. Prior to the demonstration, about 500 gallons of free-phase DNAPL were pumped from the recently-installed well field and sent for incineration,

The demonstration was conducted in two phases. The first of these phases comprised a partitioning interwell tracer test (PITT) followed by a DNAPL solubilization test, both of which were conducted in May and early June 1996. The PITT determined the spatial distribution and volume of DNAPL in the test zone of the alluvial aquifer. The solubilization test verified the efficiency of the selected surfactant, determined if the surfactant would cause the deflocculation and mobilization of fine-grained particles resulting in a reduction in permeability of the aquifer, and also addressed the issue of the effect of the surfactant-rich effluent on the efficiency of the steam stripping system at the site. This test involved the injection of an 8% surfactant solution into one injection well at 2 gpm for 0.6 days, producing an interfacial tension of 0.1 dynes/cm between the surfactant solution and the OU2 DNAPL.

"Preliminary evaluations of the chemical delivery/recovery systems and the delivery sequence were conducted using the numerical model UTCHEM. UTCHEM is described in detail by Delshad, et al. (1996).

Overall, the field demonstration involved the following sequence of fluid delivery and recovery:

Phase I PreTest Waterflood (1.4 PV)

Initial Partitioning Interwell Tracer Test (4.3 PV)

Phase I Chemical Delivery (0.4 PV SB-2 Only) Phase 1 Water Flushing (3.2 PV)

Phase I Post-Test Recovery Only (2.9 PV)

Phase 2 PreTest Waterflood (1.2 PV)

Electrolyte flood (0.7 PV)

Intermediate Partitioning Interwell Tracer Test (2.9 PV)

Phase 2 Chemical Delivery (PV 2.4)

Phase 2 Water Flushing (PV 7.8)

Final Partitioning Interwell Tracer Test (PV 4.3)

Typical fluid delivery rates were on the order of 7.5 gpm, with flow split equally between the wells. Typical recovery rates were slightly higher, on the order of 9.2 gpm, and again flow was split equally between the wells. The water delivery rate to the hydraulic control well was approximately 7 gpm.

Fluids produced during the field demonstration were initially treated to approximately 10 mg/L TCE by an existing onsite steam stripping unit. Fluids from this system were subsequently discharged to the AFB wastewater treatment system. This effort will develop data supporting the potential use of this technology for larger scale applications. In addition, researchers at the U.S. EPA Cincinnati Laboratory collected approximately 5,000 gallons of Phase II fluids to be used in testing of membrane filtration technologies for reuse of surfactant. This effort is funded by the U.S. Navy."

Approximately 800 gallons of DNAPL was present in the test section of the aquifer. However, approximately 450 gallons of DNAPL was free-phase DNAPL and was removed by pumping prior to the first PITT. During the solubilization test, with an 8% surfactant injection over 0.6 days (0.6 pore volumes), the TCE concentration in the central monitoring well rose from approximately 600 mg / L prior to the injection to 40,000 mg / L after. The maximum DNAPL solubilization capacity was calculated to be 61,000 mg / L for this surfactant injection concentration. The concentrations in the 3 extraction wells were lower, likely due to dilution caused by streamtube convergence on these wells. Problems with surfactant foaming in the steam stripper occurred during this phase, which the investigators attempted to remedy in Phase II.

The PITT indicated that there was a total of 346 gallons of residual DNAPL in the 4-ft thick test zone with an average residual DNAPL saturation of 20% (i.e., Sr = 0.20) or approximately 4% when measured over the whole, 20-ft thick, swept volume of the aquifer (i.e., Sr = 0.036). The solubilization test showed the selected surfactant to be extremely effective, and that there was no significant head loss due to mobilization of fines across the line-drive test zone. Furthermore, the steam stripper at OU2 readily treated the surfactant-rich waste waters.

The results of the Phase I field operations were used to finalize the design of the Phase II surfactant flood. The Phase II flood, the purpose of which was to remove all remaining DNAPL from the test zone in the alluvium, was preceded and followed by PITTs so that the performance of the flood could be assessed. The surfactant flood consisted of the injection of a solution of 8% surfactant, 4% isopropyl alcohol and 0.7% NaCl, producing an interfacial tension of 0.02 dynes/cm. The Phase II field operations lasted for 30 days, of which surfactant injection at 7.5

gpm accounted for 3 days (i.e., 2.4 pore volumes), the follow-up water flood took 5.5 days and the final PITT took 6 days. This final PITT indicated that the average residual DNAPL saturation over the 20-ft thick swept zone of the aquifer had been reduced from 0.036 in early May to 0.0004 in late August in a swept volume of approximately 15,000 gallons. Therefore, the PITTs had shown that the two surfactant floods had recovered 341 of the 346 gallons of DNAPL within the test zone of the OU2 alluvial aquifer. This represents a total recovery of 99% of the DNAPL determined by the Phase I PITT to be present in the test zone of the OU2 aquifer.

Following completion of the field work, it was estimated from analysis of the final PITT that approximately five gallons of DNAPL was left in place at the end of the demonstration. The remediation time for these last five gallons has been calculated for various scenarios - as a pool and as vertical fingers with DNAPL blobs or ganglia of differing lengths trapped within the alluvium. Collectively, these scenarios reveal the relative efficiencies of SEAR versus waterflooding versus traditional pump-and-treat.

For the less probable case of a five-gallon pool of DNAPL remaining at the base of the aquifer (less probable, because such a pool would have been observable in monitoring well SB-6), the injection of 3, rather than 2.4, pore volumes of the surfactant/alcohol solution would have dissolved the pool during the demonstration by extending it a few days to a week at most. If instead, the injection of clean water at 7.5 gpm had been continued at the end of the surfactant flood, the five gallons of pooled DNAPL would have been removed by dissolution over a period of ten years. However, if the site reverted to pump-and-treat remediation with only groundwater extraction, then it would take 50 years to dissolve a five gallon pool of DNAPL.

The second case, the more probable one, is that of five gallons of residual DNAPL distributed throughout the aquifer as blobs or "ganglia" of different geometries and surface area. For this case, the injection of 3, rather than 2.4, pore volumes of the surfactant/alcohol solution would have dissolved the ganglia during the demonstration by extending it a day or two at most. If instead, the injection of clean water at 7.5 gpm were continued, the five gallons of DNAPL would have been removed by dissolution over a period of a few months, but less than one year in total. However, if the site had reverted to pump-and-treat remediation with only groundwater extraction and no injection of clean water, then it would take a few months to up to four years to dissolve the DNAPL.

Thus, over the course of a few months, at a cost of about $3,000/gallon, 98.5% of the residual DNAPL was removed. This can be compared with the original USAF estimate for cleanup of the DNAPL that used the traditional time frame of 30 years with a cost of recovery now running at $32,000/gallon. The estimate of 30 years was based on a purely speculative estimate of the efficiency of pump-and-treat remediation and has no basis in fact. However, the cost of $32,000 per gallon of DNAPL recovered is similar to other pump-and-treat systems (e.g., McClellan AFB, CA and DOE Portsmouth, OH) that use ground-extraction wells and an air-stripping system to capture and treat TCE plumes. Furthermore, the recovery of some 500 gallons of free-phase DNAPL before the surfactant flood, and therefore prior to its dissolution and subsequent downgradient extraction and treatment, resulted in a cost savings of approximately $15 million to the USAF.

The two surfactant floods conducted at OU2, Hill AFB during the period May through August 1996 demonstrated the technical practicability of removing ~99% of residual DNAPL from alluvium, provided the site in question is well characterized and an exhaustive design protocol is followed. This level of DNAPL-zone remediation has significant implications for the regulatory issues of technical impracticability and natural attenuation.

Report(s)/Publication(s) (Additional Information Sources):

Brown, C.L., Delshad, M., Dwarakanath, V., Jackson, R.E., Londergan, J.T., Meinardus, H.W., McKinney, D.C., Oolman, T., Pope, G.A., and Wade, W.H. 1996. "A Successful Demonstration of Surfactant Flooding of an Alluvial Aquifer Contaminated with DNAPL." Submitted to Environmental Science & Technology.

Delshad, M., Pope, G.A., and Sepehrnoori, K. 1996. "A Compositional Simulator for Modeling Surfactant Enhanced Aquifer Remediation, 1: Formulation," Journal of Contaminant Hydrology, Vol. 23, pp. 303-327.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Intera, Inc. 1996. "Phase I Work Plan: Demonstration of Surfactant-Enhanced Aquifer Remediation of DNAPLs at Hill Air Force Base." Prepared for the Air Force Center for Environmental Excellence, Technology Transfer Division, Brooks AFB, Texas.

Oolman, T., Godard, S.T., Pope, G.A., Jin, M., and Kirchner, K. 1995. "DNAPL Flow Behavior in a Contaminated Aquifer: Evaluation of Field Data," Journal of Ground Water Monitoring & Remediation, Vol. 15, No. 4.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0020

Project Name: Confidential

City: **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): Confidential
Confidential

Report(s)/Publication(s) (GWRTAC Source):

Project Summary:

The following text is from notes from August 1998 conversation with confidential source:

In situ flushing was implemented in August 1998 to enhance pump and treat remediation of a dissolved arsenic contaminant plume. A horizontal well will be used for groundwater extraction and injection. Approximately 100 gpm of contaminated groundwater is to be extracted, treated above ground, supplemented with additives, and re-injected. A proprietary compound is added as the flushing reagent.

Report(s)/Publication(s) (Additional Information Sources):

GWRTAC ID: FLSH0021

Project Name: Former Dry Cleaning Faciliy, Jacksonville, FL

City: Jacksonville **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): Kevin Warner
Levine Fricke Recon

Report(s)/Publication(s) (GWRTAC Source):

Project Summary:

The following text is from notes from an August 1998 conversation with EPA ORD (R.S. Kerr Laboratory) representative, and an October 1998 update from a representative of Lavine Fricke Recon:

This project is located at the site of a former dry cleaning facility in Jacksonville, FL. PCE DNAPL present in an unconfined aquifer will be targeted by flushing with a cosolvent (95% ethanol and 5% water). Alcohol injection began the week of August 1, 1998. The aquifer consists of a sandy alluvium. The target depth is 26 to 31 feet below the ground surface (bgs). Partitioning tracers and coring will be utilized to determine the amount of PCE removed. The separate phase PCE (both free-phase and residual) is targeted for remediation. EPA ORD (R.S. Kerr Laboratory) will evaluate long-term impacts after completion of flushing (dissolved plume fate, microecology, etc.)

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0022

Project Name: Hill Air Force Base, UT (Test 1, OU 1 - Cosolvent Solubilizatio

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Sillan, R.K., M.D. Annable, and P.C.S. Rao, Editors, 1997: Executive Summary, "In-Situ Cosolvent Flushing for Enhanced Solubilization of a Complex NAPL: Comprehensive Field-Scale Evaluation", Draft Final Report, CRADA CR-821990, May 1997.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Cosolvents, EPA 542-K-94-006, U.S. EPA OSWER (5102W), TIO, Washington, DC, available at www.gwrtac.org

Project Summary:

The following was excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org, U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Cosolvents, EPA 542-K-94-006, U.S. EPA OSWER (5102W), TIO, Washington, DC, available at www.gwrtac.org, Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, and Sillan, R.K., M.D. Annable, and P.C.S. Rao, Editors, 1997: Executive Summary, "In-Situ Cosolvent Flushing for Enhanced Solubilization of a Complex NAPL: Comprehensive Field-Scale Evaluation", Draft Final Report, CRADA CR-821990, May 1997:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. The saturated zone pore volume (PV) within each cell is variable from 1,000 to 2,500 gallons per cell. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For Test 1, at OU1, a mixture of 70% ethanol, 12% n-pentanol, and 28% water was used as flushing solution. This was the first test performed at Hill AFB and was a comprehensive, field-scale evaluation of in-situ cosolvent flushing for enhanced remediation of NAPL-contaminated aquifers. The experiment was conducted in a hydraulically-isolated test cell (about 4.3 m x 3.5 m or 14.1 x 11.5 feet) constructed in a surficial sand-gravel-cobble aquifer, underlain by a deep clay confining unit. This surficial aquifer was contaminated with a multi-component NAPL as a result of jet fuel and chlorinated solvents disposal during the 50's and 60's. Prior to all testing, the water table in the cell was raised to 5 meters (16.4 feet) below ground surface to saturate the NAPL smear zone, necessary due to a water table decline from drought conditions in the few years prior to the test. At the test site, the LNAPL mixture occurred as a coating on particles and as globules in pore spaces in the groundwater and above it in the vadose zone.

Analysis of soil cores taken from the test cell prior to cosolvent flushing indicated the following: (1) the NAPL was located in a 1.5 meter (4.9 feet) smear zone immediately above the clay confining unit; (2) the largest amounts of NAPL were near the water-table position prior to test cell installation (5.8 m (19.0 feet) below the ground surface (bgs)); and (3) NAPL penetrated about 0.5 m (1.6 feet) into the confining unit via sand stringers near the aquifer-aquitard interface. Soil core analysis was also used to estimate NAPL saturation within the test of 1.6 to 3.8%. A series of non-reactive and reactive tracer tests were conducted to characterize hydrodynamic properties and NAPL distribution. A non-reactive tracer test was first conducted (using bromide and a mixture of methyl alcohols) to characterize the hydrodynamic characteristics of the saturated zone within the test cell; these data were used to guide the design of other tests in the cell. Results from this test showed a highly variable flow velocity distribution within the test cell. The first field test of inter-well partitioning tracers (IWPT) was conducted as an alternative to the traditional intrusive techniques (i.e. soil coring) to quantify both the residual NAPL volume and distribution within the test cell. Data from the IWPT test estimated an average NAPL saturation of 4.6 to 5.4% (approximately 250 L or 66 gallons). The IWPT test data indicated that the NAPL saturation was highly variable within the test cell and increased with depth and from the eastern end (EW-1 side) to the western end (EW-3 side) of the cell.

The in-situ cosolvent flushing technique provides accelerated site clean up due to enhanced solubilization or mobilization of NAPL, and enhanced desorption of sorbed contaminants. The field-scale cosolvent flushing test consisted of pumping about 40,000 L (10,568 gallons) (approx. nine pore volumes) of a ternary cosolvent mixture (70% ethanol, 12% n-pentanol, and 18% water) through the test cell over a period of 10 days, followed by flushing with water for another 20 days. Behavior of the cosolvents and solubilized NAPL constituents during the cosolvent and subsequent water flood was monitored with aqueous samples from three extraction wells and 60 multi-level sampling points (12 nested wells at 5 depths). Extraction well fluids with alcohol concentrations

>1% were transported off Base for incineration while all other fluids were disposed through the industrial wastewater treatment plant at Hill AFB.

The NAPL removal effectiveness achieved by cosolvent flushing was assessed using the following data: (1) NAPL constituent mass removal, based on extraction and analysis of pre- and post-flushing soil core samples; (2) cumulative NAPL mass removed for several target contaminants, as determined from analysis of the fluids generated at the extraction wells; (3) NAPL constituent mass decreases, based on pre- and post-flushing analysis of groundwater samples for target analytes; and (4) NAPL constituent mass removal, based on analysis of pre- and post-flushing IWPT tests. The results obtained by these methods are consistent, indicating that on the average >85% mass of several target contaminants was removed as a result of the cosolvent flushing; NAPL removal effectiveness was greater (90-99+%) in the upper 1 meter zone, in comparison to about 70-85% in the bottom 0.5 m zone near the clay confining unit.

The first IWPTT indicated a NAPL content of 7% of the porosity. Results indicated that > 90% of several target contaminants and > 75% of the total NAPL mass was removed. The co-solvent pumping strategies were not optimized based on cost considerations, as post-treatment of the NAPL and co-solvent was not attempted. The primary goal was to conduct this study as a proof-of-concept test, and to extend the database for research and development purposes.

The extraction well data were used to estimate an average NAPL saturation of 4.6-5.4 percent within the test cell. NAPL saturations estimated by using measured concentrations in soil cores of two significant compounds present in the NAPL were 3.0 and 4.6 percent (Annable, et al., 1996a)

The results obtained by the various methods agree, and indicate that > 90 percent mass of several target contaminants and > 80 percent of the total NAPL mass present in the test cell was removed as a result of the cosolvent flushing (Annable, et al., 1996b; Rao, et al., 1996).

At the end of the field study, <1% of the injected cosolvent volume remained in the test cell along with approximately 40 L (0.8% saturation) of NAPL based on post-flushing IWPT test results. It is suspected that the remaining cosolvent will easily biodegrade whereas the remaining NAPL mass behaves more like a pitch (high molecular weight components with very low aqueous solubilities).

Report(s)/Publication(s) (Additional Information Sources):

Annable, M. D.; Rao, P. S. C.; Hatfield, K.; Graham, W. D.; Wood, A. L., Use of Partitioning Tracers for Measuring Residual Napl Distribution in a Contaminated Aquifer: Preliminary Results from a Field-Scale Test, proceedings, 2nd Tracer Workshop, Univ. of Texas, Austin, TX.

Annable, M.D., Rao, P.S.C., Graham, W.D., Hatfield, K., and Wood, A.L. 1996a. "Use of Partitioning Tracers for Measuring Residual NAPL: Results From a Field-Scale Test." A.ccepted for publication in the Journal of Environmental Engineering.

Annable, M.D., Rao, P.S.C., Sillan, R.K., Hatfield, K., Graham, W.D., Wood~ A.L., and Enfield, C.G.. 1996b. "Field-Scale Application of In-Situ Cosolvent Flushing: Evaluation Approach." Proceedings of the Non-Aqueous Phase Liquid Conference, ASCE, Washington D.C., pp. 212-220.

Augestijin, D. C. M.; Rao, P. S. C. Enhanced Removal of Organic Contaminants by Solvent Flushing, ACS Symposium Series, submitted, 1995.

Augustijin, D.C.M.; Dai, D.; Rao, P.S.C.; and Wood, A.L. "Solvent Flushing Dynamics in Contaminated Soils." In Transport and Reactive Processes in Aquifers. T.H. Dracos and F. Stouffer (eds.). Balkema/ Rotterdam/Brookefield, 1994.

Augustijin, D.C.M.; Jessup, R.E.; Rao, P.S.; and Wood, A.L. "Remediation of Contaminated Soils by Solvent Flushing". Journal of Environmental Engineering, 120 (1) Jan/Feb 1994, p 42-57.

Augestijin, D. C. M.; Rao, P. S. C. Enhanced Removal of Organic Contaminants by Solvent Flushing, ACS Symposium Series, submitted, 1995.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Pope, G. A.; Jin, M.; Dwarakanath, V.; Rouse, B.; Sepehrnoori, K., Partitioning Tracer Tests to Characterize Organic Contaminants, proceedings, 2nd Tracer Workshop, Univ. of Texas, Austin, TX.

Rao, P. S. C.; Lee, L. S.; Wood, A. L., Solubility, sorption, and transport of hydrophobic organic chemicals in Complex Mixtures, U.S. Environmental Protection Agency, EPA/600-M-91-009, March, 1991.

Rao, P.S.C., M.D. Annable, R.K. Sillan, D.P. Dai, K. Hatfield, W.D. Graham, A.L. Wood, and C.G. Enfield, "Field-Scale Evaluation of In-Situ Cosolvent Flushing for Remediation of a Shallow, Unconfined Aquifer Contaminated with Residual LNAPL." Submitted to Water Resources Research.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Sillan, R.K., M.D. Annable, and P.C.S. Rao, Editors, 1997: Executive Summary, "In-Situ Cosolvent Flushing for Enhanced Solubilization of a Complex NAPL: Comprehensive Field-Scale Evaluation", Draft Final Report, CRADA CR-821990, May 1997.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Cosolvents, EPA 542-K-94-006, U.S. EPA OSWER (5102W), TIO, Washington, DC, available at www.gwrtac.org.

Wood, A. Lynn; Bouchard, D; Brusseau, M.; Rao, P. S. C., Cosolvent effects on sorption and mobility of Organic Contaminants in Soils," Chemosphere, 21:575-587, 1990.

GWRTAC ID: FLSH0023

Project Name: Hooker Chemical/Ruco Polymer, NY

City: Hicksville **State/Province:** NY

Primary GWRTAC Personal Communication Source (Name/Organization): Linda Ross
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC.

Project Summary:

The following text is from notes from a July 1998 conversation with the EPA RPM:

It is planned that groundwater will be pumped, treated above ground, and re-injected via one or two sumps (sumps 1 and 2) located in existing and constructed recharge basins. It is estimated that 100 gpm must be pumped to achieve hydraulic control, although the number and depths of wells are still to be determined. The geologic material targeted with in situ flushing at the site is sand and gravel of the Upper Glacial Formation. The water table at the site is approximately 35 feet below the ground surface (bgs). There is no shallow confining layer at the site; containment of the flushing operation would be strictly hydraulic control. The maximum depth of the target contaminants (VOCs (PCE, TCE, 1,2-DCE, vinyl chloride), phenol, and TICs (tentatively identified compounds)) is between 25 and 50 feet bgs.

Report(s)/Publication(s) (Additional Information Sources):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC.

GWRTAC ID: FLSH0024

Project Name: Howard University, Washington, DC - Treatment of PCBs with

City: Washington **State/Province:** DC

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

Project Summary:

The following is excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org:

Researchers currently are conducting tests on treatment of PCBs with surfactants with the support of the Great Lakes/Mid-Atlantic Hazardous Substance Research Center

Report(s)/Publication(s) (Additional Information Sources):

Chawla, R.C.; Cannon, J.N.; Johnson, J.H.; and Porzucek, C. "Importance of Soil-Contaminant-Surfactant Interactions in In-Situ Soil Washing." ACS Symposium on Emerging Technologies for Hazardous WasteTreatment. Atlantic City, New Jersey, June 4-7, 1990, p 23.

Porzucek, C. Surfactant Flooding Technology for In Situ Cleanup of Contaminated Soils and Aquifers -A Feasibility Study. Los Alamos National Laboratory, UD-702.LA-11541-MS, November 1989.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

GWRTAC ID: FLSH0025

Project Name: JADCO-Hughes, Belmont, NC

City: Belmont **State/Province:** NC

Primary GWRTAC Personal Communication Source (Name/Organization): Michael Townsend
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes from a August 1998 conversation with the EPA RPM:

The site is a former landfill, and soil vapor extraction (SVE) is currently being implemented to remediate vadose zone soils. After the SVE portion of the remedy had been completed, then in situ flushing will begin, using clean water. Target vadose zone contaminants are VOCs; the maximum depth of the contaminants is 10 to 15 feet below the ground surface (bgs). The clean water will be injected through the existing SVE manifold system. A groundwater treatment system is currently in place; extraction wells and trenches currently collect groundwater for above ground treatment, and discharge to the POTW. There is no slurry wall in place at the site; hydraulic control will contain the future flushing system. At this time, it is planned to start in situ flushing without additives, but the site owners have been directed to consider addition of surfactants to enhance contaminant recovery if deemed necessary after the start up of the operation.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0026

Project Name: Laramie, WY, Private wood treating site

City: Laramie **State/Province:** WY

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Oct. 1991: Eng. Bull. In Situ Soil Flushing, EPA 540-2-91-021, U.S. EPA OERR, Washington, DC

Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following is excerpted from Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993 and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997. Direct quotes are from Rice, 1997:

"From 1987 to 1990, a suite of in situ remedial technologies were field tested at a former wood-treating facility in Wyoming where a shallow alluvial aquifer had become contaminated with creosote based waste wood-treating oils (density 1.03 g/cms, viscosity 54 centipoise). A primary component of these studies was the analysis of chemically enhanced recovery of the oils. This involved laboratory testing followed by a small-scale field demonstration in 1988 (Sale, et al., 1989) and a large-scale field demonstration in 1989 (Pitts, et al., 1993)."

The 100-acre site contained over 500,000 yd3 PAH-impacted alluvial deposits, with significant DNAPL and LNAPL. The contaminated zone is contained by underlying shale aquitard, a perimeter bentonite slurry wall, and a negative hydraulic gradient. A 12 foot deep test cell was isolated from surrounding alluvium aquifer by 27 x 27 foot sheet-pile wall. Alluvial sediments graduated from fine sands, silts, and clays at surface to coarse sands and fine gravels at base. The lower three feet of alluvium was saturated by waste wood-treating oil of density 1.04 g/cm3 and viscosity 54 Cp. Delivery and recovery of flushing solution was accomplished through 4-inch horizontal drain lines spaced 15 feet apart in parallel and located at the alluvium-bedrock contact. One pore volume (PV - volume of liquid required to saturate the cell) was estimated at 5,000 gallons. (Mann, 1993).

The pilot test sequence consisted of three steps: waterflooding, soil flushing, and reconditioning. In the first, waterflooding step, 144,000 gallons (28 PV) of water was cycled between the delivery and recovery drain lines (dual drains) to displace all mobile free-phase oil, and allow subsequent soil flushing performance determination where only residual oil remained. The second soil flushing step consisted of delivery of 30,000 gallons of flushing solution into the test cell. The flushing solution was a mixture of alkaline agents, polymer, and surfactants determined from laboratory test studies; the information below summarizes the composition of the various solutions. Initially as part of the soil flushing step, 10,000 gallons (2 PV) of Polystep A-7R was used to produce reusable wood-preserving oil, followed by 10,000 gallons (2 PV) of Makon-10R to achieve lower cleanup levels. After the first 20,000 gallons of flushing solution delivery, 10,000 gallons (2 PV) of water was delivered to continue fluid movement while waiting for the arrival of additional flushing solution. Then, 10,000 additional gallons (2 PV) of Makon-10R was delivered to the cell to complete the soil flushing step. Lastly, in a reconditioning step, the cell was flooded with 150,000 gallons (30 PV) of water to displace mobilized oil and soil-washing solution remaining in the aquifer. (Mann, 1993).

The flushing solutions used were the Makon-10R System and the Polystep A-7R System (Mann, 1993).

The Makon-10R System was comprised of alkaline agents Na2CO3 (0.825% by wt) and NaHCO3 (0.65% by wt), polymer Xanthan Gum Biopolymer (1,050 mg/L), and surfactant Makon-10R(a) (1.4% by wt).

The Polystep A-7R System was comprised of alkaline agents Na2CO3 (0.1% by wt) and NaHCO3 (0.72% by wt), polymer Xanthan Gum Biopolymer (1,050 mg/L), and surfactant Polystep A-7R(b) (1% by wt).

(a) Ethoxylated nonylphenol
(b) Sodium dodecyl benzene sulfonate

A total of 1,900 gallons of PAH-contaminated oil was removed from the test cell. On average, primary oil recovery reduced oil concentration from 93,000 to 15,500 mg/Kg and in situ soil flushing further reduced oil to a final concentration of 5,100 mg/Kg, a 94% overall reduction. More agressive techniques or in situ bioremediation were recommended to further reduce contaminant concentration. Flushing solution additives were 61 to 99% recovered. In addition, the removal of oil increased the soil bulk permeability form 15 to 30 Darcy. (Mann, 1993).

"The primary result of the small-scale field demonstration was a decision to proceed to a large-scale effort. The large-scale pilot was performed in an area in which waterflood oil recovery had been applied in 1988. Sheet-pile walls were driven to isolate a test cell with the dimension of 130 by 130 feet. Chemical solutions were delivered to a central 120-foot delivery drainline. Fluids were produced from two 120-foot recovery drainlines spaced 60 feet from and parallel to the delivery drainline. During the 235-day pilot test, approximately 7,400 pounds of polymer, 39,700 pounds of surfactant, and 81,900 pounds of alkaline agents were delivered to the subsurface.

Through the delivery of chemicals and subsequent flushing of mobilized oil and residual chemicals, an equivalent of approximately 23,600 gallons of oil were produced. The corresponding reduction in soil contaminant concentrations was from an initial concentration of approximately 25,000 mg oil/kg soil to a final concentration of 4,000 mg oil/kg dry soil. Final concentrations ranged from 290 to 11,000 mg oil/kg dry soil, reflecting the impact of preferred flow paths within the contaminated interval (Pitts, et al., 1993).

While large amounts of mass were removed from the site, it was also recognized that the remaining subsurface alluvial contamination, together with the contamination in the underlying bedrock, would act as a long-term source of groundwater contamination. Groundwater approaching equilibrium with this remaining contamination would contain dissolved PAH at concentrations near the concentrations present under the initial conditions. Thus, it was recognized that implementation of in situ soil flushing would likely not eliminate or reduce the need for continuation of current groundwater containment practices in place at the site.

During the in situ soil flushing process, fluids were generated that were characterized by stable oil/water emulsions, high contaminant concentrations, high organic content, elevated pH, high alkalinity, and high salinity. These characteristics made the fluids very difficult to treat. The need for an effective and efficient process for treatment of the fluids is evident through consideration of the volume of fluids that would be generated in full-scale application of the soil flushing method (100 acres). Based on extrapolation of the 1989 in situ soil flushing pilot test, approximately 275 million gallons of fluid with these characteristics would be produced in a full-scale application. Considering effluent recycling and chemical reuse, fluid discharge, and residuals management, no complete process was identified for the treatment of fluids produced during in situ soil flushing (Sale and Piontek, 1992).

Full-scale applications of the chemically enhanced recovery technique would require an extensive piping network and large amounts of fluids and chemicals. Based on extrapolation from the 1989 pilot test, full-scale in situ soil flushing would require more than 125 million gallons of soil flushing solution containing more than I million pounds of polymer, nearly 10 million pounds of surfactant, and approximately 16 million pounds of alkaline agents. Based on the limited risk reduction achieved, unresolved technical issues, and implementation costs on the order of $500,000 per acre, this technology is no longer being considered at the site (CH2M HILL, 1993)."

Report(s)/Publication(s) (Additional Information Sources):

CH2M HILL. 1990. "Union Pacific Railroad Laramie Tie Plant In Situ Treatment Process Development Program: Milestone IV Report."

CH2M HILL. 1993. "UPRR Laramie Tie Plant Site Draft Corrective Measures Study Report." Submitted to U.S. Environmental Protection Agency, Region VIII, Denver, Colorado.

Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993

Piontek, K.R., and Simpkin, T.J. 1994. "Practicability of In Situ Bioremediation at a Wood-Preserving Site." In Bioremediation of Chlorinated and Polycyclic Aromatic Hydrocarbon Compounds, R.E. Hinchee, A. Leeson, L. Semprini, and S.K. Ong, Eds., Lewis Publishers, pp. 117-128.

Pitts, M.J., Wyatt, K., Sale, T.C., and Piontek, K.R. 1993. "Utilization of Chemical-Enhanced Oil Recovery Technology to Remove Hazardous Oily Waste from Alluvium," SPE/DOE paper no.

25153. presented at the SPE International Symposium on Oilfield Chemistry, New Orleans, Louisiana, March 2-5, pp. 33-44.

Pitts, M.J., Surkalo, H., and Wyatt, K. 1995. "Design and Field Implementation of Alkaline-Surfactant-Polymer Chemical Enhanced Oil Recovery Systems." Proceedings of the UNITAR International Conference on Heavy Crude and Tar Sands, February 12-17, Vol. 1, pp. 795-803.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Sale, T.C., Piontek, K.R., and Pitts, M.J. 1989. "Chemically Enhanced In-Situ Soil Washing," Proceedings of NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration, November 15-17.

Sale, T.C., and Piontek, K.R. 1992. "A Decade of Remedial Action at a Former Wood-Treating Facility." Proceedings of Water Environment Federation 65th Annual Conference and Expositions on Detection and Restoration of DNAPLs in Ground Water at Hazardous Waste Sites. New Orleans, Louisiana, September 20-24

Sale, T.C., and Applegate, D. 1996. "Mobile NAPL Recovery: Conceptual, Field and Mathematical Considerations." Revised manuscript submitted to Ground Water.

Sale, T.C., and Applegate, D. 1996. "Oil Recovery at a Former Wood-Treating Facility," Water Environment Research, Vol. 68, No. 7, pp. 1116-1122.

Sale, T.C., Pitts, M., Piontek, K., and Wyatt, K. 1996. "In Situ Remediation of DNAPL Compounds in Low Permeability Media Fate/Transport, In Situ Control Technologies, and Risk Reduction." In Chemically Enhanced In Situ Recovery. Oak Ridge National Laboratory, ORNL/TM-13305.

U.S. EPA, Oct. 1991: Eng. Bull. In Situ Soil Flushing, EPA 540-2-91-021, U.S. EPA OERR, Washington, DC

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0027

Project Name: Lee Chemical, Liberty, MO

City: Liberty **State/Province:** MO

Primary GWRTAC Personal Communication Source (Name/Organization): Steve Kinser
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes from an April 1997 and July 1998 conversations with the EPA RPM:

The site is a Missouri-lead site, and is located one mile away from the Kansas City reach of the Missouri River; river loses water through this reach. Missouri River bottom sediments are contaminated with chlorinated solvents. Flushing project is targeting vadose zone by re-circulating untreated groundwater through four infiltration fields on site. There is no shallow confining layer beneath the site. The city wellfield is located significant distance from site, however, a preferential flowpath exists between one of these wells and the site. Water is pumped from one extraction well; approximately 700,000 gallons per day of water is pumped and infiltrated; there is no on-site treatment prior to re-injection. Over one recent three month period (April, May, June 1996), the total water applied to the site was a little over two million gallons.

The site is to be remediated to MCLs. Performance results are not yet available. A five year review will be conducted in June 1998; EPA has not yet received a copy of the five year report, but indicated that the flushing system is operating without any problems. The city water supply has not been impacted by the operation. Project costs were not available from reference source.

Report(s)/Publication(s) (Additional Information Sources):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

Internet URL http://www.epa.gov/superfund/index.htm

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0028

Project Name: Lipari Landfill, Pitman, NJ

City: Pitman **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): Fred Cateneo
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

CDM Federal Programs Corporation, 1996: "Lipari Landfill Superfund Site, On-Site Remediation System Final 1994 Annual Report, Lipari Longterm Remedial Action, Lipari Landfill, Pitman, New Jersey", Prepared for U.S. EPA, New York, NY, Prepared by CDM Federal Programs Corporation, 125 Maiden Lane, 5th Floor, New York, NY 10038, May 2, 1996

Internet URL: http://www.epa.gov/superfund/index.htm;

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following text is from notes from an Apil 1997 conversation with the EPA RPM and Internet URL EPA.gov:

The six-acre Lipari Landfill site is located in the township of Mantua, adjacent to the towns of Pitman and Glassboro, New Jersey. Landfill used for disposal of household waste, municipal refuse, liquid and semi-solid chemical wastes, and other industrial materials. Best estimates indicate approximately 12,000 cubic yards of solid wastes and 2.9 million gallons of liquid wastes were disposed. Wastes include solvents, paint thinners, formaldehyde paints, phenol and amine wastes, dust collector residues, resins and ester press cakes.

RODs (8/3/82,9/30/85) indicate the six acre landfill and a ten acre contaminated area between the landfill and Chestnut Branch were to be contained inside bentonite/soil slurry wall keyed into underlying aquitard, and capped (with impermeable synthetic membrane liner) as Phase I of remedy. Phase II of remedy involves in situ flushing within slurry wall. RPM (4/23/97) indicates slurry wall is 30 to 50 feet deep, and surrounds 15.3 acres of the site. In situ flushing is conducted within the upper water table aquifer (Cohansey Aquifer), which is underlain by a nine to 15 foot thick clay layer (Kirkwood clay). Approximately 26 extraction wells and 14 injection wells are utilized; wells vary from 30 to 50 feet in depth, depending upon the area of the landfill. In situ flushing is conducted in a "batch flushing" operation, and began in spring 1993. Source of flushing water is deep well in uncontaminated Mount Laurel Aquifer, which pumps approximately 200 gpm.

This water flows by gravity to the 14 injection wells, for injection in eight MM gallon batches within the containment system. After injection of each 8 MM gallons, the 26 extraction wells remove the contaminated water, where it is treated aboveground, and discharged to POTW. The treated extracted groundwater is not re-injected.

RPM indicates it had been estimated that the in situ flushing project would be completed in 2001, although it will probably run longer. Remediation goals are federal and state ambient water quality criteria. RODs indicate an estimated 15 years would be required to remove 90% of the water-borne contaminants from groundwater within the containment system. (The Kirkwood Aquifer, which underlies the clay layer beneath the Cohansey Aquifer, is being remediated by conventional pump and treat.)

Annual reports (most recently through 1994) have been prepared, however performance of in situ flushing/trends data are not yet available as project was not at full operation. RPM verifies that in situ flushing has been effective in reducing contaminant load, though concentration reductions were not quantified.

Figures from Table 2-2 as reported in the 1994 Annual Report indicate the following estimated mass of COCs extracted compared with initial concentrations in groundwater and soils.

Contaminant	Total Mass Extracted 1993 & 1994 (kg)	Est. Mass in Containment Syst. Groundwater (kg)	Est. Mass in Landfill Soil (kg)
methylene chloride	227	409	2157
chloroform	0.2	234	383
benzene	94	174	567
1,2-dichloroethane	501	1240	2444
4-methyl-2-pentanone	194	598	1639
toluene	973	1526	48,247
chlorobenzene	0.8	NA	NA
ethylbenzene	85	184	10,099
xylenes (total)	349	734	70,647
phenol	183	596	2,891
bis(2-chloroethyl)ether	598	1,938	3,840
arsenic	NA	1.4	3,754
chromium	NA	7.55	32,152
lead	NA	1.99	6,945
mercury	NA	0.035	71
nickel	NA	3.69	4,744
selenium	NA	0.645	NA
silver	NA	1.36	NA
zinc	NA	92.4	25,905

Digits are retained for correpsondence to calculations. Only 2 digits of accuracy apply. Detection limits of metals laboratory analyses may have been too high to detect removals.
Estimated Mass in Containment System Groundwater calulated based on 1992-1993 groundwater quality data.

Estimated Mass in Landfill Soils as reported in Baseline Soil Study, (CDM, 1987)
NA - Not available or not able to be calculated.

Report(s)/Publication(s) (Additional Information Sources):

CDM Federal Programs Corporation, 1996: "Lipari Landfill Superfund Site, On-Site Remediation System Final 1994 Annual Report, Lipari Longterm Remedial Action, Lipari Landfill, Pitman, New Jersey", Prepared for U.S. EPA, New York, NY, Prepared by CDM Federal Programs Corporation, 125 Maiden Lane, 5th Floor, New York, NY 10038, May 2, 1996

Internet URL: http://www.epa.gov/superfund/index.htm;

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

GWRTAC ID: FLSH0029

Project Name: Michigan State University - Surfactant Research and Soils Mo

City: East Lansing **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

Project Summary:

The following is excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org:

Dr. Stephen Boyd is working on three research projects involving surfactants:

1) Surfactant treatment of soils and sediments

Basic research is being conducted to study the effects of different classes of surfactants on the partitioning of contaminants between the water and solid phases of sediments and sandy soils. Tests have been conducted on DDT, PCBs, and PAHs such as naphthalene and phenanthrene.

2) Modification of soils with cationic surfactants

Clayey soils are being treated with cationic surfactants to make the soil more sorptive to common organic contaminants. Though the work is basic research, a projected use of the technique would be to inject the cationic surfactant into the ground in a location through which a contaminant plume would flow. Theoretically, contaminant concentrations in the water downgradient from the treated (sorptive) zone would be substantially reduced. The contaminants immobilized within the zone could then be treated with enhanced bioremediation to provide a comprehensive in-situ remediation technology. In a related application, the cationic organo-clays could be used as components of barrier walls. They would not only seal an area, but sorb any contaminants threatening to seep through.

3) Effects of low levels of surfactants on bioremediation

Through a cooperative agreement with ERL-Athens, laboratory work has just begun to study how the biological dechlorination of PCBs in sediments can be enhanced by treating the sediments with low levels of surfactants.

Report(s)/Publication(s) (Additional Information Sources):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0030

Project Name: Montana Pole & Treating, Butte, MT

City: Butte **State/Province:** MT

Primary GWRTAC Personal Communication Source (Name/Organization): Neil Marsh
Montana DEQ

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

Internet URL http://www.epa.gov.superfund.htm

Project Summary:

The following text is from notes from a July 1998 conversation with the Montana DEQ RPM:

The site has 10-15 acres of pentachlorophenol (PCP)-contaminated area bisected by an interstate highway. The ROD calls for accessible soils to be excavated and treated aboveground via landfarming and aerated biopiles. To date, soil excavation has taken place on the north side of the interstate, and excavation on the south side of the interstate will begin in 1999.

A total of about 200,000 cubic yards of contaminated soils will be excavated and treated ex situ. However, approximately 50,000 cubic yards of contaminated soil lies beneath the interstate highway, and will be remediated via in situ flushing, although ozone injection is also under consideration for these soils In situ flushing will also be used to remediate groundwater. Much LNAPL at the site (comprised of diesel fuel and 5% PCP), was removed at the time of soil excavation, however remaining LNAPL will also be targeted with in situ flushing. The remediation goals for PCP for the site are 34 ppm in soil and 1 ppb in groundwater.

The geologic material of the subsurface area targeted for in situ flushing is comprised of sandy alluvial material. The water table is present at approximately 5 to 8 feet below the ground surface. At the time of soil excavation north of the interstate, the excavations were extended to about two feet below the water table. The excavations were backfilled with clean soil, and recharge basins were constructed to allow current recharge of treated groundwater for flushing. (In the future after soils treated aboveground are replaced, the current recharge basin system will be replaced with a subsurface manifold system to deliver the treated groundwater to the subsurface).

Two interception trenches (approximately 30 feet deep) have been installed north of the interstate. The downgradient trench is designed to prevent contaminated groundwater from leaving the site. Approximately 150 gpm groundwater is extracted from this trench and treated via carbon absorption with discharge to surface water or recharge to groundwater through the aeration/infiltration basins. The upgradient trench is designed to intercept both contaminated groundwater and LNAPL before it reaches the north site excavated area. About 150 gpm groundwater is exrracted, treated, and discharged. LNAPL is intercepted by a physical plastic barrier and perforated culvert and recovered by a pumping system and oil/water separator.

In the future at this site, soil excavation will be completed south of the interstate highway which bisects the site. At that time, a system for in situ flushing will be constructed in a similar manner to that currently operatiing on the north side of the interstate.

Performance data for the in situ flushing system is not yet available.

Report(s)/Publication(s) (Additional Information Sources):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

Internet URL http://www.epa.gov.superfund.htm

GWRTAC ID: FLSH0031

Project Name: Ninth Avenue Dump, Gary, IN

City: Gary **State/Province:** IN

Primary GWRTAC Personal Communication Source (Name/Organization): Bernie Schorle
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following text is from notes from a July 1998 conversation with the EPA RPM:

Groundwater was extracted about 10 to 15 feet below the water table. Extracted fluids were treated above ground (with oil/water separation for collection of LNAPL, physical/chemical treatment for iron precipitation, and a sequencing batch bioreactor). The treated groundwater re-injected through perforated pipes on top of the ground; the pipes were covered with soil. A slurry wall surrounds the site, and the flushing operation was conducted within the slurry wall. The slurry wall is keyed into a confining layer present at 28 to 30 feet below the ground surface. The NPDES permit allowed for discharge of surface water from on-site ponds, not treated groundwater. It is possible, however that groundwater may have entered ponds.

Chemical oxygen demand (COD) was reduced by 10-20% and attributed to the flushing operation.

Report(s)/Publication(s) (Additional Information Sources):

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0032

Project Name: Ormet Corp., Hannibal, OH

City: Hannibal **State/Province:** OH

Primary GWRTAC Personal Communication Source (Name/Organization): Tony Rutter
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC; http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes from a July 1998 conversation with the EPA RPM:

Two high capacity pumping wells are used to extract groundwater and provide hydraulic control. In June of 1998, construction was completed on a sprayfield system for the site. Treated site groundwater (no additives) is used for flushing solution, and will be applied surficially via the sprayfield system sprinklers to flush vadose zone soils. There is no slurry wall or other constructed containment means at the site. The geologic material being targeted for flushing is comprised primarily of fairly porous and well sorted sands, though some silt is present. Information on areal extent, depth of system, etc. unavailable.

Report(s)/Publication(s) (Additional Information Sources):

None

GWRTAC ID: FLSH0033

Project Name: Patuxent Naval Air Test Center

City: Patuxent **State/Province:** MD

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 112

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 112:

The objective of this study was to evaluate the feasibility of surfactant-enhanced biodegradation of JP-5 in soil from Patuxent Naval Air Test Center (NATC) under simulated conditions of soil venting. Surfactants and emulsifiers were screened for microbial toxicity and for their capacity to solubilize jet fuel from soil. Three surfactants were subsequently evaluated in 60-day flask aerobic biodegradation experiments. One surfactant was tested in soil columns under simulated soil venting conditions for 47 days. The results of the soil column study showed that the surfactant plus soil venting failed to enhance biodegradation of JP-5 compared to soil venting alone. Soil venting appears to overcome oxygen limitations in unsaturated soil and should be considered for enhanced biodegradation and soil bioremediation at NATC.

Report(s)/Publication(s) (Additional Information Sources):

Arthur, et al., 1992: "Evaluation of Innovative Approaches to Stimulate Degradation of Jet Fuels in Subsoils and Ground Water, Final Report, June 1988 to August 1989, Battelle Columbus Labs, OH, June 1992, 35 pp.

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 112

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0034

Project Name: Peak Oil Co./Bay Drum Co., Tampa, FL

City: Tampa **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): Randal Chafins
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

Project Summary:

The following text is from notes from April 1997 conversation with EPA RPM and Internet URL EPA.gov:

Treated site groundwater would be used as flushing solution; nutrient additives are being considered. In situ flushing project is in early design phase, and will be conducted within a slurry wall containment area. The depth of the confining layer is approximately 15 feet below the ground surface. ROD estimates five year duration for flushing project; remediation must continue until groundwater standards are achieved. Current plans are to infiltrate water through horizontal piping network.

Report(s)/Publication(s) (Additional Information Sources):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

GWRTAC ID: FLSH0035

Project Name: Picatinny Arsenal, NJ

City: Picatinny Arsenal **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): Jim Smith
University of Virginia

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, available at www.gwrtac.org.

Project Summary:

The following was excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org and U.S. Environmental Protection Agency (EPA), and April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC:

The Picatinny Arsenal is a USGS National Research Site, having been selected as such in 1986. The site is located on a golf course. At Picatinny Arsenal, TCE was used for years as degreasing solvent, and contaminated the sand and gravel aquifer at concentrations of about 1 to 5 mg/kg with aqueous phase concentrations of 1 to 5 mg/L. The water table is ten feet below the ground surface. A ten to 15 feet thick lower confining unit is 50 feet below the surface. A pump and treat system was installed as an interim remedy at this Superfund site; wells are installed to a depth of approximately 20 feet above the confining layer. For this project, surfactants were injected to cause desorption of TCE from soil and the increase of TCE levels in groundwater were monitored. The treatment area for the small-scale field test was 60 x 20 feet. The test site is upgradient from the existing pump and treat system; pump and treat systems thus removed the surfactant and TCE.

Previous laboratory work was completed to determine type and concentration of optimum surfactant to use for flushing pilot project. Wells were installed and tracer tests conducted to confirm hydraulic control of test area. Three injection wells, 10 ft apart, were installed perpendicular to the natural gradient and tangential to the pump-and-treat extraction well, approximately 100 yards down-gradient. One monitoring well is located 30 ft up-gradient and three monitoring wells located down-gradient at 10 ft intervals from the injection wells. Clean water was pumped to all three injection wells for approximately 30 days at 3 gal / min. The water in the center injection well was replaced with 400 mg / L Triton X-100 at the same flow rate for 30 days while clean water continued in the outer wells. Clean water was pumped to all three wells for an additional 4 months. The purpose of this study was to investigate whether the surfactant would increase the rate of desorption of TCE from the solid phase. Hence, researchers modeled the transport of the surfactant and the TCE.

Note: Univesity of Virginia submitted "preproposal" to U.S. EPA SITE program for Picatinny Arsenal project in which soils will be flushed with surfactants to render sorbed TCE more amenable to oxygen-enhanced bioremediation.

Several publications are available detailing results, as listed above; see these references for a complete understanding of results. Analysis of data from the wells and model suggests that the rate of TCE desorption increased about 30% as a result of Triton X-100 injection.

Discussion from one source (Smith, et al., 1997) indicated that Triton-X sorption to natural soil is rate-limited and cannot be accurately described by equilibrium sorption models. Implications of this for surfactant-based technologies for remediation include potentially faster transport of surfactant through the subsurface, initially beneficial to the operation, but if the surfactant must be removed, the rate-limited sorption may be problematic at the conclusion of the surfactant flushing operation. In comparison to anionic surfactants and some other nonionic surfactants, Triton X-100 sorbs relatively strongly to the field soil, which would increase material costs for surfactant remediation operations, though this strong sorption to soils may be the reason for the ability of Triton X-100 to increase the rate of desorption of other sorbed organic pollutants such as TCE and carbon tetrachloride.

Report(s)/Publication(s) (Additional Information Sources):

Deitsch, J. J. and Smith, J. A., 1996: "Surfactant Enhanced Remediation of Ground Water at Picatinny Arsenal, New Jersey," in Morganwalp, D. W. and Aronson, D. A., eds., U.S. Geological Survey Toxics Substances Hydrology Program-Proceedings of the Technical Meeting. Colorado Springs, Colorado- September 20-24, 1993, U.S. Geological Survey Water Resources Investigations Report 94-4015, pp. 355--360.

Deitsch, J. J. and Smith, J. A., 1995: "Effect of Triton X-100 on the Rate of Trichloroethene Desorption from Soil to Water," Environmental Science and Technology, Vol. 29, No. 4, pp. 1069-1080.

Di Cesare, D. and Smith, J. A., 1994: "Effects of Surfactants on the Desorption Rate of Nonionic Organic Compounds from Soil to Water," Reviews of Environmental Contamination and Toxicology, Vol. 134, pp.1-29.

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Sahho, D., Smith, J.A., Imbrigotta, T.E., and McLellan, H.M., 1996: "Enhanced Trichloroethene Desorption from Long-term Contaminated Soil Using Triton X-100 and pH Increases: Proceedings, ASCE North American Water and Environement Congress 1996, Anaheim, CA, June 22-28.

Sahoo, D., and Smith, J.A., 1997: "Enhance Trichloroethene Desorption from Long-term Contaminated Soil Using Trion X-100 and pH Increases: Environmental Science and Technology, Vol. 31, No. 7, pp. 1910-1915.

Sahoo, D., Smith, J.A., Imbrigotta, T.E., and McLellan, H.M., 1998: "Surfactant-enhanced Remediation of a Trichloroethylene (TCE) Contaminated Aquifer 2. Transport of TCE", Environmental Science and Technology, Vol. 32, pp. 1686-1693.

Smith, J.A., Sahoo, D., McLellan, H.M. and Imbrigotta, T.E., 1997: "Surfactant-enhanced Remediation of a Trichloroethylene (TCE) Contaminated Aquifer: 1. Transport of Triton X-100", Environmental Science and Technology, Vol. 31, No. 12, pp. 3565-3572.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, available at www.gwrtac.org.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0036

Project Name: Rasmussen's Dump, Brighton, MI

City: Brighton **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): Ken Glatz
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes from July 1998 conversation with EPA RPM:

In situ flushing begain approximately June 1996. At the site, there is an upper well-sorted sand aquifer, a clay confining layer, which is located about 35 to 40 feet below the ground surfact (bgs), and is 10-15 feet thick, and a lower aquifer below the clay confining layer. There is a "pinch out" of the units, so that water from the upper aquifer can enter the lower aquifer through a "waterfall effect", so that the lower aquifer is also contaminated. The targeted contaminants at the site are located within the vadose zone and within the unconfined aquifer.

In the in situ flushing operation, water is pumped from the upper and lower aquifers via four or five extraction wells. The wells are pumped at different rates, but a total of approximately 120 gpm is pumped. The entire 120 gpm is re-injected continuously, via infiltration galleries located just below the surface, and which are approximately two acres in areal extent. No slurry wall is present at the site. The flushing operation is contained via hydraulic containment. The lower aquifer is not directly targeted by the in situ flushing operation.

A total of about 330 million gallons of groundwater is contaminated at the site; roughly divided half and half between the upper and lower aquifers.

Report(s)/Publication(s) (Additional Information Sources):

http://www.epa.gov/superfund/index.htm

U.S. EPA, Nov. 1996: Innovative Treatment Technologies: Annual Status Report (Eighth Edition), EPA 542-R-96-010, Number 8, U.S. EPA OSWER (5102G) TIO, Washington, DC

GWRTAC ID: FLSH0037

Project Name: Serrener/Varisco Consortium, Canada

City: Drummondville **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Internet URL http://echs.ida.org/s13/report/intrm04.html "Field Demonstration of an In Situ Treatment for Hydrocarbon Contaminated Sites Using Wellpoints

Project Summary:

The following text was excerpted from marketing information provided by GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4 in August 1998:

The Serrener/Varisco Consortium developed an in situ treatment technology using a combined physico-chemical and biological approach. The concept, the injection of solutions for the treatment and recovery of contaminants, is based on the use of well points, which had been developed by Varisco, Italy and proven to lower the water table and control groundwater. The selected approach consists of isolating the surfact to be treated and saturating the contaminated soil during successive hydraulic operations. This treatment technique is viable on all four phases of a contamination enclave, which are the free, adsorbed, dissolved, and volatile phases.

The process is applied in four stages: 1. Primary recovery of free-phase contaminants; 2. Secondary recovery of contaminants by injection of water; 3. Tertiary recovery of contaminants by injection of surfactants; 4. Biodegradation of residual contaminants by injection of nutrients and air. A lab study was conducted to optimize the treatment process for application on the contaminated soil at a former oil depot site in Drummondville, QC, followed by an on-site demonstration. The project's total cost was $1,073,736. (Canadian).

The project was conducted on an experimental land parcel at an old oil depot site. Mineral oil and grease (MOG) and gasoline were present. The study area occupied a volume of 520 m3 (approx. 680 yd3) at a high point of the water table so as to prevent recontamination of the area after the demonstration. The experimental parcel is comprised of low permeability till (10-5 cm/sec) covered with a 1 m (approx. 3.3 ft) thick layer of fill, consisting of granular material in a silty matrix. Rock is located at approximately 3 m (approx. 9.8 ft) deep. The site is greatly heterogeneous, and exhibited great variability of results, both for soil and groundwater analysis. The mean concentration of MOG was 11,000 ppm, with values up to 25,000 ppm.

The laboratory work consisted of assessing the efficiency of different surfactants to extract the contaminants and assessing contaminant biodegradation and toxicity. Soil biotreatability was also verified and validated. The goal of the on-site demonstration was to evaluate the effects of surfactants and washing on biological activity, to assess and optimize the well points in controlling the treatment, and to assess the effect of nutrients and other environmental factors on biological activity.

Laboratory Results

Using an experimental computer-designed multifactorial plan, the lab studies optimized the selection of surfactants as a function of the percentage of hydrocarbons extracted. The results were used to formulate a mixture of surfactanats with no mutagenic effect on E. Coli. Also, the soil contains a microbial flora that is able to biodegrade contaminants marked with heterotrophic cell counts on the order of 106 bacteria/gm. Of this number, about 6% of the microorganisms are BTEX degraders. Respiratory activity in the soil indicates that it is biologically very active. One-column soil assays identified a condition conducive to a significant 25% reduction in MOG over a 30-day period.

Washing Test Results

Varying conditions of soil saturation were experimented. The distribution of solutions thorugh the network of well points, with no surface infiltration, provided better hydraulic control of the injected solutions. Low surfactant concentrations were nonetheless measured outside the site and in the rock below the experimental plot of land. In a general sense, surfactant showed low efficiency in extracting hydrocarbons. It appears that the complexity of the geological conditions of the site influenced these results. Washing with surfactants had little or no effect on either the toxicity of the soil or groundwater. Moreover, following the washing, mean concentrations of heterotrophic and specific bacteria were equivalent to those obtained prior to washing, except in groundwater, where a sproradic increase was noted. Lastly, a reduction or absence of effect on respiration and on hexadecane mineralization was observed.

Tracer Test Results

A tracer test was done after the washing tests, but before the biological phase, so as to ensure that the injected solutions were distributed throughout the lot. Horizontal and vertical distribution were shown to be almost total. Only one characterized zone, possibly containing silt heterogeneities, was not reached. The vertical migration of the injected solution was generally limited to the experimental lot. Low concentrations were measured in rock.

Biodegradation Test Results

Oxygen consumption, measured by an in situ respirometric test, varied from 0.1% per hour to 5.1% per hour. Using a kinetic rate of zero, an estimate of the hydrocarbon degradation rate was obtained, which, at best, was 137 mg/kg-j. Analysis of gaseous oxygen in the soil pointed out the unequal distribution of oxygen during aeration: certain zones, possibly containing silt heterogeneities, remained anaerobic. The vertical and horizontal migration of nutrients is not limited to the experimental plot of land. Concentrations of NO3- and NH4+ were measured in unsolidated deposits and in rock off the site.

In general, the population of aerobic heterotrophic bacteria (AHB) in the soil grew during treatment, with the surface population being more numerous than the subsurface population. Higher concentrations of these bacteria are also found in the soil rather than in water.

One area of the lot showed an appreciable reduction in MOG (13,400 ppm to 3,078 ppm), associated with the highest total bacteria population growth (10 3 to 10 7), mineralization growth (21 to 52% 14 CO2) and growth in carbon-specific bacteria of 10 1 to 10 5 (Alk B genetic probe).

The initial reduction in soil toxicty was observed with Photobacterium phosphoreum (Microtox bioassay) on organic extracts. No significant effect was reported in soil elutriates using direct-contact germination or growth tests on barley. These results are encouraging for such a short study period (two months). In groundwater, no alarming toxic effect was detected by the Microtox bioassay. The biotreatability protocol utilized during the project allowed us to confirm the relevance of this tool as a monitoring/control and optimization method, both in the lab or in the field.

The physico-chemical extraction work carried out at the site did not reach the targeted decontamination criteria. The duration of the biological treatment test was insufficient to demonstrate complete decontamination. In addition, the complexity of the site offered conditions beyond the scope of application of this technology.

Report(s)/Publication(s) (Additional Information Sources):

"Demonstration sur le terrain d'un procede de traitement in situ pour les sols contamines", November 1996

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Internet URL http://echs.ida.org/s13/report/intrm04.html "Field Demonstration of an In Situ Treatment for Hydrocarbon Contaminated Sites Using Wellpoints

GWRTAC ID: FLSH0038

Project Name: Sindelfingen, Germany

City: Sindelfingen **State/Province:** GERMANY

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following was excerpted from U.S. EPA, Oct. 1991: Eng. Bull. In Situ Soil Flushing, EPA 540-2-91-021, U.S. EPA OERR, Washington, DC:

TCE was discharged into the aquifer at the site of a spill in Sindelfingen, Germany. The contaminated aquifer is a high-permeability (k= 5.10 x 10-4 m/sec) layer overlying a clay barrier. Soil flushing was accomplished by infiltrating water into the ground through ditches. The leaching liquid and polluted groundwater were pumped out of eight wells and treated with activated carbon. The treated water was recycled through the infilration ditches. Within 18 months, 17 metric tons of chlorinated hydrocarbons were recovered.

Report(s)/Publication(s) (Additional Information Sources):

Stief, K., 1984: Remedial Action for Groundwater Protection Case Studies Within the Federal Republic of Germany, Presented at the 5th National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, DC, 1984.

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

GWRTAC ID: FLSH0039

Project Name: Camp Lejeune Marine Corps Base

City: Camp Lejeune **State/Province:** NC

Primary GWRTAC Personal Communication Source (Name/Organization): Fred Holzmeyer
Duke Engineering & Services

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text was provided in a project summary on September 8, 1998 by Duke Engineering & Services of Austin, TX:

A Remedial Investigation (RI) recently conducted at Marine Corps Base Camp Lejeune, North Carolina has revealed the presence of an extensive aqueous plume of tetrachloroethene (PCE) in the vicinity of the Base dry cleaning facility known as Building 25. The RI delineated the extent of the ground-water plume for this area, referred to as Site 88, and reported aqueous PCE concentrations up to 54 mg/L. However, this large-scale investigation did not confirm the presence of dense nonaqueous phase liquids (DNAPL) in the subsurface. Site 88 was listed by Naval Facilities Engineering Service Center (NAVFAC) as a candidate site (i.e. likely to have DNAPL present in the subsurface) for conducting a field demonstration of surfactant enhanced aquifer remediation (SEAR) with surfactant recycling and reinjection. The SEAR field demonstration is funded by the Navy's Environmental Securities Technology Certification Program (ESTCP) to promote the advancement of innovative technologies for effective remediation of Department of Defense sites contaminated with DNAPL and/or light nonaqueous phase liquids (LNAPL). However, before Camp Lejeune could be selected by ESTCP as the SEAR demonstration site, the DNAPL source zone at Site 88 had to be located, characterized, and evaluated per site selection criteria.

In support of the ESTCP site selection process, a DNAPL source-zone investigation was conducted at Site 88 by Duke Engineering & Services (DE&S) which included three phases of investigation. The objectives of Phase 1 of this investigation were to: (1) locate the DNAPL zone, (2) delineate the horizontal and vertical extent of DNAPL at the site, and (3) characterize the geosystem of the DNAPL zone (i.e. hydrostratigraphy, hydraulic and geochemical properties of the aquifer, and approximate DNAPL saturations). The Phase 1 investigation consisted of a relatively small scale, detailed program of soil borings and included collection of methanol-preserved soil samples. Borings were completed beneath the building and around the perimeter of the building to a depth of about 21 feet below ground surface. The DNAPL investigation found free-phase and residual DNAPL located at a depth interval of approximately 17 to 20 feet below ground surface. The DNAPL zone is bounded below by a clay aquitard which functions as an effective capillary barrier to prevent further downward migration of DNAPL. The DNAPL zone is located beneath the northern portion of Building 25 and also extends to an area approximately 20 to 30 feet beyond the north side of the building. This investigation also revealed the presence of LNAPL smeared across the water table at a depth of approximately 7 to 10 feet below ground surface. The LNAPL is composed of Varsolâ which was used as the facility dry cleaning solvent and was stored in underground storage tanks until the 1970s. PCE replaced Varsolâ as the dry cleaning solvent at that time because of the fire hazard represented by Varsolâ.

Phase 2 of the DNAPL investigation combined laboratory and modeling studies to design a partitioning interwell tracer test (PITT) for measuring the volume and relative distribution of DNAPL at the site. Laboratory studies were conducted using DNAPL and sediments collected from the site, and resulted in the selection of a suite of tracers suitable for a PITT under the site specific conditions at Site 88. Then, using information gained during the Phase 1 field investigation, a geosystem model of the site was constructed for preliminary PITT-design simulations using UTCHEM, a three-dimensional fluid flow simulator for multiphase and multi-component chemical composition simulations. UTCHEM is an EPA-approved simulator developed by the University of Texas at Austin. The objective of the UTCHEM simulations was to determine the preliminary design flow rates and test duration of the PITT. The PITT design consists of nine wells in a 3X3X3 line-drive wellfield configuration, with three injector wells and six extractor wells; the three injectors are configured as a central line wells in the nine-well array. For tracer injection and extraction, the wells are screened from approximately 16 to 20 feet below ground surface and terminate in the clay aquitard. The area formed by the PITT wells is 20 feet wide by 30 feet long, with a resulting interwell distance of 15 feet between any given injector and extractor. The size of the PITT wellfield was economically constrained by the time required for tracers to travel the interwell distance between injectors and extractors through the low permeability shallow aquifer which is composed of fine to very-fine sand (Kavg @ 0.3 ft/day or 10-4 cm/sec). Design modeling suggested that the PITT would require approximately 35 to 50 days to be completed in the DNAPL-contaminated aquifer at Site 88. Since Building 25 is still fully operational as the Base dry cleaning facility, the PITT wells were installed outdoors on the north side of the building to minimize logistical conflicts with the dry cleaning operations during the PITT and subsequent SEAR.

Phase 3 of the DNAPL source-zone investigation included field implementation of the PITT as well as several additional field activities required prior to the PITT. First, free-phase DNAPL recovery was undertaken by means of a water flood to minimize the amount of free-phase DNAPL in the test zone. Secondly, a conservative interwell tracer test (CITT) was conducted to evaluate the preliminary PITT design (i.e. flow rates, test duration) as determined by the Phase 2 design modeling. A CITT provides empirical evidence of the degree of aquifer heterogeneity present in the test zone, thus allowing PITT design revisions to be made before starting the PITT, and thereby ensuring the success of the PITT. Bromide was used as a conservative tracer for the CITT, and tracer breakthrough was measured at the six extractor wells to determine the actual tracer residence time in the interwell swept pore volume between a given pair of injection and extraction wells. The results of the CITT showed that only minor changes were needed in the injection and extraction design flow rates for the final design of PITT.

The PITT began on May 13, continued for 40 days, and was terminated on June 22, 1998. PITT data analysis revealed that 87 gallons of DNAPL is present in the 4,800gallon swept pore volume of the test zone. DNAPL saturations in the test zone are highest in the area adjacent to the north wall of the building, at approximately 4%, and decrease in a northerly direction away from the building to about 0.4% saturation at a distance of approximately 20 feet north of Building 25. The PITT provides baseline data on DNAPL conditions in the test zone prior to the SEAR. The SEAR demonstration with surfactant recycling will be conducted in early 1999. The SEAR will be immediately followed by a second PITT to measure the volume of DNAPL remaining in the test zone. PITT 1 and PITT 2 will be compared to evaluate the effectiveness (i.e. performance assessment) of the surfactant flood to remove DNAPL from the test zone at Site 88.

The DNAPL source-zone investigation at Camp Lejeune was co-funded by Navy ESTCP and Navy LANTDIV, and was conducted in a teaming arrangement between DE&S and Baker Environmental (the LANTDIV CLEAN program contractor at Camp Lejeune). The above funding and teaming arrangement remains in place for the SEAR and PITT 2.

Report(s)/Publication(s) (Additional Information Sources):

None

GWRTAC ID: FLSH0040

Project Name: OK Tool Area at Savage Well Site

City: **State/Province:** NH

Primary GWRTAC Personal Communication Source (Name/Organization): Dick Willey
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text is from notes from an August 1998 conversation with EPA ORD (R.S. Kerr Laboratory) representative, and an October 1998 communication with Duke Engineering & Services:

A neutral-buoyancy surfactant flood will be tested for remediation of PCE DNAPL at this site in New Hampshire. Before-and-after partioning interwell tracer tests (PITTs) will be performed to estimate the volume of PCE DNAPL present prior to, and after commencenment of the surfactant flood demonstration. Surfactant-Enhanced Aquifer Remedation - Neutral Buoyancy (SEAR-NB), as this version of the SEAR is known, has been developed by Mike Shook of INEEL and Gary Pope at the University of Texas at Austin and is patent pending. Field operations are due to begin in late 1998.

The surfactant flood will be conducted within a slurry wall which was installed around the source area. The slurry wall is keyed into a till layer of lower hydraulic conductivity than the target treatment zone, as no confining layer is present. The target treatment zone is approximately 50 feet below the ground surface (bgs), and consists of poorly sorted outwash plain materials, which are primarily coarse grained. A metamorphic bedrock sequence is present at about 100 feet bgs. Soil vapor extraction is also anticpated to be conducted within the slurry wall. The PRPs are responsible for pumping and treating the mile-long dissolved plume outside the slurry wall to expedite the decrease in dissolved phase contaminants. It is anticpated that the extraction of groundwater and re-injection of surfactant solution within the slurry wall will take place using only vertical wells, that will be approximately 50 feet in depth. Final design as to the number of wells, volume of groundwater, etc., will be completed after the PITT test. Some hydraulic control within the slurry wall will be designed to maintain an inward gradient.

Report(s)/Publication(s) (Additional Information Sources):

None

GWRTAC ID: FLSH0041

Project Name: Texas Eastern Transmission Facil. Delmont, PA

City: Delmont **State/Province:** PA

Primary GWRTAC Personal Communication Source (Name/Organization): Fred Baldisari
Pennsylvania DEP

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was excerpted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, which cited a July 29, 1996 Technology Report provided by S.S. Papadopulus & Associates, Inc., and "Field Demonstration of Surfactant Injections to Enhance PCB Removal from Fractured Rock, Delmont, PA", Main Report, S.S. Papadopulos & Associates, Inc., May 1996:

Since 1993, staff with S.S. Papadopulus & Associates, Inc. have been working at a site near Delmont, in Westmoreland County, Pennsylvania where soils and groundwater have been impacted by pipeline liquids containing polychlorinated biphenyls (PCBs). As part of this effort, extensive work has been conducted in characterizing a fracture zone that passes beneath the site and results in a spring at a distance of approximately 150 m (492 feet) downgradient of a former pipeline liquids pit. Concentrations of total PCBs in the spring water have been measured at. approximately 5 ug/L for the past 8 years. The spring, (SP01), has an average annual flow of about 2.5 gpm, and discharges from a fractured zone in the sandstone bedrock underlying the area. The geology at the Delmont site consists of interbedded sandstone, shale, clay, limestone, and coal of the Pennsylvanian age Conemaugh Group. The local geologic structure is represented by the lower coal unit which strikes northwest and dips 3 to 4 deg. northeast. On the hillside above spring SP01, a few feet of overburdern overlies a sandstone unit, and the sandstone unconformably overlies a shale unit. The water table is located within the sandstone unit, and the spring is a discharge point for the groundwater flowing within the sandstone unit, as confirmed by tracer studies. Average groundwater velocties of 110 to 860 feet per day, depending on the flow rate of the spring, have been determined through tracer studies.

In an effort to explore the use of an innovative technology to remove PCBs from the fractured rock environment and remediate the spring, two surfactant tests have been conducted at the site. Prior to surfactant delivery, tracer tests were conducted using conservative tracers. The primary conclusion of the tracer tests was that most of the tracer could be recovered in a period of two weeks.

The initial test was conducted in 1993. This involved delivery of 110 gallons of cocamidopropyl betaine (Mirataine CB) via a monitoring well located near the pipeline liquids pit. The net effect of this effort was to increase PCB concentrations at the spring from 5 to approximately 260 ug/L. The primary conclusion drawn from this effort was that increased levels of PCB removal could be achieved as long as surfactant concentrations were maintained at concentrations above the critical micelle concentration.

The second test was conducted in 1995 and consisted of two periods of surfactant delivery. In this case, the chemical system included 91 wt% ethoxylated alcohols (Witconol SN-70) and 9 wt% cocamidopropyl betaine (Mirataine BET C-30). The first period involved 91 gallons delivered over 42 hours. The second period involved 200 gallons delivered over 27 hours. Produced fluids were treated using an onsite biological treatment unit.

Enhanced concentrations of PCBs were observed at surfactant concentrations exceeding 500 mg/L. Peak surfactant concentrations observed at the spring during this test were 11,000 and 13,000 mg/L, respectively, for the first and second periods. Correspondingly, peak PCB concentrations were 8,000 and 3,200 ug/L. Lower concentrations from the second period are attributed to lower groundwater temperatures.

During the 1995 tests, an estimated mass of 0.320 kg of PCB was recovered. Key conclusions cited by the author include the following:

The mass recovered was probably small relative to the total mass of PCBs in the subsurface.

The mass recovered in 1995 was large relative to the mass recovered during the 1993 effort.

The mass recovered in 1995 was equal to the total mass that would have been discharged from the spring under natural conditions over a period of 16 years.

Following both of the 1995 surfactant delivery periods, PCB concentrations at the spring returned to their historical level of 5 ug/L.

At present, no plans exist for further surfactant flushing at the site. Instead, recovery and treatment of PCBs at the spring is planned. The limiting factor controlling the duration of the surfactant injections presented above was the ability to effectively treat the surfactant-containing spring water. A more efficient treatment system would be needed for successful operation of a long-term surfactant injection system.

Report(s)/Publication(s) (Additional Information Sources):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

S.S. Papadopulos & Assoc., Inc., 1996: "Field Demonstration of Surfactant Injections to Enhance PCB Removal from Fractured Rock, Delmont, Pennsylvania, Main Report", Prepared for Texas Eastern Transmission Corporation, Houston, TX, Prepared by S.S. Papadopulos & Assoc., INc., Bethesda, MD, May 1996

GWRTAC ID: FLSH0042

Project Name: Thouin Sand Quarry, Quebec, CA

City: L'Assomption **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. EPA, Aug 1996: Completed North American Innovative Remediation Technology Demonstration Projects, EPA 542-B-96-002, PB 96-153-127, U.S. EPA OSWER (5102G), TIO, Washington, DC 20460

Project Summary:

The following is excerpted from Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, which referenced Martel, et al. (1996):

The Thouin Sand Pit site is located in L'Assomption, Quebec, approximately 20 km northeast of Montréal and is characterized by a thin silty sand layer (2 m or 6.6 ft) underlain by a 30 m (98 ft) thick deposit of silty clay. Waste oils and organic compounds dissolved in water have been flowing in ditches and nearby creeks. Historic activities at the site involved disposal of waste oils from petroleum refining and other industrial activities. The NAPL present at the site consists of a mixture of chlorinated and nonchlorinated hydrocarbons with a density greater than water. Sediments at the site consist of approximately 2 m (6.6 ft) of silty sand underlain by approximately 30 m (98.4 ft) of siltly clay.

During the fall of 1994, a field test of aquifer washing using a micellar solution was conducted at the Thouin Sand Pit. The overall objective of this effort was to evaluate the use of a washing solution including a surfactant, an alcohol, two solvents, and a mobility control blank of polymer to recover a DNAPL. The washing solution was designed after several laboratory column experiments and after construction of several phase diagrams. Based on extensive laboratory work, a chemical system involving the following components was selected:

· n-Butanol

· Hostapur (SAS) (Hoechst GmbH) · Toluene
· d-Limonene

The evaluation considered the following:

Efficiency of the chemical solution

Effectiveness of the delivery/recovery strategy, including the field testing of polymers for mobility control

Effects of the solution density and viscosity

Mechanism of DNAPL recovery

Post soil flushing soil treatment

Treatment of produced fluids

The test plot, 4.3 m by 4.3 m (14.1 x 14.1 ft) and covering less than 0.075% of the area, was equipped with one central injection well, four recovery wells spaced in a square, and 12 multilevel observation wells. Recovery wells were 3 meters (9.8 ft) from the injection well, resulting in approximately 17 m3 (600 ft3) of contaminated soil in the saturated zone within the treatment area. The pore volume was approximately 6 m3 (212 ft3 or 1,585 gal). During well installation, 42 soil samples were taken. The average initial DNAPL concentration was 55,000 mg / kg dry soil.

The test plot was flooded with: (1) 1.34 PV water, (2) 0.54 PV polymer, (3) 0.9 PV surfactant, (4) 1.6 PV polymer, (5) 1.4 PV water, (6) and finally with an injection of bacteria and nutrients to increase biodegradation of the remaining DNAPL.

Based on soil cores collected before and after the flood in the saturated zone, in the zone swept by the washing solution, 86% of (980 kg) the residual DNAPL was recovered using 0.9 pore volumes of surfactant and those rinses described above. Average pre- and post-flushing concentrations were 33,000 and 4,500 mg/kg, respectively. DNAPL between extraction wells was not removed well due to insufficient flow in these areas. The use of a polymer solution before and after injection of the surfactant solution appeared to be beneficial in insuring that the surfactant solution swept the majority of the total treated volume, despite the heterogeneity of the soil. Rinse cycles were not completed because of weather.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-02, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org

Martel, Richard; Gélinas, Pierre, Surfactant solutions developed for NAPL recovery in contaminated aquifers, Ground Water, 34:143-154, 1996.

Martel, Richard; Gélinas, Pierre, Residual diesel measurement in sand columns after surfactant/alcohol washing, Ground Water, 34:162-167, 1996.

Martel, Richard; Gélinas, Pierre; Laurent Saumure, In situ recovery of DNAPL in sand aquifers: clean-up test using surfactants at Thouin Sand Quarry, presented at the 5th Annual Symposium on Ground-water and Soil Remediation, Toronto, Ontario Canada, Oct. 2-6, 1995.

Martel, Richard; Gélinas, Pierre; Desnoyers, Jacques E.; Masson Anne, Phase diagrams to optimize surfactant solutions for oil and DNAPL recovery in aquifers, Ground Water, 31:789-800, 1993.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

U.S. EPA, Aug 1996: Completed North American Innovative Remediation Technology Demonstration Projects, EPA 542-B-96-002, PB 96-153-127, U.S. EPA OSWER (5102G), TIO, Washington, DC 20460

GWRTAC ID: FLSH0043

Project Name: Umatilla Army Depot (Lagoons), Hermiston, OR

City: Hermiston **State/Province:** OR

Primary GWRTAC Personal Communication Source (Name/Organization): Harry Craig
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Internet URL http://www.epa.gov/superfund/oerr/impm/products/nplsites

U.S. EPA, Nov 1996: Innovative Treatment Technologies: Annual Status Report (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G), TIO, Washington DC

Project Summary:

The following text is from notes from May 1997 and August 1998 conversations with the EPA RPM:

Residual explosives (TNT, RDX, TNB, HMX) contamination was present from the surface to a depth of 53 feet below the ground surface (bgs), beneath an old lagoon area approximately one-half acre in areal extent. The original lagoon was approximately five feet deep, and the area was excavated to a depth of 20 feet bgs. Consequently, the current contaminated zone being flushed is from approximately 20 to 53 feet bgs. (Excavated soils were treated via bioremediation (composting)). The contaminated zone consists of sandy alluvium with low organic content. The average hydraulic conductivity of the treatment zone is 10-5 cm/sec. The contaminated soil volume is approximately 48,400 yd3.

The water table is present at an approximate 53 foot depth bgs. The groundwater contamination plume covers a 350 acre area. A confining layer is present at 80 to 90 feet bgs, and consists of a 20 to 30 foot thick solid basalt layer. Ground-water is extracted via three pumping wells at depths of 100 to 150 feet bgs, at a rate of approximately 1,600 gpm. Extracted ground-water is treated with carbon, and 400 gpm are re-injected via infiltration galleries. Containment is via hydraulic control. It is estimated that the in situ flushing project will continue for one to two years, and that groundwater treatment will continue for 27 years.

The specific groundwater cleanup goals for each of the four main constituents are:

TNT (2.8 ppb), RDX (2.1 ppb), TNB (1.8 ppb), and HMX (350 ppb). As of August 1998, monitoring wells adjacent to the flushing operation have exhibited a 90% reduction in leachable explosives in groundwater in the first year of operation. A slug of the four target contaminants (spike of 9,000 ppb in a monitoring well) had also moved through between the lagoon flushing zone and the closest extraction well. The spikes had not yet been seen in the extraction wells.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

Internet URL http://www.epa.gov/superfund/oerr/impm/products/nplsites

U.S. EPA, Nov 1996: Innovative Treatment Technologies: Annual Status Report (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G), TIO, Washington DC

GWRTAC ID: FLSH0044

Project Name: United Chrome Products, Corvallis, OR

City: Corvallis **State/Province:** OR

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following is excerpted from Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993:

The site is an eight acre, former industrial hard-chrome plating facility located just north of the Corvallis Airport Facility. Hexavalent chromium contaminates surface water, soils and groundwater. The site is underlain by two water-bearing zones separated by a silty clay aquitard. The upper water-bearing zone is the primary zone of contamination, and consists mostly of silt. The shallow contaminated zone extends from the source area, to approximately 300 feet downgradient of the source area, with concentrations of Cr+6 up to 19,000 mg/L. The deep aquifer consists of sand and gravel, and is capable of supplying potable water for commercial and residential use. The deep contaminated zone extends from the source area, to approximately 400 feet downgradient of the source area, with concentrations of Cr+6 up to 223 mg/L. Delivery of flushing solution was accomplished through two open bottom infiltration basins (pits resulting from excavation of 1,100 tons of soil containing highest chromium concentrations) and one infiltration trench (used intermittently); these flushed Cr+6 from the vadose zone to the water table. Recovery of flushing solution was accomplished through a series of 23 shallow extraction wells to extract groundwater from the upper water-bearing zone. An on-site treatment facility removed chromium prior to effluent discharge to the POTW. Deep groundwater extraction had not begun at the time of this project summary.

The magnitude of Cr+6 impact in the upper water-bearing zone has been reduced, off-site migration of the plume has been prevented, and the dischage of impacted groundwater to local surface drainage ditches has been reduced. Over a three year duration, 9.7 MM gallons of impacted groundwater containing 26,732 lbs of Cr+6 have been removed. A total of 5.2 MM gallons of city-supplied water was recharged through the two infiltration basins and one infiltration trench. (An additional 30% of the extracted volume was estimated to be due to precipitation.) Cr+6 concentrations have been reduced from the overall average of 1,923 mg/L (August 1988) to 87 mg/L (June 1991). The maximum Cr+6 concentration of 19,000 mg/L was reduced to 530 mg/L. The site cleanup goal of 10 mg/L was achieved in four of 23 extraction wells and ten of 11 monitoring wells tested in April 1991.

Remediation progress is highly variable, and dependent upon the well location; wells near infiltration basins have yielded the largest volume of groundwater and display the greatest Cr+6 decline. The rate of Cr+6 decline began to exhibit a tailing effect as the project progressed, likely due to more apparent effects of variable length contaminant flow paths, slow diffusion of Cr+6 from fine-grained sediments, hydrodynamic isolation, and desorption of Cr+6 from soils/dissolution of solid phase Cr+6. A pore volume (PV - volume of groundwater within the plume) at this site contains approximately 2.6 MM gallons of water (using 10 mg/L Cr+6 as the definition of the plume). The time required to remove a PV at this site (PV (gal)/pumping rate (10 gpm)) is approximately every six months, if the 10 gpm pumping rate is sustained. However, due to highly variable well yields, some areas are flushed much more rapidly than others, and within areas of low well yield, cleanup rates are reduced. It was planned to alter the operation of the delivery and extraction system to increase contact time of infiltration water and solid/sorbed Cr+6, deliver recharge area to other areas within the extraction well network, and assist in preventing short circuiting, and thereby maximize Cr+6 recovery per gallon of groundwater extracted.

Cleanup duration estimates for this site to achieve the 10 mg/L Cr+6 remediation goal have ranged from five to 15 years. Cleanup duration is difficult to predict due to uncertainties related to sediment heterogeneity, distribution of contaminant mass, variable groundwater extraction rates, and seasonal weather patterns limiting groundwater availability.

Cost estimates indicate that treatment costs were estimated at $40/lb of Cr+6 removed for the first 25,000 lbs. As Cr+6 concentrations drop in later phases of operation, it is estimated that costs will double to $80/lb of Cr+6 removed.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

Mann et al., 1993: Innovative Site Remediation Technology Soil Washing/Soil Flushing, Vol. 3 of 8, WASTECH, William C. Anderson, P.E., DEE, Ed., American Academy of Environmental Engineers, 1993

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October

1991.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0045

Project Name: University of Michigan - Surfactant Remediation of NAPL-Cont

City: Ann Arbor **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

Project Summary:

The following is excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org:

Nonionic surfactant (polyoxyethylene (20), sorbitan monooleate (trade name Witconol 2722 or Tween 80) are being studied as flushing solution for NAPL removal.

Dr. Abriola's research group has been conducting laboratory and numerical modeling studies to evaluate the use of surfactants for remediating aquifers contaminated by nonaqueous phase liquids (NAPLs). This work has been funded by the EPA's R.S. Kerr Environmental Research Laboratory and Great Lakes Mid-Atlantic Hazardous Substance Research Center (HSRC). The specific objectives of this research are to: screen and select surfactants that will enhance the solubility of NAPLs in water; measure the solubilization of representative NAPLs (e.g., dodecane, PCE, o-DCB) in aqueous surfactant solutions; quantify the ability of selected surfactants to recover entrapped NAPLs from soil columns; and develop and evaluate numerical models capable of predicting surfactant-enhanced solubilization and mobilization of NAPLs in ground-water systems.

Soil column experiments were conducted to test the ability of a nonionic surfactant, polyoxyethylene (20) sorbitan monooleate (trade name Witconol 2722 or Tween 80), to recover entrapped dodecane. After injecting a 4% surfactant solution, the concentration of dodecane exiting the column increased by approximately 100,000 times. Removal of 10% of the residual dodecane required 0.7 liters of surfactant solution, while comparable recovery without surfactant would have required 130,000 L of water. Numerical models were developed to explore the optimal surfactant flushing strategies based on the flow rate, flushing time, and volume of surfactant required to remove NAPLs from soil columns. Additional studies are underway to investigate the effects of rate-limited solubilization, NAPL mobilization and sorption on surfactant-based remediation technologies. No field demonstrations have been conducted to date, but it was anticipated that these studies will provide the basis for such work.

Report(s)/Publication(s) (Additional Information Sources):

"Surfactant Flushing Research to Remove Organic Liquids from Aquifers," Ground Water Currents, March 1994. EPA 542-N-92-002.

"Surfactants Can Trap, Untrap Contaminants" Centerpoint, 1 (2) 1993. (A publication of the HSRCs).

"Surfactant-Enhanced Solubilization of Residual Dodecane From Soil Columns 1. Experimental Investigation, 2. Modeling Investigation" Environmental Science & Technology, 27, 1993, p 2332-2351

"Surfactant-Enhanced Remediation of Soil Columns Contaminated by Residual Tetrachloroethylene,"
Journal of Contaminant Hydrology, 16, 1994, p 35-53.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), TIO, Washington, DC, avail. at www.gwrtac.org

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0046

Project Name: Purdue University - Phototransformations of PCBs in Micellar

City: West Lafayette **State/Province:** IN

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 7.

Project Summary:

The following was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 7:

This paper discusses photolysis as a destructive process for polychlorinated biphenyls (PCBs) extracted from soils with surfactant solutions. Photodechlorination may eliminate the need to physically separate these contaminants from the washing solution. Photochemical reactions of the PCB congener mixture, Aroclor 1254, and the specific congener, 2,3,4,5-tetrachlorobiphenyl (2,3,4,5-TeCB), were investigated in aqueous solutions containing surfactant micelles with UV light at 253.7 nm. The main decay pathway in which lesser chlorinated congeners were formed as intermediates was shown to be photoreduction through photodechlorination. The quantum yield for decay of 0.1µ M 2,3,4,5-TeCB in 0.5 mM Brij 58 micellar solutions was over six times greater than in water alone. Surfactant loss to the soil proved to be the limiter for sequential extraction from a soil and photoreduction of 2,3,4,5-tetrachlorobiphenyl by Brij 58 solutions.

Report(s)/Publication(s) (Additional Information Sources):

Chu, Wei, Chad T. Jafvert, Claude A. Diehl, Karen Marley, Richard A. Larson, 1998: "Phototransformations of Polychorobiphenyls in Brij 58 Micellar Solutions", in Environmental Science and Technology, Vol. 32, No. 13, pp. 1989-1993, July 1, 1998.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0047

Project Name: Cape Canaveral Lodge Complex 34

City: Cape Canaveral **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): Tom Early
Oak Ridge National Lab

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text is from notes from August 1998 conversations with EPA ORD (R.S. Kerr Laboratory) and Oak Ridge National Laboratory (DOE) representatives:

Three side by side DNAPL remediation demonstration projects are being planned at NASA's Cape Canaveral to allow comparison of the technologies. One of those being planned is an in situ flushing demonstration, which may be either a surfactant or a cosolvent flood. Also planned is a thermal enhancements demonstration using either steam or electrical resistance heating, and an in situ chemical oxidation demonstration using either Fenton's reagent or permanganate. All three technologies will be demonstrated in separate, approximately 50 x 75 ft. demonstration plots within the TCE DNAPL source area. The TCE contamination resulted from the cleaning of engine parts in this area. The majority of the DNAPL is present below the water table, within an unconfined aqufier comprised of barrier island sediments. These sediments consist of sands with silts and clay and are heterogeneous in nature. The maximum depth of the target treatment zone is approximately 45 to 50 feet below the ground surface (bgs), which is also the depth of a clay confining layer. Installation of a slurry wall or other barrier around the test areas has not been ruled out, but researchers would prefer not to install a physical barrier. Hydraulic containment will be practiced, though the delivery and extraction systems are still in design. Site characterization work (including characterization of the dissolved phase plume) was done by NASA as part of an RFI at the site,and the residual satuaration of DNAPL in the source areas is fairly well know from cores which have been collected. Additional site characterization work prior to conducting the site demonstrations must still be completed. As of September 1998, all site demonstrations are in the design phase. It is not yet known whether in situ flushing will involve the use of surfactants or cosolvents.

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0048

Project Name: Vineland Chemical, Vineland, NJ

City: Vineland **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): Matthew Westgate
U.S. EPA

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following text is from notes from April 1997 conversation with EPA RPM, and from Internet URL EPA.gov:

ROD (9/28/89) indicates site is located in Vineland, Cumberland County, New Jersey, in residential/industrial area, and bordering Blackwater Branch Stream, a tributary to Maurice River, which flows into Union Lake. Facility consists of several herbicide manufacturing and storage facilities, wastewater treatment facility and several lagoons, and produces approximately 1,107 tons of herbicide waste by-product salts (K031) per year. These K031 wastes were stored on site in surficial piles, in unlined lagoons, and in abandoned chicken coops, and arsenic-impacted wastewater was discharged into the unlined lagoons until 1980. Due to the high solubility of the salts, the past improper storage has resulted in extensive arsenic contamination of soil, groundwater, and sediment.

ROD (9/28/89) indicates selected remedies for the site include in situ flushing of 126,000 cubic yards of soil (OU 1). Of this soil, 54,000 cubic yards will be excavated and consolidated with 72,000 cubic yards of undisturbed soil.

RPM (4/25/97) indicates that currently, a pump and treat system is in operation at the facility, consisting of 13 extraction wells completed in the Cohansey Aquifer, at depths varying from 30 to 50 feet. Each well is used to pump an average of 100 gpm, for a total of 2 MM gpd. Isolated areas of contaminated soil with >20 ppm arsenic will be collected and placed into a former lagoon area above the main body of impacted soil. It is planned to re-inject treated groundwater via a discharge pipe into the former lagoon area to flush the arsenic impacted soils present in the 12 to 15 foot unsaturated zone, as well as those collected from the isolated areas. Site aquifer soils consist of medium to fine sand, with low organic content, and are therefore conducive to in situ flushing. (River sediments adjacent to site contain appreciable fines, such as clays, as well as higher organics, and will be subjected to ex situ soil washing, and are part of a separate operable unit.)

Performance results are not available (have completed pilot, and are at 65% design for full-scale). Remediation goals are 20 ppm As (soil), 50 ppb total As (groundwater).

Report(s)/Publication(s) (Additional Information Sources):

U.S. EPA, Nov. 1996: Inn. Trtmt. Techs.: Ann. Status Rpt. (8th Ed.), EPA 542-R-96-010, No. 8, U.S. EPA OSWER (5102G) TIO, Wash., DC

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0049

Project Name: Volk Air National Guard Base, WI

City: Camp Douglas **State/Province:** WI

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Nash, J. H., 1988, Project Summary Field Studies of In Situ Soil Washing, EPA/600/S2-87/110, U.S. Environmental Protection Agency, February 1988.

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

Project Summary:

The following was excerpted from Nash, J. H., 1988, Project Summary Field Studies of In Situ Soil Washing, EPA/600/S2-87/110, U.S. Environmental Protection Agency, February 1988:

Laboratory Study

Soil impacted by fire training operations at the Volk Air National Guard Base, Wisconsin was characterized in a laboratory. Physical tests performed included grain size, TOC, CEC, mineralogy by x-ray diffraction, and permeability. Grain size indicated 98% sand, x-ray diffraction indicated alpha-quartz, with a minor amount of feldspar was present. Other results were TOC (14,900 ug/g) and CEC (5 meq/100 g). The permeability of the fire pit soil, at 10-3 and 10-4 cm/sec, was one to two orders of magnitude less than adjacent uncontaminated soil. Dichloromethane, chloroform, TCA and TCE were present at levels up to 3 ppm, and total chlorinated solvents were found at concentrations up to 3.5 ppm. The level of hydrocarbon contamination was in the hundreds of ug/g, based on the laboratory analysis. Soil adsorption constants (K) for the soil contaminants ranged from 10 to 1,000,000. Ground-water from the aquifer below the fire training pit contained chlorinated and non-chlorinated hydrocarbons above 300 ppm. The soil was recompacted into glass columns creating a simulated in situ environment. Under gravity flow, 12 pore volumes (PV) of aqueous surfactant solutions were passed through each column. Previous laboratory work had identified a 50/50 blend of two commercially available surfactants (Adsee 799 and Hyonic PE-90, sold by Witco Chemical and Diamond Shamrock, respectively) that work well in removal of soil contaminants. GC analyses of the washing effluent and soil was performed to determine removal efficiency (RE), with encouraging results.

Field Study

Ten two by two foot, one-foot deep holes were dug into the impacted surface of the fire training pit, and surfactant solutions were applied to each hole at the rate of 1.9 gpd/ft2. The daily dosage was applied in four increments, and since the holes percolated at different rates, the time interval between doses varied from hole to hole. Testing in three pits was stopped when time intervals between surfactant applications approached ten hours, creating unacceptable permeabilities were being created. After seven days of washing the pits received rinses of local, potable well water.

Undisturbed soils beneath each hole were analyzed for residual contamination after nine to 14 PV of surfactant solution had been applied, and after the final potable water rinses. Contaminant concentrations in these soils were 5,000 to 10,000 ug/g, which was comparable to prewash conditions. Researchers concluded that the in situ soil washing was not measurably effective, and that it is likely that the same ineffectiveness would occur at other chronic spill sites with contaminants with high soil-sorption values (K>103).

Project costs were not available from reference source.

Report(s)/Publication(s) (Additional Information Sources):

Nash, J. H., 1988, Project Summary Field Studies of In Situ Soil Washing, EPA/600/S2-87/110, U.S. Environmental Protection Agency, February 1988.

U.S. Environmental Protection Agency, 1991: Engineering Bulletin In Situ Soil Flushing, EPA/540/2-91/021, U.S. EPA Office of Emergency and Remedial Response (OERR), Washington, DC 20460, Office of Research and Development (ORD), Cincinnati, Ohio 45268, 8 pp., October 1991.

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0050

Project Name: Gulf Power - Lynn Haven, FL

City: Lynn Haven **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): Jim Redwine
Southern Company Services

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 7

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 7. and from notes from August 1998 conversation with representative of Southern Company Services, Inc. Direct quotes are from EPA, 1996:

"Redwine (1995) provides brief case study and description of soil flushing to treat contaminated groundwater. Selected reagents may be added to the flushing water to enhance contaminant removal. In the iron coprecipitation process, an iron salt is added to the contaminated water and the pH is adjusted to induce precipitation of iron oxyhydroxides. During floc formation, trace elements adsorb onto the iron floc. Cross-flow ceramic membrane filtration can be used to remove any remaining contaminant in the feed stream. In field tests, an arsenic plume flushed with citric acid was reduced by 73 percent after 6 months of treatment."

In situ flushing was implemented in November 1994 to enhance pump and treat remediation of a dissolved arsenic contaminant plume which resulted from application of an arsenic-based herbicide. This is the first known full-scale application in the United States of in situ flushing at a site where flushing additives are in use to enhance contaminant recovery. At the site, contaminated vadose zone soils had been excavated. The depth to the water table is about five feet below the ground surface (bgs), and a confining unit is present at about 25 feet bgs. The geologic unit targeted for flushing is comprised of a silty fine sand (The Coastal Plain Surficial Aquifer). The confining layer is the Jackson Bluff Clay, which is approimately one foot thick beneath the site. The unconfined Surficial aquifer (approximately 20 feet thick beneath the site is the unit targeted by the flushing project.

Approximately 14 wells are used either for groundwater extraction or injection. Each well is instumented with piping that will allow it to function as either an extraction or an injection well, as the need arises. The wells are screened from the top of the water table to about five feet above the confining layer (about 5 to 20 feet bgs). Monitoring wells have also been utilized as part of the flushing system as needed. At the site, approximately 10 gpm of contaminated groundwater is extracted, treated above ground, supplemented with additives, and re-injected. Originally, citric acid was used as the flushing additive. Currently, a proprietary compound is added as the flushing reagent.

Remediation goals are to achieve MCLs (50 ppb) for dissolved arsenic for off site groundwater. As of August 1998, site closure was requested. Based on an overall view of the site, it has been determined that flushing is twice as efficient as unenhanced pump and treat, based on contaminant removed. Injection of the flushing agent into a given well, followed by a waiting period and removal from the same well has increased contaminant removal up to 100 times that expected with unenhanced pump and treat, however, only the aquifer in the immediate vicinity of the well could be affected in this manner. To enable implementation of this project, the regulatory agency has required assurance that the flushing additives being used were benign. Research needs identified by technical team members include a need to bridge the gap between laboratory and field demonstration work to full-scale implementation of in situ flushing where flushing agents are used, and to optimize the concentration of the flushing agent needed for the project.

Report(s)/Publication(s) (Additional Information Sources):

Redwine, et al, 1997: "Innovative Technologies for Remediation of Arsenic in Soil and Groundwater", EPRI Report TR-106701, Electric Power Research Institute, Palo Alto, CA, April 1997.

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 7

Redwine, J.C.,1995: "Soil Flushing, Iron Coprecipitation, and Ceramic Membrane Filtration: Innovative Technologies for Remediating Arsenic-Contaminated Soil and Groundwater", Southern Company Services, Inc., in Proceedings: ACS Special Symposium: Emerging Technologies in Hazardous Waste Management, Atlanta, GA Sept. 17-20, 1995, pp. 1129-1132., Report no. CONF-9509139.

GWRTAC ID: FLSH0051

Project Name: U.S. Coast Guard, Traverse City, MI

City: Traverse City **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): Steve Schmelling
U.S. EPA ORD

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC, and GWRTAC, 1996: TE-96-002, Surfactants/Cosolvents, Jafvert, Purdue U, avail. at www.gwrtac.org, Knox, et. al, 1997: "Surfactant Remediation Field Demonstration Using a Vertical Circulation Well", and Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, Rice University further cites Sabatini, et al. (1996); Knox, et al. (1996); and U.S. EPA (1995b). See also Martel, et al. (1996):

In the summer of 1995, a field demonstration of surfactant injection and recovery was conducted at a Coast Guard station in Traverse City, Michigan. Overall, the primary focus of this effort was to evaluate the use of a vertical circulation well (VCW) for cycling fluids through a targeted interval. A secondary objective of the test was to assess the behavior of a surfactant solution in the subsurface with the goal of maximum surfactant recovery. Laboratory batch and column studies were first performed to test removal efficiencies of the contaminants and the surfactant. Modeling studies were performed on the VCW system. The VCW was a single borehole well system with two 5 ft screen lengths separated by a 3 ft spacer. The screens were isolated from each other within the well with packers. Water/surfactant was injected through the top screen and water/contaminants/surfactant extracted through the bottom screen. Preliminary tracer studies using fluorescein and sodium chloride were conducted at the site prior to installation of the VCW to characterize the system hydraulics.

Sediments beneath the site consist of well-sorted eolian sands. The test occurred in a highly conductive, unconfined aquifer, consisting of a sand formation with natural ground-water velocities of 3 to 5 ft / day. The saturated zone was at a depth of less than 10 ft below the surface. The soil and groundwater at the site was found to be contaminated with low concentrations of a mixture of PCE, TCE, and weathered jet fuel (methylated alkanes). The compounds treated were PCE and aviation fuel at up to 1000 µg / kg and 1000 mg / kg, respectively. PCE in the ground-water was typically at 10 µg / L. The low concentrations were the result of previous remediations activities conducted at the site. Fluids were introduced to the target area via an upper well screen and recovered via a lower well screen located in the same casing. The innovative hydraulic system both injects a surfactant solution and extracts the ground-water/contaminant/surfactant fluid from a single borehole. Simultaneous injection to, and extraction from, a common vertical borehole creates a circulating flow pattern that can be used to capture mobilized contaminants that migrate vertically. In addition, a total of four monitoring wells (one upgradient, three downgradient) were installed. Each of the monitoring wells was screened over the top five feet of the saturated zone. Two piezometers were installed at different depths adjacent to the VCW. The shallow piezometer had a 2-foot screened section intercepting the seasonal water table; the deep piezometer has a 2-foot screened section coinciding with the bottom 2 feet of the VCW. The demonstration area was 10 feet by 10 feet and the depth to ground water is 15 feet. The Dow Chemical Co., a manufacturer of surfactants, has formed a partnership with the investigators to promote the development of this technology. The surfactant used was Dowfax 8390 at a delivered concentration of 36,000 mg/L (10 times the cmc value (3.8 wt%)). Dowfax 8390 has FDA approval for use as an indirect food additive. Prior to surfactant delivery a tracer test was performed using fluorescein and sodium chloride.

The delivery/recovery sequence consisted of the following steps:

Injection of 540 gallons of Dowfax 8390 Solution (36,000 mg/L) at a rate of 1 gpm,
1 hour later, recovery of 40 gallons of surfactant/water solution,
20 hours after surfactant delivery, freshwater cycling.

It was found that due to the high hydraulic conductivity at the site, the extraction rate necessary to capture the surfactant and solubilized contaminants had to be about 10 to 15 times the injection rate. Produced fluids were analyzed at intervals to document surfactant mass removal. The analytical results showed that the surfactant increased the contaminant mass extracted by 40-fold and 90-fold for the PCE and jet fuel constituents, respectively. The surfactant solution demonstrated minimal sorption (retardation) and did not precipitate in the subsurface formation.

Mass recovery for the surfactant solution exceeded 95 percent for the demonstration study. PCE concentration in the effluent was increased by more than two orders of magnitude (from 5 ug/L up to a high of 800 ug/L); LNAPL constituent concentrations were increased by more than an order of magnitude (from 10 mg/L up to 974 mg/L).

A portion of the produced fluids were concentrated using micellar-enhanced ultrafiltration and then disposed of by a licensed contractor. The remainder of the effluent was sent to a carbon treatment system currently in operation at the site. At present, there are no known plans for further testing of surfactant systems at the Traverse City site.

Researchers made the following recommendations as a result of this study (See Knox, et al., 1997 for more detail).

1) The importance of pre-demonstration efforts (such as extensive site characterization work, and conductance of laboratory batch and column studies) cannot be overemphasized.
2) Adopt realistic recovery estimates. While complete, 100% recovery is virtually impossible, appropriate hydraulic controls can be instituted to achieve significant recovery of most solutions introduced to the subsurface.

Also, as a helpful hint, the authors found that facility infrastructure (proximity and availability of power, water, shelter, heat and ancillary services such as well drillers, analytical laboratories, and waste disposers) should also be considered before site selection for field demonstration.

Report(s)/Publication(s) (Additional Information Sources):

Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants/Cosolvents, Technology Evaluation Report TE-96-002, Surfactants/Cosolvents, Dr. Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, available at www.gwrtac.org

Knox, Robert C.; Sabatini, David A.; Harwell, Jeffrey H.; West, Candida C.; Blaha, Frank; Griffin, Chris; Wallick, David; Quencer, Lisa, Traverse City field test, presented at Workshop on In Situ Surfactant Use, Kansas City, MO, sponsored by the R. S. Kerr Environmental Research Laboratory, Ada OK, held September 20, 1995.

Knox, R. C.; Sabatini, D. A.; Harwell, J. H. Brown, R. E.; West, C. C.; Blaha, F., Griffin, C., 1997: "Surfactant Remediation Field Demonstration Using a Vertical Circulation Well" in Ground Water, Vol. 35, No. 6, November-December 1997.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Sabatini, D. A.; Knox, R. C.; Harwell, J. H. eds. Surfactant Enhanced Subsurface Remediation: Emerging Technologies, ACS Symposium Series, number 594, American Chemical Society, Washington, D.C., 312 pages, 1995.

Sabatini, D. A.; Knox, R. C.; Harwell, J. H.; Soerens, T.; Chen, L.; Brown, R. E.; West C. C., 1997: "Design of a Surfactant Remediation Field Demonstration Based on Laboratory and Modeling Studies" in Ground Water, Vol. 35, No. 6, November-December 1997.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0052

Project Name: University of Michigan - Partitioning Characteristics of PAHs

City: Ann Arbor **State/Province:** MI

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC, available at www.gwrtac.org:

Researchers with the Great Lakes/Mid-Atlantic Hazardous Substance Research Centers are conducting basic research to determine the partitioning characteristics of PAHs such as phenanthrene. This information applies to the use of cationic surfactants to reduce the mobility of contaminants such as PAHs. Such treatment may be used in conjunction with bioremediation to keep the contaminants from migrating over the relatively long period for complete biodegradation to occur.

Report(s)/Publication(s) (Additional Information Sources):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Surfactant Enhancements, EPA 542-K-94-003, U.S. EPA OSWER (5102W), EPA Technology Innovation Office, Washington, DC

1993: "Surfactants Can Trap, Untrap Contaminants", Centerpoint, 1 (2). (A publication of the Hazardous Substances Research Center).

GWRTAC ID: FLSH0053

Project Name: U.S. Air Force, Plant 4, Fort Worth, TX

City: Fort Worth **State/Province:** TX

Primary GWRTAC Personal Communication Source (Name/Organization): Jacqui Avvoukomides
Duke Engineering & Services

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was provided by Duke Engineering and Services (formerly INTERA) of Austin, TX, on August 28, 1998, and Jacobs Engineering on October 15, 1998:

During the period June 1995 to August 1997, INTERA (now Duke Engineering and Services) and the University of Texas at Austin, a subcontractor to INTERA, conducted a series of field, laboratory, and numerical-simulation studies to characterize the contamination by trichloroethene (TCE) of the terrace alluvial aquifer beneath the East Parking Lot of USAF Plant 4 in Fort Worth, Texas. The principal purpose of these studies was to characterize the distribution and volume of TCE present as a dense, non-aqueous phase liquid (DNAPL) in the terrace alluvial aquifer. These studies included (1) an extensive program of coring the terrace alluvium, (2) laboratory experiments to select appropriate partitioning tracers to detect and quantify TCE DNAPL in the terrace alluvium, (3) field tests to determine the hydraulic properties of the terrace alluvial aquifer, and, most importantly, (4) a partitioning interwell tracer test (PITT) to measure the spatial distribution and volume of TCE DNAPL in the terrace alluvial aquifer.

The site chosen for the hydraulic and tracer testing is adjacent to monitoring well HM-88 in the center of the East Parking Lot. This well has consistently measured aqueous TCE concentrations ranging from 35 to 75 mg/L since late 1993. Consequently, HM-88 met the "rule-of-thumb" criterion that aqueous solvent concentrations of 1% or more of the effective solubility of an immiscible solvent is an indication of nearby DNAPL (EPA, 1992). However, soil cores collected during the drilling and instrumentation of a 5-spot wellfield pattern and preserved in the field with methanol showed no evidence of TCE DNAPL. An eight-day PITT conducted in December 1996 that swept approximately 3,600 gallons of terrace alluvial aquifer pore space failed to detect any DNAPL in the 5-spot pattern. Thus, it is concluded that TCE DNAPL is not present beneath the center of the East Parking Lot at Plant 4. Furthermore, alluvial coring in 1995 by INTERA indicated that DNAPL was absent from a cross-section of boreholes much closer to the Plant itself. While a narrow TCE-DNAPL zone could easily have passed between the boreholes that were spaced 50 feet apart, it is increasingly likely that the TCE DNAPL zone is mainly under Buildings 181 and 182 of the Plant.

The results of this investigation indicate that surfactant enhanced aquifer remediation is not necessary in the area from well HM-88 to the "window" since no TCE DNAPL is likely to be present in this area. The results of the work reported in the final report (available from DE&S) indicate that recovery of the aqueous TCE plume in the East Parking Lot can, however, be improved by reconfiguring the geometry of the existing ground-water extraction wellfield to include one or more of the PITT wells, and/or by locating additional recovery wells within the primary TCE plume migration pathway in the East Parking Lot terrace alluvial aquifer.

Capillary pressure tests indicate that the bedrock beneath Plant 4 and the East Parking Lot, as well as the terrace alluvium which is derived from the bedrock, can be wetted by TCE, i.e., like typical carbonate materials that are frequently "oil wetting". This has important implications for remediation; i.e. if oil wet conditions exist at Plant 4, only surfactant enhanced aquifer remediation will be capable of removing DNAPL from the oil-wet sediments.

Report(s)/Publication(s) (Additional Information Sources):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

GWRTAC ID: FLSH0054

Project Name: U.S. DOE Gaseous Diffusion Plnt, Paducah, KY

City: Paducah **State/Province:** KY

Primary GWRTAC Personal Communication Source (Name/Organization): Jacqui Avvoukomides
Duke Engineering & Services

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was excepted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

In 1994, a single-well surfactant injection-withdrawal field pilot test was conducted at the U.S. Department of Energy Paducah Gaseous Diffusion Plant (PGDP) located in Paducah, Kentucky (Intera, 1995). The test was completed in an alluvial aquifer located 20 to 30 m beneath a vapor degreasing facility located within Waste Management Unit 11 (WMU-11). It is estimated that 10,000 gallons of trichloroethylene (TCE) may have leaked from the degreasing facility to the subsurface. The aquifer beneath the facility is characterized as a gravely, fine to medium sand having a hydraulic conductivity of approximately 3 x 10-3 cm/s. TCE concentrations in sampled groundwater in the vicinity of the test site varied up to approximately 10 percent of the aqueous solubility of TCE, suggesting that immiscible-phase TCE may be present in the subsurface. Immiscible-phase TCE has not been observed in monitoring wells at the site.

A total of 99 surfactants (25 nonionics and 74 anionics) were screened to asses their ability to solubilize TCE. The purpose of the surfactant injection was to solubilize TCE, not mobilize TCE. The screening procedure consisted of stirring TCE-surfactant mixtures for a minimum of 24 hours, followed be centrifugation at 3,500 rpm for 1 hour and gas chromatography (GC) analysis. A total of 10 of the 99 surfactants (5 nonionics and 5 anionics) solubilized TCE to concentrations greater than 15,000 ppm, representing a factor of approximately 13 increase in aqueous solubility. The final surfactant selected was a sorbitan monooleate, capable of solubilizing TCE to approximately 16,000 mg/L using a 1 percent micellar-surfactant solution. The sorbitan monooleate is approved for use as a food-grade additive by the U.S. Food and Drug Administration. The critical micelie concentration (CMC) of this surfactant is reported to be 0.012 percent (by volume).

Prior to initiation of the field test, an assessment of vertical DNAPL mobilization was carried out. The interfacial tension between TCE and a 1 percent surfactant solution was measured to be 11.7 dynes/cm, indicating that a lowering of interfacial tension does occur upon exposure to the selected surfactant. It is not clear what equilibration time was used ' prior to conducting the interfacial tension measurements. As a result, it is not clear whether or not the minimum interfacial tension was measured given the exposure time expected for the field test. The mobility of residual DNAPL under reduced interfacial tension conditions was assessed using a capillary and bond number analysis. The vertical mobility of pooled DNPAL in response to a lowering of interfacial tension was not assessed.

The field test consisted of injecting a 1 percent surfactant solution into a single injection well for 3.75 days at a rate of 3.8 liters per minute (1 gpm). Groundwater was then extracted from the same well for 16 days at a rate of 3.8 liters per minute. The extraction phase therefore lasted greater than four times the injection phase, in an attempt to ensure that all surfactant solution would be recovered. Sampling of the extracted groundwater, however, indicated that only 34 percent of the injected surfactant was recovered, and that no increase in TCE concentration was achieved. It was hypothesized that the low surfactant recovery was due to surfactant sorption to aquifer solids, precipitation of the surfactant, liquid crystal formation of the surfactant, or some combination of these processes.

It is important to point out that the propensity for surfactant losses through sorption, precipitation, and liquid crystal formation were not assessed prior to execution of the field test. Laboratory methods are available to asses these processes, but were not employed because of difficulties in shipping aquifer and groundwater samples off site. It is very likely that the field performance of the surfactant system could have been improved had such laboratory tests been carried out.

Report(s)/Publication(s) (Additional Information Sources):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

GWRTAC ID: FLSH0055

Project Name: Hill Air Force Base (OU 2 - Foam Flood)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

AATDF Spring 1998 Newsletter: Summary "Surfactant/Foam Process for Aquifer Remediation"

Rice University, The Center for Petroleum and Geosystems Engineering The University of Texas, and Duke Engineering & Services Company (formerly Intera), 1997: "AATDF Surfactant/Foam Process for Aquifer Remediation", Prepared for AATDF, Rice University, Houston, TX., November 1997.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following text is excerpted from the AATDF Spring 1998 Newsletter: Summary "Surfactant/Foam Process for Aquifer Remediation" and Rice University, The Center for Petroleum and Geosystems Engineering The University of Texas, and Duke Engineering & Services Company (formerly Intera), 1997: "AATDF Surfactant/Foam Process for Aquifer Remediation", Prepared for AATDF, Rice University, Houston, TX., November 1997:

The first field demonstration of the surfactant/foam process for removal of dense non-aqueous phase liquid (DNAPL) from heterogeneous alluvial aquifers was conducted during the spring of 1997 at Hill Air Force Base in Utah. The surfactant was designed to mobilize and solubilize the contaminant, which was located in the lowest part of the saturated zone of an aquifer contained in a channel eroded into thick clay deposits; the clay provided a capillary barrier to contaminant migration.

The field test of the surfactant/foam process was conducted at Hill Air Force Base, Utah, Operable Unit 2 (OU2). The shallow, unconfined aquifer at OU2 consists of interbedded sands and gravels; it forms a channel because is confined on its sides and beneath by clay deposits. A fine-grained sand is at the contact with the underlying clay unit. The clay confining unit is 13.7 m (45 ft) below ground surface (bgs); the depth to groundwater fluctuates seasonally and can range from 7.6 to 10.7 m (25 to 35 ft) bgs.

OU2 contains DNAPL contamination that has resulted from the disposal of waste solvents in two disposal trenches. The DNAPL is composed of 60 - 70% trichloroethene (TCE), 20% trichloroethane (TCA) and 10% tetrachloroethene (PCE). The DNAPL traveled downward through the unconfined aquifer and is present as residual contamination and as liquid collected in topographic lows along the base of the alluvial sand aquifer. The highest DNAPL residual saturation was detected at less than one meter above the confining clay unit, in fine-grained sands with a hydraulic conductivity from 1 to 3 x 10-2 cm/s (permeabilities of 10 to 30 darcy) . From one to one and a half meters above the clay unit, no DNAPL was detected in the coarse sands (K >10-1 cm/s). DNAPL has not been detected in the clay unit. Initial borings and a partitioning interwell tracer test (PITT) indicated that about 0.079 m3 (21 gallons) of contaminant was present initially. This amount corresponds to 668 mg/kg soil. Thus, the demonstration area was not that of a pool but of a migration path of the contaminant to known pools located nearby which were sites for testing other remediation technologies.

Subsurface heterogeneity is an important factor in the ultimate utility of surfactant-enhanced remediation. In a heterogeneous aquifer, surfactant and cosolvent solutions flow through the more conductive zones. After flushing with a surfactant or cosolvent solution in a heterogeneous aquifer, the NAPL mass remaining in the less permeable zones can still serve as a continuing source. As NAPL is removed from a high conductivity zone, the relative permeability of the high conductivity zone to the aqueous phase will increase, making the possibility of flushing the lower conductivity zone even more remote. If surfactant can be directed to more zones of a heterogeneous aquifer through mobility control, the sweep efficiency of surfactant-enhanced remediation will be improved. Less surfactant might be required to achieve the same level of NAPL removal or perhaps greater overall NAPL mass removal could be achieved.

In the surfactant/foam process, alternating pulses of surfactant and air are used to create an in situ "foam". The first pulse of surfactant flows through the more permeable zones and removes residual NAPL. When air is next pulsed, it also flows into the more permeable zone, forming a foam. The third pulse, which is of surfactant, is now directed to the finer-grained soils with residual NAPL, because the foam is blocking pores in the more permeable zone. In this manner, the sweep efficiency of the surfactant/foam process is improved over that of the typical addition of surfactant to the subsurface.

The surfactant/foam process was first optimized and tested in the lab, scaling up from a column to 2D models of increasing size and complexity. Regulation of pressure, rather than velocity, was determined to produce the optimum generation and propagation of foam in the laboratory-scale models. The surfactant system selected for the field test was MA-80, a dihexyl sulfosuccinate, at 3.5% and 10,250 ppm NaCl.

The field test area was 6.1 m long x 4 m (20.0 x 13.1 feet) wide. The site contained three injection wells, three extraction wells, and two multilevel monitoring wells. The monitor wells were located near the center of the channel, 1/3 and 2/3 of the distance from the central injection well to the central extraction well. The injectors and extractors had a 1.5 m (4.9 foot) screened interval. The multilevel wells had three screened intervals: 0.3 m (0.98 ft), 1.2 to 1.8 m (3.9 to 5.9 ft), and 3 to 4 m (9.8 to 13.1 ft) above the clay unit. There were also two hydraulic control wells, one 3 m (9.8 ft) upgradient and one 3 m (9.8 ft) downgradient of the central injector and extractor, respectively. During installation of the wells, a small depression in the aquitard surface was discovered in the center of the well pattern with significant DNAPL contamination (>12% saturation).

The removal of DNAPL from the test area was assessed by two measures, soil core analysis and partitioning tracer tests before and after the surfactant/foam flood. Fluid samples from the injection and extraction wells allowed the determination of a mass balance on the injected fluids. The multilevel wells were used to assess the propagation of the foam through the test area. Numerical simulation aided in both the design and interpretation of the field test.

At the outset of the field test, one-half pore volume of partitioning tracers, isopropanol and heptanol, was injected to estimate DNAPL mass in the test area. The tracer test was followed by a water flood (4.9 pore volumes) and a NaCl flood (1%, 1.1 pore volumes). After the injection of one-half pore volume of surfactant, air injection (for two-hour durations each) alternated at each injection well. Air was injected through the upper portion of the screened interval to create a foam in the high permeability zone, while surfactant continued to be injected through the base of the screen. Approximately three pore volumes (total) of the surfactant solution, 3.5% sodium dihexyl sulfosuccinate and 10,250 ppm NaCl, was added. The surfactant solution also contained a conservative tracer. The surfactant/foam field test concluded with a one-half pore volume flood of 0.8% NaCl followed by a water flood (8.4 pore volumes) to break the foam. The post-surfactant/foam flood tracer test (1 pore volume of isopropanol and octanol) was followed by a 6.3 pore volume water flood.

Both the soil core and partitioning tracers yielded similar estimates of initial DNAPL contamination in the test area. The core analysis estimated that 74.5 L to 107 L (20 to 28 gal) of DNAPL were present; the tracer analysis estimated 79.1 + 26.8 L (21+7 gal). A mass balance on the fluids that were injected during the field test showed that 99% of the surfactant, 110% of the NaCl, 84% of the pre-flood tracers, and 82% of the post-flood tracers were recovered. An increase in injection pressure and the production of foam from multiple levels of the monitor wells were evidence of the in situ generation of foam. The conservative tracer injected with the surfactant solution showed that there was a 50% reduction of the swept volume of the aquifer, which is another indication that foam was in place. (Subsequent waterflooding broke the foam and restored the swept volume to its initial value, as shown by the final PITT). During transport through the subsurface, the surfactant/NaCl solution underwent ion exchange with calcium present in the clays, resulting in a slightly over-optimum formulation and the production of a DNAPL-rich, high density microemulsion.

One hundred and thirty nine L (36.5 gal) of DNAPL was produced in addition to the 42 L (11 gallons) of dissolved contaminant that would have been produced in a waterflood. Since this DNAPL recovery exceeds the 79 L (21 gallon) estimate of initial volume present, even allowing for uncertainty of 27 L (7 gallons) in the latter, it is thought that additional contaminant entered the pattern from the region beyond the injection wells, a conclusion supported by data from the extraction and monitoring wells. Some DNAPL remained in the center of the pattern, as shown by the detection of DNAPL in a post-flood soil core and in the two wells in the deepest part of the channel. Soil cores showed that 6.1 L (1.6 gal) of DNAPL remained in test pattern; partitioning tracers indicated that 9.8 + 7.6 L (2.6 + 2.0 gal) DNAPL remained. The final DNAPL concentration in the pattern averaged 0.03% or 77 mg/kg. This first field test of the surfactant/foam process demonstrated that foam could be generated in situ and propagated; the surfactant/foam was also responsible for an approximately 89% reduction in DNAPL in the test area.

Report(s)/Publication(s) (Additional Information Sources):

AATDF Spring 1998 Newsletter: Summary "Surfactant/Foam Process for Aquifer Remediation"

Hirasaki, G.J., Miller, C.A., Szafranski, R., Lawson, J.B., and Akiya, N. 1996. "Surfactant/Foam Process for Aquifer Remediation," SPE paper no. 37257. To be presented at the SPE International Symposium on Oil Field Chemistry, Houston, Texas, February 18-21, 1997.

Oolman, T., Godard, S.T., Pope, G.A., Jin, M., and Kirchner, K. 1995. "DNAPL Flow Behavior in a Contaminated Aquifer: Evaluation of Field Data," Journal of Ground Water Monitoring & Remediation, Vol. 15, No. 4.

Rice University, The Center for Petroleum and Geosystems Engineering The University of Texas, and Duke Engineering & Services Company (formerly Intera), 1997: "AATDF Surfactant/Foam Process for Aquifer Remediation", Prepared for AATDF, Rice University, Houston, TX., November 1997.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0056

Project Name: Hill Air Force Base (Cell 4, OU 1 - Cyclodextrin Solubilization)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following text was excerpted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997 and Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996: Surfactants / Cosolvents,Technology Evaluation Report TE-96-002, Chad T. Jafvert, Purdue University, for GWRTAC, Pittsburgh, PA, December 1996, available at www.gwrtac.org:

Hill AFB Operational Unit 1 (OU1) consists of two fire training areas, two chemical disposal pits, and two landfills. The primary contaminant is LNAPL (light lubricating oils, jet fuel). At OU1, the design of each test is process dependent, however, each test cell (of nine test constructed test cells) that will undergo some type of flushing is basically the same. Each cell is constructed of sheet piling driven into a clay layer approximately 30 feet below the surface, each occupying a rectangular surface area of 3 m x 5 m. The sheet piling has inter-locking grout-sealed joints to hydraulically isolate the cell from its surroundings. This type of containment is sometimes referred to as a Waterloo Barrier system. The poorly sorted sand and gravel aquifer is approximately 15 to 20 ft below the surface to the clay aquitard. Four injection and three extraction wells are located on the opposite 3 m sides of each cell. Well screens are variable from the clay layer to above the water table. In the interior are 12 evenly spaced sampling wells, each with nested ports at 5 vertical depths. The saturated zone pore volume (PV) within each cell is variable from 1,000 to 2,500 gallons per cell. The hydraulic conductivity of the saturated potion of the upper sand and gravel unit at OU1 is 10-1 to 10-2 cm/sec based on aquifer test data, and 10-2 to 10-5 cm/sec based on slug test data. For all of the flushing experiments (those with surfactants, cosolvents, and cyclodexdrin), the flushing rate will be approximately one pore volume per day. Prior to and after treatment of each cell, a partitioning tracer test has or will be performed. The mix of tracers will be designed according to the expected volume of NAPL within the cell before and after treatment. Among the tracers, hexanol and dimethylpentanol may be included.

For the test at Cell 6, OU 1, a field trial was conducted using a complexing sugar solution, beginning in summer 1996. Ten pore volumes of a 10 wt% Hydroxypropyl-B-Cyclodextrin (HPCD) solution were cycled through a 5 m by 3 m test cell. The mass removal mechanism envisioned is entrapment and transport of dissolved NAPL consituents within the HPCD molecule. This mechanism would provide enhanced NAPL solubility. As of February 1997, analysis of the data collected was underway. Formal documentation of results is anticipated in 1997.

Report(s)/Publication(s) (Additional Information Sources):

Montgomery Watson. 1995. "Final Interim Report: Evaluation of Bench Test Results for the Surfactant Flushing Treatability Study at Operable Unit 1, Hill Air Force Base, Utah." USAF Contract No. 2208.0804.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

GWRTAC ID: FLSH0057

Project Name: Hill Air Force Base (OU2 1/5 Full Scale Surfactant Flood)

City: Layton **State/Province:** UT

Primary GWRTAC Personal Communication Source (Name/Organization): Jon Ginn
U.S. Air Force

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text is from notes recorded from a July 1998 conversation with a U.S. Air Force representative and quoted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997, which cited Hirasaki, et al., 1996:

"Operable Unit #2 is a closed chemical disposal area. Materials present in subsurface sediments include both chlorinated and nonchlorinated solvents and degreasers. This mixture of compounds forms a DNAPL that has accumulated above a low-permeability lacustrian clay. Sediments in the DNAPL target zone consist of poorly sorted fluvial deposits."

OU2 will be remediated in increments. In this project, funding to remediate 1/5 of OU2 has been received. A full-scale (1/5 full scale) surfactant flood will be performed, likely beginning in the fall of 1999, to effect this remediation. This source area remediation will be larger than any other demonstration performed at Hill AFB to date.

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0058

Project Name: Hialeah County, FL

City: **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was quoted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

"In 1988, a combination of alkali and polymer was used to recover hydraulic oil present in limestone beneath a commercial facility in Hialeah County, Florida (Pouska, et al., 1989). The hydraulic oil had a density of 0.915 g/crn3 and a viscosity of 130 centipoise. An estimated 35,000 gallons of hydraulic oil was present beneath an area of 40,000 ft2. Free product thickness in wells was observed at thicknesses ranging from 0.01 to 1.5 ft. Average depth to the contamination was 7 ft. Average oil saturation in the free oil layer was 65 percent of the pore space, while oil saturation in areas having only adsorbed oil averaged 35 percent or less. Injection of water left a residual oil saturation of 20 percent, which resulted in an evaluation of enhanced recovery methods.

The site geology is complex, consisting of a solution cavity limestone that exhibits a number of depression features. These depression features are in-filled with a clay and organic-rich sand. The limestone mounds were determined to be the main conduits of oil because the hydraulic conductivity of the limestone (1,000 ft/day) was 1 to 2 orders of magnitude greater than the clay and organic-rich sand.

A laboratory program was performed to define the optimum chemical system to remove residual oil. A mobilization mechanism was selected. Interfacial tensions were lowered to ultra low values with either alkali or alkali plus surfactant addition to injection water. In situ components in the oil reacted with the alkali to develop surfactants which lowered the interfacial tension. The solution selected for injection was 0.5 wt% Na2 CO3 plus 1.1 wt% NaHCO3, plus 0.5 wt% Na2 O(Si02)3.22, plus 0.01 wt% Chloramine T plus 1000 mg/L xanthan gum. Xanthan gum polymer was added to the injected solution to improve contact and displacement efficiencies. Because of the high hydraulic oil viscosity, the mobility ratio for water displacing hydraulic oil was adverse indicating a need for polymer.

The pilot was confined in a 10-foot by 10-foot area. A 10-foot slotted lateral delivery drainline bisected the pilot area at a depth of 4 feet. The drainline was placed 5 feet from four vertical production wells, which were situated at the four corners of the pilot area. Vertical production wells were drilled to a depth of 11 feet with slotted PVC in the bottom 3 feet. 125,000 gallons of water were initially injected, which recovered 62 gallons of oil or 20 percent of the original oil saturation. After water injection, two chemical slugs were injected. The first slug was 1,300 gallons of 15 centipoise chemical solution followed by a second slug of 2,000 gallons of 46 centipoise solution followed by 2,000 gallons of polymer solution to displace the previously injected chemical solution from the pilot area. 142 gallons of hydraulic oil, or 45 percent of the original oil saturation, were recovered by chemical injection for a total of 204 gallons of oil, or 65 percent of the original oil saturation. The pilot pore space was 500 gallons.

A water-in-oil emulsion was produced by alkali-polymer injection which was removed to an offsite treatment facility. Waterflood oil was separated from the produced stream using an oil/water separator with the water discharged to the sanitary sewer after passing through a filter and an activated carbon column to remove trace oil.

The pilot was not expanded to the entire 40,000 ft3 area for a variety of reasons. A management change, a cost and benefit analysis to remove a nonhazardous oil, and the location of the contaminate under a functioning structure made expansion difficult."

Report(s)/Publication(s) (Additional Information Sources):

Pouska, G.A., Trost, P.B., and Day, M. 1989. "APS Remediation of a Shallow Aquifer Containing Viscous Oil." In Proceedings of the 6th National Conference on Hazardous Wastes and Hazardous Materials, New Orleans, Louisiana, pp. 423-430.

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0059

Project Name: Fredricksburg, VA Wood Treating Site

City: Fredricksburg **State/Province:** VA

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

Project Summary:

The following was quoted from Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997:

"In 1990, a combination of an alkaline agent, surfactant, and polymer were used to recover creosote-based wood-treating oils from soils at a wood-treating site in Fredricksburg, Virginia. Soils of concern consisted of a clay-silt alluvium. Characteristics of the oil included a density of 1.03 g/cm3and a viscosity of 50 centipoise.

The site geology was complex, with clay lenses on which creosote based oil was perched. Hydraulic conductivity was low and varied as the soil composition changed. Soil composition resulted in varying oil saturations that changed with time as perched creosote moved off of clay lenses.

A laboratory program was undertaken to define the optimum chemical system to remove the oil. A mobilization mechanism was selected. Interfacial tensions were lowered to ultra low values with a combination of alkali and surfactant. The solution selected for injection was 0.5 wt% Na2 CO3 plus 0.1 wt% Makon-10 (nonyl phenol with 10 moles ethylene oxide) and 1,500 mg/L xanthan gum. Polymer was added to the injected solution to improve contact and displacement efficiencies. Mobility ratio for water displacing creosote was adverse indicating need for polymer.

Existing wells were used for the field demonstration. A single vertical injection well and a single vertical production well were used. Spacing between the wells was 6 feet. Injection of the chemical solution was the limiting factor. Injection of the chemical solution was attempted for approximately 1 month with minimal success.

Oil recovery as a result of the alkaline-surfactant-polymer solution was low for two reasons. Low chemical solution injectivity reduced the planned injection volumes to less effective amounts and the creosote saturation in the area selected was low as a result of perched material moving off clay lenses. The pilot project was not expanded.

The failure of the application points out the critical need for accurate and reliable site assessment and matching each site to appropriate technologies. The inability to inject fluid at the Fredricksburg, Virginia site was the primary limiting factor. Accurate site evaluation would have saved time, money, and frustration."

Report(s)/Publication(s) (Additional Information Sources):

Rice University, 1997: Technology Practices Manual for Surfactants and Cosolvents, Rice University, 6100 Main Street, Houston, TX 77005-1892, February 1997

GWRTAC ID: FLSH0060

Project Name: National Water Res Inst, Env Canada - Humic Acid Flushing

City: Burlington **State/Province:** ON

Primary GWRTAC Personal Communication Source (Name/Organization): None None

Report(s)/Publication(s) (GWRTAC Source):

Lesage, et al., "Use of Humic Acids to Enhance the Removal of Aromatic Hydrocarbons from Contaminated Aquifers Part II: Pilot Scale"

Project Summary:

The following was excerpted from Lesage, et al., "Use of Humic Acides to Enhance the Removal of Aromatic Hydrocarbons from Contaminated Aquifers Part II: Pilot Scale":

In this project, the aqueous solubility enhancement of aromatic hydrocarbons by humic acids was studied in laboratory columns (Xu et al, 1994) and in a large scale model aquifer (Lesage, et al.,). A petroleum source was placed into a constructed model aquifer with a very dense monitoring network. A humic acid (obtained as the sodium salt and prepared in solution) was used to flush the model aquifer. The purpose of the study was to determine whether humic acids could be used cost-effectively to enhance dissolution and transport of aromatic hydrocarbons and provide an environmentally suitable alternative to artificial surfactants.

The model aquifer tank was constructed of 1/4" industrial grade stainless steel (rectangular 2m x 6m x 2m deep) with an external support structure made of steel beams. To induce water flow, a head tank separated from the aquifer material by a porous plate was used. The plate was constructed of 1/4" stainless steel, but perforated with 1" holes so as not to impede water flow. The sand aquifer material was retained by a polyester geotextile. To provide experimental control, the aquifer model was divided in half longitudinally using a series of stainless steel plates that were sealed and bolted together. The monitoring well network consisted of 72 bundles of 1/8" stainless steel tubes. Each bundle consisted of five sampling tubes terminating at 30 cm depth intervals. The bundles were spaced at 30 cm and 25 cm centres, parallel and perpendicular to the flow direction, respectively. Two withdrawal wells were installed, one on each side of the tank (5 cm ID, 10 cm OD). A medium to coarse-grained sand (particle size range 75 um to 2.4 mm); hydraulic conductivity of 0.04 m/s) was used for the aquifer medium. Care was taken to prevent air entrapment and to remove residual chlorinated compounds during dry sand emplacement and subsequent tap water saturation, and the sand allowed to settle for a few weeks prior to conducting tracer experiments.

A conservative tracer test was used to determine optimal placement of the petroleum source. The source was placed at a depth of 1.2 m, approximately 0.5 m downgradient from the head tank. Five additional monitoring well bundles were added along the center-line. The residual capacity of the sand was determined using a column experiment and it was found that approximately 500 mL of diesel fuel could be retained by 20 kg of sand. To emplace the source, 500 mL of diesel was added and mixed to 25 Kg of sand. A wooden form was used to maintain the space where the source was emplaced, and removed by overhead pulley after the source was emplaced. Humic acid, obtained as sodium salt and prepared as a solution using tap water at a concentration of 1 g/lL pH 8.5) was added to the head tank to provide a well-defined concentration gradient.

An average three-fold increase in PAHs was observed when humic acid was added. A ten-fold increase in solubilization was observed for trimethyl naphthalene. This was consistent with earlier column studies and is generally the case with surfactants, where the least soluble compounds benefit the most of the addition of a solubilization agent. In this large model, because the emplaced diesel source was designed not to exceed the holding capacity of the sand, dissolution only was observed. Unlike what is generally observed with surfactants, the increase in solubility occurred below the critical micelle concentration for humic acids (7.4 g/L for Aldrich humic acid). Most of the humic acid was recuperated at the withdrawal wells and this allowed recirculation of the treatment in a closed loop system, resulting in significant cost savings. The effluent was collected in a reservoir which was assayed for humic acid concentration and replenished as necessary by the addition of a concentrate through a recirculating pump. Based on the evolution of the PAH plume, it was evident that despite the dissolution enhancement by the humic acids, rapid cleanup will not occur using dissolution alone. Plans for a next step will be to study the potential of bioremediation under these conditions.

Report(s)/Publication(s) (Additional Information Sources):

Lesage, et al., "Use of Humic Acids to Enhance the Removal of Aromatic Hydrocarbons from Contaminated Aquifers Part II: Pilot Scale"

Xu, H., S. Lesage and L. Durham, 1994. "The Use of Humic Acids to Enhance Removal of Aromatic Hydrocarbons from Contaminated Aquifers. Part I. Laboratory Studies". Fourth Annual Symposium on Groundwater and Soil Remediation, Calgary, Alberta, Sept. 21-23. Pgs. 635-666.

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0061

Project Name: Dover AFB, Dover, DE (Test Cell 2, Surfactant Solubilization)

City: Dover **State/Province:** DE

Primary GWRTAC Personal Communication Source (Name/Organization): Tim McHale
Mantech Environmental

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes taken during May 1997 and July 1998 conversations with personnel stationed at Air Force Laboratory, Dover Air Force Base, Delaware, and additional information provided to GWRTAC.

A series of demonstrations will be conducted at the Groundwater Remdiation Field Laboratory (GRFL) site at Dover Air Force Base, Delaware. The GRFL site was established in 1996 to test and evaluate innovative remediation technologies geared towards the cleanup or containment of soil and groundwater contamination, specifically from chlorinated solvents. The GRFL site is funded by the Strategic Environmental Research and Development Program (SERDP) established to develop innovative technologies for the cleanup of soil and groundwater contamination. SERDP was developed as a partnership between the EPA, DoD, and the DOE to support these environmental efforts.

Two in-ground 3 meter by 5 meter test cells with sheet metal framing have been constructed. The test cells are keyed into a clay unit present at 40 feet below the ground surface. A secondary containment cell is also present. (Three test cells had been constructed; test cells 2 and 3 will be used for the enhanced source removal (ESR) project demonstrations.

Six different pilot tests will be conducted at Dover AFB, beginning in August 1998; five of the six tests will be in situ flushing demonstrations, with the sixth being an air sparging/SVE demonstration. Each test will be run for approximately seven months, including phases for tracer studies, demonstration, and post-tracer studies for delineation of residual contamination. A total of 12 injection/extraction wells were to be installed in an array.

Each in situ flushing technology tested will consist of flushing the test cell with a remedial fluid to remove PCE. Researchers know only that the permit allowed for the release of up to 100 liters, or 26 gallons, of PCE, thus simulating a 1/2 barrel spill. Recovered PCE/remedial fluids will be extracted from the test cell and treated at the surface or at an off-site facility. After each demonstration, the test cell will be flushed again with clean water to remove any remaining remedial fluids.

The second in situ flushing project will be conducted in test cell 2 at Dover AFB. University of Oklahoma researchers will identify the volume of PCE released into the test cell. They will then use surfactants for remedial in situ flushing testing surfactant solubilization as the removal mechanism.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0062

Project Name: Dover AFB, Dover, DE (Cosolvent Mobilization)

City: Dover **State/Province:** DE

Primary GWRTAC Personal Communication Source (Name/Organization): Tim McHale
Mantech Environmental

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes taken during May 1997 and July 1998 conversations with personnel stationed at Air Force Laboratory, Dover Air Force Base, Delaware, and additional information provided to GWRTAC.

A series of demonstrations will be conducted at the Groundwater Remdiation Field Laboratory (GRFL) site at Dover Air Force Base, Delaware. The GRFL site was established in 1996 to test and evaluate innovative remediation technologies geared towards the cleanup or containment of soil and groundwater contamination, specifically from chlorinated solvents. The GRFL site is funded by the Strategic Environmental Research and Development Program (SERDP) established to develop innovative technologies for the cleanup of soil and groundwater contamination. SERDP was developed as a partnership between the EPA, DoD, and the DOE to support these environmental efforts.

Two in-ground 3 meter by 5 meter test cells with sheet metal framing have been constructed. The test cells are keyed into a clay unit present at 40 feet below the ground surface. A secondary containment cell is also present. (Three test cells had been constructed; test cells 2 and 3 will be used for the enhanced source removal (ESR) project demonstrations.

Six different pilot tests will be conducted at Dover AFB, beginning in August 1998; five of the six tests will be in situ flushing demonstrations, with the sixth being an air sparging/SVE demonstration. Each test will be run for approximately seven months, including phases for tracer studies, demonstration, and post-tracer studies for delineation of residual contamination. A total of 12 injection/extraction wells were to be installed in an array.

Each in situ flushing technology tested will consist of flushing the test cell with a remedial fluid to remove PCE. Researchers know only that the permit allowed for the release of up to 100 liters, or 26 gallons, of PCE, thus simulating a 1/2 barrel spill. Recovered PCE/remedial fluids will be extracted from the test cell and treated at the surface or at an off-site facility. After each demonstration, the test cell will be flushed again with clean water to remove any remaining remedial fluids.

The third in situ flushing project will be conducted by Clemson University researchers who will first identify the volume of PCE released into the test cell. They will then use tert-butyl alcohol for remedial in situ flushing testing cosolvent mobilization as the removal mechanism.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0063

Project Name: Dover AFB, Dover, DE (Macromolecular Solubilization)

City: Dover **State/Province:** DE

Primary GWRTAC Personal Communication Source (Name/Organization): Tim McHale
Mantech Environmental

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes taken during May 1997 and July 1998 conversations with personnel stationed at Air Force Laboratory, Dover Air Force Base, Delaware, and additional information provided to GWRTAC.

A series of demonstrations will be conducted at the Groundwater Remdiation Field Laboratory (GRFL) site at Dover Air Force Base, Delaware. The GRFL site was established in 1996 to test and evaluate innovative remediation technologies geared towards the cleanup or containment of soil and groundwater contamination, specifically from chlorinated solvents. The GRFL site is funded by the Strategic Environmental Research and Development Program (SERDP) established to develop innovative technologies for the cleanup of soil and groundwater contamination. SERDP was developed as a partnership between the EPA, DoD, and the DOE to support these environmental efforts.

Two in-ground 3 meter by 5 meter test cells with sheet metal framing have been constructed. The test cells are keyed into a clay unit present at 40 feet below the ground surface. A secondary containment cell is also present. (Three test cells had been constructed; test cells 2 and 3 will be used for the enhanced source removal (ESR) project demonstrations.

Six different pilot tests will be conducted at Dover AFB, beginning in August 1998; five of the six tests will be in situ flushing demonstrations, with the sixth being an air sparging/SVE demonstration. Each test will be run for approximately seven months, including phases for tracer studies, demonstration, and post-tracer studies for delineation of residual contamination. A total of 12 injection/extraction wells were to be installed in an array.

Each in situ flushing technology tested will consist of flushing the test cell with a remedial fluid to remove PCE. Researchers know only that the permit allowed for the release of up to 100 liters, or 26 gallons, of PCE, thus simulating a 1/2 barrel spill. Recovered PCE/remedial fluids will be extracted from the test cell and treated at the surface or at an off-site facility. After each demonstration, the test cell will be flushed again with clean water to remove any remaining remedial fluids.

The fourth in situ flushing project will be conducted by University of Arizona researchers who will first identify the volume of PCE released into the test cell. They will then use a complexing sugar for remedial in situ flushing testing macromolecular solubilization as the removal mechanism.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

GWRTAC ID: FLSH0064

Project Name: Dover AFB, Dover, DE (Single-phase Microemulsion)

City: Dover **State/Province:** DE

Primary GWRTAC Personal Communication Source (Name/Organization): Tim McHale
Mantech Environmental

Report(s)/Publication(s) (GWRTAC Source):

Internet URL http://www.epa.gov/superfund/index.htm

Project Summary:

The following text is from notes taken during May 1997 and July 1998 conversations with personnel stationed at Air Force Laboratory, Dover Air Force Base, Delaware, and additional information provided to GWRTAC.

A series of demonstrations will be conducted at the Groundwater Remdiation Field Laboratory (GRFL) site at Dover Air Force Base, Delaware. The GRFL site was established in 1996 to test and evaluate innovative remediation technologies geared towards the cleanup or containment of soil and groundwater contamination, specifically from chlorinated solvents. The GRFL site is funded by the Strategic Environmental Research and Development Program (SERDP) established to develop innovative technologies for the cleanup of soil and groundwater contamination. SERDP was developed as a partnership between the EPA, DoD, and the DOE to support these environmental efforts.

Two in-ground 3 meter by 5 meter test cells with sheet metal framing have been constructed. The test cells are keyed into a clay unit present at 40 feet below the ground surface. A secondary containment cell is also present. (Three test cells had been constructed; test cells 2 and 3 will be used for the enhanced source removal (ESR) project demonstrations.

Six different pilot tests will be conducted at Dover AFB, beginning in August 1998; five of the six tests will be in situ flushing demonstrations, with the sixth being an air sparging/SVE demonstration. Each test will be run for approximately seven months, including phases for tracer studies, demonstration, and post-tracer studies for delineation of residual contamination. A total of 12 injection/extraction wells were to be installed in an array.

Each in situ flushing technology tested will consist of flushing the test cell with a remedial fluid to remove PCE. Researchers know only that the permit allowed for the release of up to 100 liters, or 26 gallons, of PCE, thus simulating a 1/2 barrel spill. Recovered PCE/remedial fluids will be extracted from the test cell and treated at the surface or at an off-site facility. After each demonstration, the test cell will be flushed again with clean water to remove any remaining remedial fluids.

The fifth in situ flushing project will be conducted by University of Florida researchers who will first identify the volume of PCE released into the test cell. They will then use a cosolvent and a surfactant for remedial in situ flushing, to test the single-phase microemulsion as a removal mechanism.

Report(s)/Publication(s) (Additional Information Sources):

Internet URL http://www.epa.gov/superfund/index.htm

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0065

Project Name: Pearl Harbor

City: Pearl Harbor **State/Province:** HI

Primary GWRTAC Personal Communication Source (Name/Organization): John Londergan
Duke Engineering & Services

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text was provided in a project summary on September 8, 1998 by Duke Engineering & Services of Austin, TX:

Pearl Harbor Naval station is contaminated with petroleum hydrocarbons that are present in the subsurface as light non-aqueous phase liquids (LNAPL). In particular, petroleum hydrocarbons are seeping into Pearl Harbor at Quarry Loch. To address this problem, the Navy has funded a project intended to demonstrate the effectiveness of various remediation technologies. A demonstration area adjacent to Quarry Loch has been dedicated for this project. The LNAPL contaminant at the site is mainly Navy Special Fuel Oil (NFSO), a highly viscous fuel oil. Duke Engineering and Services (DE&S) will demonstrate the use of Surfactant Enhanced Aquifer Remediation (SEAR) to remove the LNAPL contamination.

In early December, 1997 DE&S began a hydrogeologic characterization of the Quarry Loch vicinity in search of a suitable area for the demonstration. The characterization concluded in January, 1998 with the installation of the demonstration well array and aquifer testing. Information obtained during this investigation was used to build a geosystem model. The numerical code used for the model is UTCHEM, a multi-phase, multi-dimensional chemical compositional simulator developed at the University of Texas at Austin.

A major challenge of this project has been to develop a surfactant that is capable of effectively solubilizing the NSFO. The NSFO in the demonstration area is highly viscous (2,000 to 3,000 cp) and is not readily solubilized by commercially available surfactants. Laboratory work conducted on solubilizing the recalcitrant NAPL at Pearl Harbor eventually led to the development of a new surfactant and includes the additional requirement that the subsurface be heated to approximately 50°C to achieve satisfactory remediation performance.

To accurately assess the efficiency of the SEAR demonstration, two partitioning interwell tracer tests (PITTs) will be conducted at the SEAR site. The first PITT will be performed to accurately measure the volume of NAPL present in the test zone before the surfactant flood. The SEAR will be immediately followed by a second PITT to measure the volume of DNAPL remaining in the test zone. PITT 1 and PITT 2 will be compared to evaluate the effectiveness (i.e. performance assessment) of the surfactant flood to remove DNAPL from the test zone. Laboratory studies have been completed to select a suite of conservative (non-partitioning) and partitioning tracers for the

PITTs.

The present test configuration is composed of an injection well, a hydraulic-control backstop well, and three extraction wells. A conservative interwell tracer test (CITT) will be conducted first to: (1) demonstrate hydraulic control of the injectate, (2) determine the actual swept pore volume of the test zone, and (3) provide empirical data to fine tune the final design of PITT/SEAR/PITT demonstration. Following the CITT, the subsurface will be heated to approximately 50°C through the injection of heated potable water. Once the subsurface in the demonstration area is at the proper temperature, the PITT/SEAR/PITT sequence will be conducted. Current design calls for the injection of approximately 3,200 gallons of surfactant solution, corresponding to a five to six pore volume surfactant flood over a five day period. The introduction of surfactant will be followed by approximately three days of water flooding to remove the remaining surfactant and solubilized NAPL from the subsurface before the final PITT. The field work is scheduled to begin in early December 1998.

Report(s)/Publication(s) (Additional Information Sources):

None

GWRTAC ID: FLSH0066

Project Name: Aluminum Company Site

City: **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): Charles Boulanger
GSI Environnement

Report(s)/Publication(s) (GWRTAC Source):

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Project Summary:

The following text was excerpted from marketing information provided by GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4 in August 1998:

The site was contaminated with transformer oil and PCBs. Initial concentrations were 60,000 ppm MOG and 20 ppm PCB. The 1,000 m3 (approx. 1,300 yd3) contaminated zone extended from 0,0 to 1.5 m (0.0 to 4.9 ft) below ground surface (bgs), and was comprised of heterogeneous silty backfill material. After performance of a risk assessment, treatability studies were conducted in the laboratory, and ultimately, surfactants were developed which would provide highly efficient treatment of the source material. To lower concentrations to a non-toxic level for biodegradation to take place, Injecsol TM enhanced in situ soil flushing was applied to the contaminated matrix, and the site remediation was completed with in situ bioremediaiton. The Injecsol TM technology was used for enhanced flushing, nutrient injection and free phase recovery. All work was done without interruption to plant activities or dismantling of existing infrastructures. The contaminant levels were lowered to 5,000 ppm (MOG) and 10 ppm (PCB). The project was performed over a one year duration, at a cost of +/- $300,000. (Canadian).

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0067

Project Name: Petroleum Company (Bulk Plant)

City: **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): Charles Boulanger
GSI Environnement

Report(s)/Publication(s) (GWRTAC Source):

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Project Summary:

The following text was excerpted from marketing information provided by GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4 in August 1998:

The contaminants at the site consisted of gasoline (BTEX) and diesel (MOG) at 15,000 ppm. The 9,000 m3 (approx. 11,800 yd3) contaminated zone extended from 2 to 6 m (6.6 to 19.7) below the ground surface, and was comprised of sand with boulders. This former bulk petroleum plant is located less than 300 feet from the St. Lawrence River, and the water table is tidally influenced. The containment of the surfactant and contaminants was thus a concern during project implementaiton. The Injecsol TM hydrodynamic process creates hydraulic barriers that keep all contaminants and surfactants in the contaminated area. After a treatability study, specific surfactant solutions were developed for a highly efficient treatment. Injecsol TM enhanced in situ flushing was used to reduce the concentration of Mineral Oil and Grease of the contaminated matrix. BTEX were extracted by pumping groundwater and air simultaneously. The mobile water treatment unit, consisting of coalescent separators, dissolved air flotation units, sand filters, and activated carbon filters separated the water from the surfactants and contaminants at a rate of 400 liters per minute (approx. 106 gpm) and enabled the expeditious results. All work was performed taking tidal fluctuations into consideration and leaving existing railroad tracks in place. Contaminants were remediated to levels as low as 1017 ppm MOG, 0.67 ppm (benzene), 0.99 ppm (toluene) and 2.53 ppm (xylene). The project duration was 4 months, and the project cost was +/- $300,000. (Canadian).

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries

GWRTAC Case Study Database

GWRTAC ID: FLSH0068

Project Name: Petroleum Company (Residential Site Contamination)

City: **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): Charles Boulanger
GSI Environnement

Report(s)/Publication(s) (GWRTAC Source):

GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4, Marketing Information

Project Summary:

The following text was excerpted from marketing information provided by GSI Environnement (formerly Ecosite, Inc.), 965 Newton Ave., Office 270, Québec City, Qc. Canada G1P 4M4 in August 1998:

A residential property including several houses and utilities was located next to a former petroleum plant, and contaminated beneath houses with gasoling (BTEX) and diesel (MOG). Contaminants were present at concentrations of 10,500 ppm (MOG), 50 ppm (benzene), and 45 ppm (toluene). The 1,000 m3 (approx. 1,300 yd3) contaminated zone extended from 1,0 to 2.6 m (3.3 to 8.5 ft) below ground surface (bgs), and was comprised of organic soil (peat moss). Due to high levels of soil contamination remaining at the adjacent plant, hydraulic barriers to stop the migration of the contaminants to the residential area were provided. Installation of a vertical cutoff wall, using synthetic liners and leachate drainage network, was also necessary to recover free phase present. Several technologies were combined to lower caontamination to residential levels. While proceeding with vacuum extraction and biosparging, Injecsol TM as used to recover the free phase and for in situ flushing of the contaminated soil beneath the houses. A surfactant was developed from a laboratory treatability study to allow highly efficient treatment. Work was completed leaving all existing infrastructures in place and ensuring long term safety for the residents. Contamination was lowered to concentrations of 1,000 ppm (MOG) over a 12 month project duration, at a cost of +/- $300,000. (Canadian).

Report(s)/Publication(s) (Additional Information Sources):

None

GWRTAC ID: FLSH0069

Project Name: SEAR for LNAPL Mitigation in Capillary Fringe

City: **State/Province:**

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 4.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 4:

A surfactant enhanced aquifer remediation (SEAR) pilot study was conducted to evaluate in situ surfactant flushing as a viable option for source area remediation of light non-aqueous phase liquids (LNAPL) on ground water or residual LNAPL entrained within the capillary fringe region/below the water table. The study indicates that surfactant use can significantly enhance recovery of LNAPL and residual hydrocarbons entrained within the smear zone and capillary fringe.

Report(s)/Publication(s) (Additional Information Sources):

Winkley, William B.; James M. Figueira; Joseph C. Jordan, 1998: "Surfactant-Enhanced Aquifer Remediation Technology for LNAPL Mitigation" in Environmental Technology (Atlanta, Georgia), Vol. 8 No. 4, pp 46-48, Jul-Aug 1998

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0070

Project Name: National Tsing Hua University - Effects of Surfactants of Sorpt

City: Hsinchu **State/Province:** TAIWAN

Primary GWRTAC Personal Communication Source (Name/Organization): None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 11, U.S. EPA Technology Innovation Office Technology Information Summary Report, Sept. 1-15, 1998, page 10.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Aug. 1-15, 1998, page 11, and U.S. EPA Technology Innovation Office Technology Information Summary Report, Sept. 1-15, 1998, page 10.

To examine the feasibility of in situ remediation of monocyclic aromatic compounds, a study was conducted on the effect of anionic and nonionic surfactants on the sorption and micellar solubilization of benzene, chlorobenzene, and styrene (BCS) in soil-free and soil-water systems. Sodium dodecyl sulfate (SDS) represented the anionic surfactant and Triton X-100 the nonionic surfactant. Triton X-100 had a more significant effect on the determination of maximum adsorption capacity than did SDS, and a correlation between the maximum sorption capacity and partition coefficient was established. The results of the study suggest that a surfactant of suitable type and concentration can enhance sorption and solubilization and represents a feasible option for supporting bioremediation of soil contaminated with monocyclic aromatic compounds.

Triton X-100, sodium dodecyl sulfate (SDS), and ceyltrimethylammonium bromide (CTAB) were three surfactants tested in batch experiments to determine the optimal surfactant system for the remediation of cadmium-contaminated soil. At equilibrium, the desorbed concentrations of Cd were respectively 1.87 and 3.27 mg/kd in the Triton X-100 and SDS-amended systems. The use of CTAB hindered Cd desorption. The addition of EDTA enhanced Cd desorption from the contaminated soil, although the addition of diphenylthiocarbazone as a complexing agent lowered the extraction efficiency.

Report(s)/Publication(s) (Additional Information Sources):

Doong, Ruey A. and Wen G. Lei, Department of Nuclear Science, National Tsing Hua University, Hsinchu, Taiwan, R.O.C., 1997: "Sorption and Micellar Solubilization of Monocyclic Aromatic Compounds in the Presence of Nonionic and Anionic Surfactants", in J. Chin. Inst. Environ. Eng., Vol. 7, No. 3, pp. 219-227, 1997.

Doong, Ruey-an, Ya-Wen Wu, Wen-gang Lei, 1998: "Surfactant Enhanced Remediation of Cadmium Contaminated Soils", Water Science and Technology, Vol. 37, No. 8, pg. 65-67, 1998

GWRTAC ID: FLSH0071

Project Name: Louisiana State University - Colloidal Gas Aphron from Natura

City: Baton Rouge **State/Province:** LA

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 5.

Project Summary:

The following was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 5:

The dry fruits of Sapindus mukorossi plants in India were used to prepare natural surfactant solutions from which colloidal gas aphron suspensions were generated to assess their effectiveness in flushing columns containing hydrophobic organic compound-contaminated soils. The natural surfactant desorbed up to 90% of the total hexachlorobenzene from soil contaminated with low hexachlorobenzene concentrations. However, conventional surfactant solutions performed better than the colloidal gas aphron.

Report(s)/Publication(s) (Additional Information Sources):

Kommalapati, Raghava R.; Kalliat T. Valsaraj; W. D. Constant; Dipak Roy, "Soil Flushing Using Colloidal Gas Aphron Suspensions Generated from a Plant-Based Surfactant", in Journal of Hazardous Materials, Vol. 60, No. 1, p7 3(15) , May 1998.

GWRTAC ID: FLSH0072

Project Name: Envirogen - Surfactant Foam/Bioaugmentation

City: Lawrenceville **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 9.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 9:

A bench-scale study to evaluate remediation of TCE in situ used surfactant foam (CS-330) combined with a bioaugmentation technology (TCE-degrading bacterial strain ENV 435). Injecting the foam in a pulsed operation flushed 75% of the contaminant through the sand columns, and adding the microbes resulted in 95-99% degradation of residual TCE.

Report(s)/Publication(s) (Additional Information Sources):

Rothmel, R. K.; R. W. Peters; E. S. Martin; M. F. Deflaun, 1998: "Surfactant Foam/Bioaugmentation Technology for In Situ Treatment of TCE-DNAPLs", in Environmental Science and Technology, Vol. 32, No. 11, pp 1667-1675, June 1, 1998.

GWRTAC ID: FLSH0073

Project Name: Envirogen - Effects of Emulsion Viscosity

City: Lawrenceville **State/Province:** NJ

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 10.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Jul. 16-31, 1998, page 10:

The authors investigated the effects of in situ emulsification on the remediation process in laboratory column studies. Viscosities of emulsion solutions prepared with a 1% alcohol ethoxylate surfactant solution (Witconol registered SN90) and various concentrations of m-xylene were measured and compared with effluent collected during column-flushing experiments. Viscosity increased as m-xylene concentration in the emulsion solution increased, resulting in a decrease in relative permeability within the soil column, demanding an increase in the hydraulic gradient to maintain a constant flow rate. Even a relatively small viscosity increase could noticeably affect the mobilization process.

Report(s)/Publication(s) (Additional Information Sources):

Crawford, S C.; C J. Bruell; D K. Ryan; J W. Duggan, 1997: "", in Journal of Soil Contamination, Vol. 6, No. 4, pp. 355-370, 1997.

GWRTAC ID: FLSH0074

Project Name: SW Tank Farm, Tinker Air Force Base, OK

City: Midwest City **State/Province:** OK

Primary GWRTAC Personal Communication Source (Name/Organization): Mark Hasegawa
Surbec Environmental Services

Report(s)/Publication(s) (GWRTAC Source):

Draft report from Surbec Environmental Services, Norman, OK, phone (405) 364-9726.

Project Summary:

The following text was excerpted from October 1998 marketing information and a draft report from Surbec Environmental Services, Norman, OK, provided in November 1998:

A surfactant flushing demonstration was conducted at the Southwest Tank Farms located at Tinker AFB, Midwest City,Oklahoma. Two injection wells were utilized for surfactant injection and three recovery wells were utilized for groundwater recovery. Recovered groundwater was air stripped to remove contaminant and then subjected to Micellar Enhanced Ultrafiltration (MEUF) for surfactant recovery. Target contaminants included benzene, toluene, ethyl benzene, xylenes, and total petroleum hydrocarbons.

The primary purpose of this project was to demonstrate the effectiveness of an above ground treatment process for surfactant-contaminant separation and surfactant stream concentration for surfactant reuse. However, surfactant injection and recovery were also included to generate realistic waste streams for treatment. This project was completed in October 1997.

In examining the economics of surfactant-enhanced subsurface remediation, Krebs-Yuill et al. (1995) found that surfactant reuse is necessary for the system to be economical. In order to re-inject the surfactant solution, the contaminants must be separated from the surfactants in the waste stream and the surfactants recovered. Systems incorporating air stripping for surfactant-contaminant separation along with micellar enhanced ultrafiltration (MEUF) for surfactant recovery and reuse have shown promise (Ang et al., 1994; Lipe et al., 1996). In MEUF, ultrafiltration membranes allow water and surfactant monomers to pass through the membrane while the micelles, even though they are dynamic clusters, are retained in the membrane. This effectively concentrates the surfactant in the extraction stream (which is more dilute than the injection stream) and allows for surfactant reuse. The presence of surfactants lowers the efficiency of air stripping. Models and design equations have been developed to account for the reduced efficiency of air stripping from surfactant and thus properly size air strippers to achieve the desired removal efficiency solutions (Lipe et al., 1996; Hasegawa et al., 1996). A primary objective of this project was to demonstrate surfactant/contaminant separation and potential surfactant reuse at an actual field site. This is a major stepping stone in the eventual commercialization of surfactant-enhanced remediation systems.

Conceptual and pilot scale design of the surfactant injection and recovery system included site visits, predesign analysis, Modflow analysis, tracer test analysis, surfactant selection and optimization, surfactant recovery design, and fate transport analysis. The project was conducted within an eight month (including three weeks of actual flushing) period including procuring regulatory approval for injection.

Laboratory Methods and Results

The target chemicals included benzene, toluene, ethylbenzene xylenes (BTEX) and total petroleum hydrocarbons (TPH). Surfactants selected for laboratory testing were screened using the following criteria.

Toxicity and biodegradability
Potential enhancement of contaminant removal
Potential for economic reuse and recovery of the surfactant/cosolvent
Sorption of the surfactant/cosolvent onto the soil matrix
Potential for the surfactant/cosolvent to remove mixed wastes (i.e., solvents,
hydrocarbons, and cationic metals
Resiliency of the surfactant/cosolvent (i.e., how the surfactant resists subsurface chemical reactions

The following surfactants met the first three criteria listed above:

DOWFAX* 8390, anionic
Tween 80, nonionic
STEOL CS-330, anionic
SD-4, anionic with solvent

Additional testing was conducted to determine which surfactant best met the above criteria for the site specific conditions. The following are detailed descriptions of the procedures followed for each laboratory method utilized in the surfactant screening process.

Surfactant Precipitation. The objective of surfactant precipitation tests was to quantify the precipitation boundaries of the surfactants under investigation and to determine whether the phase boundary is crossed due to ionic composition (ionic surfactants) or ground water temperature (nonionic surfactants) of the system.

Precipitation (phase separation) assays were conducted using 120 ml glass vials with 100\~ml of solution in each vial. The ionic strength of the ground water was varied by addition of excess multivalent ions to assess precipitation of anionic surfactants; the ground water temperature was varied to assess phase separation of the nonionic surfactants. Only one set of samples was mixed and allowed to equilibrate at each target temperature. Surfactant concentrations were varied from 0.1 to 50 times the CMC for assessing phase separation. All the listed surfactants, with the exception of SD-4, demonstrated resistance to precipitation in the presence of salts. As a result, the SD-4 was eliminated from further consideration.

Surfactant Sorption. Surfactant sorption was assessed in batch systems by contacting solutions of varying surfactant concentrations with a constant mass of soil from the site. The experiments utilized 5 g of soil with 25 ml of surfactant solution with equilibration times of at least 24 hours. Upon centrifugation for solids_liquid separation, aliquots of the supernatant were analyzed for the equilibrium surfactant concentration via HPLC. The mass of surfactant sorbed was determined by mass balance (with appropriate controls to account for other losses). At least duplicates of each sample were conducted. The results showed that the STEOL exhibited the least amount of sorption while the Tween exhibited the highest (refer to Appendix A). Sorption for the STEOL was extremely low, averaging 0.004 g surf/g soil.

Contaminant Solubilization (includes mobilization systems). The objective of the solubilization tests was to quantify the solubilization potential of surfactants for the NAPL from the site. Contaminant solubilization was assessed in batch systems (40 ml EPA vials) by contacting an excess of the NAPL with solutions of varying surfactant concentrations (ranging from CMC/10 to 20x CMC) in site ground water. Aqueous NAPL concentrations were analyzed using a Gas Chromatograph (GC). Surfactant concentrations were analyzed using a high performance liquid chromatograph (HPLC). In this test, the STEOL and the Tween produced similar results (maximum of 7000 ppm TPH), exceeding the solubilization observed for DOWFAX* (maximum of 5500 ppm TPH).

As part of the solubilization study the surfactant/ NAPL solution is shaken and centrifuged. During shaking, both the Tween and STEOL formed a "gel" phase with the NAPL solution. The resulting "gel" was white and relatively stable; the gel took several hours to disperse. This phenomena was not observed in the samples containing DOWFAX*. The tests were repeated for all three surfactants with similar results. Any gel phase generated could potentially be broken chemically or thermodynamically. However, gel mitigation was not within the scope of this project.

Contaminant Extraction Column Studies. Column studies were conducted in glass liquid chromatography columns (2.5 cm diameter by 15 cm length). A time-controlled fraction collector was utilized to collect discrete effluent samples for GC or HPLC analysis. The surfactant/cosolvent concentrations for each system were selected based on predicted performance. The surfactant/cosolvent solutions were prepared using native groundwater and conducted at 15 C. Hydraulic flows rates through the column were determined prior to flushing with the surfactant solution. During surfactant flushing the following parameters were monitored continually: flow, injection rate, and pressure drop. Each effluent sample was checked for free phase NAPL and NAPL concentrations in the effluent. Flushing was continued until an asymptotic level of removal was achieved. STEOL was selected for column evaluation since it demonstrated the lowest sorption and highest solubilization potential during batch testing. The DOWFAX* was also selected for screening since it was the only surfactant that did not form a "gel" phase when mixed with the NAPL. Since there is an abundance of NAPL at the location, and the groundwater extraction system is relatively turbulent, "gel" formation is probable.

As is illustrated by breakthrough curves, the DOWFAX* demonstrated better solubilization enhancement than the STEOL. However, better recovery of the STEOL was observed (92%) versus the DOWFAX* (88%). There was no significant increase in pressure drop across the column in either test.

All of the surfactant systems tested demonstrated promise for application in this study. The Tween and the STEOL exhibited a higher solubilization potential than the DOWFAX* in the batch tests. The STEOL demonstrated significantly lower batch sorption results than the Tween or the DOWFAX*. However, during the batch solubilization tests both the STEOL and the Tween repeatedly formed a "gel" phase after agitation. This phenomenon was not observed with the

DOWFAX*. Although DOWFAX* was not the best performer in either of the batch tests, it did demonstrate better solubilization than the STEOL during the column studies. Surbec and OU proposed the use of the DOWFAX* for this project. It is the surfactant with the least probability of adverse reaction with site NAPL and groundwater.

Field Methods and Implementation and Groundwater Modeling

To determine the placement of the wells, preliminary groundwater modeling was conducted using MODFLOW. Site specific information was obtained from the site investigation report for SW Tanks and input into the model. Several well configurations were evaluated until the in line injection/recovery alignment was selected. This system offered maximum surfactant capture with minimal dilution of the surfactant. Two recovery wells (SU-1 and SU-3) and one injection well (SU-2) were installed near the west end of the southwest tank site.

Prior to well installation the depth to water was gauged and recorded in monitoring wells GW-6, I-93 and I-94. The average depth to water from ground surface was 20.5 feet. The recovery wells were designed to extend approximately 7 feet into the water table. However, the vacuum enhanced recovery system at southwest tanks resumed operation during drilling and the water table near the wells was depressed over three feet. Recovery wells SU-1 and SU-3 were gauged 24 hours subsequent to drilling activities and their respective depth to water were 23.3 and 23.1 ft. Rising head slug tests were performed on recovery wells SU-1 and SU-3. The hydraulic conductivity obtained for recovery wells SU-1 and SU-3 was 2.2 ft/day (7.8x10-4 cm/sec) and 0.5 ft/day (1.8x10-4 cm/sec) respectively.

Due to the low water table levels, each recovery well produced less than .25 gpm. Due to these low flow conditions, it was not possible to conduct a pump test using submersible pumps. As a result, a 24-hour pump test was not performed on these wells. Tracer tests were conducted on SU-1 through SU-3 to confirm capture of tracers injected into the subsurface. These tests were used as a check of modeling and laboratory results. Three field tracer tests have been conducted to date. Procedures used and results obtained for each test are summarized below. (Approximately 1500 gallons of fluids were produced during the tracer tests. All waste disposal was coordinated with Tinker officials and sent to the waste water treatment facility for treatment).

The first tracer test was conducted on July 18th, 1997 using fluorescein as a conservative (non-reacting) tracer. Recovery pumps were placed in wells SU-1 and SU-3. The pumps were operated at maximum yield; average yield was approximately 0.15 gpm per well. After the pumps had operated for approximately 1 hour and had begun to establish a cone of depression, 30 gallons of 1.5 mg/l tracer solution was injected into injection well SU-2. The injection rate was approximately 0.5 gpm and was followed with 200 gallons of tap water. Because of the lowered water tables due to the operation of the vacuum enhanced recovery system at the site, conventional pumps were not able to create significant drawdown in the extraction wells to provide timely or effective tracer recovery.

The second tracer test was conducted from July 31st to August 2nd, 1997 using fluorescein. Due to low flows and suspect capture encountered in the July 18th tracer test, a vacuum enhanced recovery system was utilized. Jet pumps (eductors) were placed in each recovery well. The jet pumps were driven by a two horsepower submersible placed in a 1000 gallon tank. The jet pumps pulled all fluids from the well and enhanced fluid recovery through vacuum extraction (creating a vacuum in the extraction well casing). Injection procedures for flourescein were identical to those listed above except the flourescein concentration was increased by a factor of five. Samples obtained from the combined extraction stream for the two wells and samples from the recovery tank indicated higher tracer recovery (about 20% recovered one day after tracer injection) than in the first test, but still insufficient for the demonstration of capture potential. However, due to the apparent photo-degradation of fluorescence in non-contaminated calibration standards, a one-gallon sample of Fluorescein was taken from the holding tank and allowed to sit in a similar container for over twelve hours. During that time, fluorescence readings were taken of the samples. The readings dropped considerably over the time period (approximately 93.5%), thereby suggesting the fluorescence of the tracer was being compromised by sunlight degradation in the recovery tank. These results led to the initiation of a third tracer test.

The third tracer test conducted at the project site utilized calcium chloride, a common salt, to demonstrate the capture zone efficiency of the well configuration installed and described in Figure 2. This test was also performed using the eductor pump system briefly described above. However, this test monitored for the presence of the chloride ion using an ion-selective probe. Baseline concentrations of chloride were obtained from the holding tank prior to injecting CaCl2. The tracer solution consisted of 467 grams of CaCl2 was mixed with 20 gallons of tap water. This solution was injected at approximately 0.33 gpm and was followed by 90 gallons of tap water at the same flow rate. Recovery rates from each well averaged approximately 0.25 gpm. Samples were taken from the holding tank and analyzed for chloride concentrations. This test showed just over 100% recovery of the injected mass of chloride ions. The above 100% recovery can be explained by the variance in pre-existing ground water concentrations of chloride (to be described below). However, the chloride tracer test was a success in that it showed a high level of capture of released tracers, thereby documenting the ability of the current well configuration to recover injected surfactants.

As mentioned, the most recent field work consisted of obtaining baseline chloride concentrations from samples obtained from the extraction wells as well as surrounding wells. Baseline samples obtained August 6th were noted to contain highly variable chloride concentrations with respect to well location. This accounts for the above one-hundred percent recovery noted from the third tracer test described above.

The results of the tracer test have been input into a ground water model (MODFLOW) to facilitate future modeling efforts. The model will then be used to design the additional wells for the surfactant test.

After the capture potential was demonstrated in the preliminary tracer tests the final well configuration could now be finalized. Two additional wells were installed to the west of the three present wells.

Final tracer tests were conducted from September 10 through September 14, 1997. Initially a tracer test was conducted using bromide as the conservative tracer. Prior to injection, pump driven eductors were placed in recovery wells SU-1, SU-3 and SU-5 and operated for 1.5 hours. Eighty five gallons of 1100 mg/l tracer solution was injected into injection wells SU-2 and SU-4 at a rate of 0.2 gpm per well. Also, 110 gallons of fresh water was injected at 0.2 gpm per well subsequent to tracer solution injection.

As of 20 hours of operation approximately 25% of the injected bromide tracer had been recovered. At that time 140 gallons of additional fresh water was flushed into the injection wells. The system was operated for an additional 8 hours and the recovery did not significantly increase. At that time the jet pumps were removed from the recovery wells and lowered an average of 2.2 feet. The system was operated overnight and the recovery increased to approximately 45%. At that time it was concluded that an additional tracer (chloride) would be added to the injection wells.

Fifty three gallons of fresh water was mixed with calcium chloride to produce 1750 mg/l chloride solution. This was injected into injection wells SU-2 and SU-4 at a rate of 0.16 gpm per well. The tracer solution was immediately followed by 110 gallons of fresh water. Recovered solution was monitored for both bromide and chloride concentrations. All samples were stored and transported to OU for analysis.

The recovery results for chloride after 24 hours after injection (approximately 80 hours after start of bromide injection) was approximately 95% (+- 5% error). At that time it is estimated that close to 60% of bromide had been recovered. The discrepancy between tracer recovery percentages is attributed to two factors. First the jet pumps were not set at their lowest possible level at the time of the bromide injection. As a result, the hydraulic gradient pulling the bromide to the extraction wells was not maximized. Second, the recovery system had been operating for only 1.5 hours prior to the injection of the bromide. Although a cone of depression was established, it may not have expanded to encompass the injection wells at that time. In order to ensure the effectiveness of the chloride tracer test, the recovery system was operated for at least 24 hours to develop cones of depression. Also, the jet pumps were lowered 2.5 feet to increase the hydraulic capture gradient.

Groundwater Modeling

In order to determine the fate of uncaptured or sorbed surfactant groundwater modeling was conducted using Visual Modflow. Inputs parameters for the model were obtained from RCRA Facility Investigation Report for the South West Tank Area (hydraulic conductivity), laboratory bench scale results (sorption), and slug test information. The main inputs for the model include:

Hydraulic Conductivity
Storage coefficients (Ss = 0.1, Sy = 1e-6)
Surfactant sorption (0.00032 ft3/d)
Dispersivity (3 ft)
Degradation constant (0.023 1/d)

The model was calibrated to reflect drawdown information for recovery well P-11 (located approximately 200 feet west of the flushed area) and recovery wells SU - 1, SU-3, and SU-5 using actual well yield values. Based on the draw down information it appears that the area adjacent to P-11 is approximately twice as conductive as the area adjacent SU-1, 3 and 5. Initial modeling results indicate that the migration of contaminants is extremely slow and that injected surfactants would not impact P-11.

System Implementation

Once tracer capture was confirmed the complete surfactant injection/recovery system, and treatment train was tested for operation. Prior to surfactant injection the eductor system was operated for 24 hours to establish a cone of depression in all the extraction wells (SU-1, SU-3 and SU-5). Two hundred and sixty eight gallons of DOWFAX* 8390 (34% active) was mixed with 2000 gallons of clean water and mixed in a 2500 gallon tank (Tank 3). Mixing was accomplished by using re-circulating pumps for a 12 hour time period. Surfactant was injected using two peristaltic pumps calibrated to yield 0.14 gpm each. Surfactant injection began in injection wells SU-2 and SU-4 at rates of 0.14 gpm.

Recovered ground water was stored in a 3000 gallon tank (Tank 1) and then sent to the air strippers for removal of contaminants from the process stream. Prior to going to the air strippers process water flowed through a heat exchanger to elevate the treatment temperature. The liquid going to the strippers was fed using a 1/2 hp jet pump and air flow generated by two air compressors.

Total flow rates feeding the treatment system ranged from 0.4 to 1.5 gpm. The air strippers were operated in a multitude of configurations ranging from one operating to several operating in series and parallel. Also, sensitivity analysis was conducted to generate information on performance in a wide range of operating parameters.

Effluent from the air strippers went to a 200 gallon storage tank (Tank 4) before being fed to the micellar enhanced ultrafiltration unit (MEUF). The MEUF was design using a centrifugal pump to feed two spiral wound 10,000 molecular weight cut off. The flow through capacity of the MEUF unit exceeds 6 gpm. Since the capacity of the MEUF greatly exceeded the capacity of the air strippers, it operated in batch mode. The MEUF would process between 140-180 gallons per batch. As with the air strippers, the operational parameters of the MEUF (i.e. back pressure) were varied to conduct sensitivity analysis. The retentate (concentrated surfactant solution) was piped to a 3000 gallon storage tank (Tank 2). The permeate (solution passing through the filter) was sent directly to a tray stripper for additional contaminant and surfactant removal.

Initial samples were taken to provide background information for ground water and tank fluids. Once injection began samples were taken on 2 hour intervals. When surfactant concentrations were high enough to run the MEUF, samples were taken when Tank 4 was filled to 175 gallons and the MEUF was run, or about every six hours. This procedure continued until the air strippers were no longer used, from that point on samples were taken at irregular intervals.

Injection and Recovery Results

Surfactant injection began on September 18 in SU-2 and SU-4 at a flow rate of .14 gpm in each well. The injected surfactant concentration was 4% by weight and the total surfactant solution injected was 1,935 gallons over 8 days. Estimated recovery of surfactant as of October 3 was calculated using final recovery tank volumes and surfactant concentration. The estimated recovery of surfactant at that time was about 85% and is shown in Table 1. However, elevated surfactant concentrations were observed in recovery well SU-3 and SU-5. As a result, an additional 1000 gallons of surfactant was reovered from those two wells and analyzed for surfactant concentrations; laboratory analysis of those samples is not complete at this time. Predicted total recovery of surfactant will be 3-5% over the numbers reported as of October 3.

Based on contaminant recovery graphs the recovered concentration of contaminants is significantly enhanced over baseline recovered concentrations. Elevated contaminant recovery was found to coincide with elevated surfactant concentration. Also, the tailing of surfactant recovery continues to enhance contaminant concentrations in the recovered groundwater. Average enhancements of contaminant concentrations in the recovered groundwater ranged from a factor of 10 to 20. It should be noted that, to ensure hydraulic control, the recovered groundwater stream was being diluted within the well bores by factor of 4:1. Actual enhancement of contaminant concentration in the flushed zone is estimated to range from 40 to 100 times the normal aqueous contaminant concentration.

The enhancement of contaminant recovery was not consistent for the BTEX compounds. The results indicate that the enhancement of benzene and toluene was consistently higher than that of xylenes. This may be due to the relative low concentrations of xylenes at this particular site or preferential solubilization.

Air Stripper Results

Three air strippers were utilized for contaminant removal, a packed column (PC) and two hollow fiber membranes (HF1 and HF2). These strippers were operated in a number of different configurations and using a wide range of operating parameters. All air strippers were operated effectively at surfactant concentrations well above the CMC. The packed column was operated at varying air to water ratios without foam production. Stripper required minmal adjustment and maintenance.

As noted by the results the stripping effectiveness of the hollow fiber membrane HF2 surpassed that of HF1. It should be noted that HF2 was new, whereas HF1 was used and did not perform as well as HF2. Also, recovered surfactant concentrations fluctuate throughout the air stripping sensitivity analysis, and could introduce some small differences in TPH removal. Baseline removal was evaluated for each of the air strippers before surfactant was introduced into the system. These values were used to determine the extent that surfactants inhibit contaminant removal using these strippers. The baseline values were calculated by running the strippers in parallel and using the same operating parameters.

Once the baseline had been established and surfactant had been introduced into the system at .5 % by weight,the strippers were operated under similar conditions (air to water ratio of 5.2:1 instead of 4:1) and the removal efficiency calculated. Results from operating the P.C., HF1 and HF2 in parallel with water flow at .25 gpm and air flow at 1.3 cfm to each were given in tabular form. It can be seen that the surfactant inhibited contaminant removal by as much as 32% in HF1 (the used hollow fiber unit) and little as 17% in the packed column.

The hollow fiber membranes were operated in series and parallel and under varying flow rate ratios of air to water. The results from operating HF1 and HF2 in series with a 4.5:1 air to water ratio were shown in a table. The average removal for HF1 and HF2 in series is the percentage removed from total TPH entering the system. That is, HF2 removed 61% of the TPH going into HF1, not 61% of the TPH leaving HF1. Table 4 also shows the same units in parallel with a ratio of 5:1 air to water. Comparison of the two tables indicate that running the HF units in parallel is somewhat more efficient. In comparison with Table 5, not much improvement was realized from by increasing the ratio from 3:1 to 5:1. Another table provides results from operating the three units in parallel at an air to water ratio of 8:1. It was seen that some improvement was realized for the HF units but none for the Packed Column.

Sensitivity analysis was conducted on the MEUF by altering the back pressure and flow rate ratio of permeate to retentate. Several batches were processed through the MEUF at approximately the same back pressure and flow rates to obtain an average efficiency for each scenario. The flow meter for the permeate was calibrated in the field and off by +10%, this was taken into consideration for MEUF calculations. The results from four scenarios are provided in the tables below:

As indicated by the results, the efficiency of the MEUF increases as the flow rate ratio of permeate to retentate approaches 1 and the back pressure increases. It is reasonable to assume that the concentration of surfactant could exceed 80%.

Tray Stripper Results

Water flow rates were varied through the stripper at a constant air flow rate in hopes of enhancing surfactant and contaminant removal. Water flow ranged from 1-4.7 gpm. The tray stripper did prove to aid in contaminant removal, and was expected, removal was highest at the lower flow rates. Results showed, however, that the stripper did not enhance surfactant removal.

Summary

Results demonstrated up to 240 fold increase in contaminant recovery over baseline ground water conditions The effective operation of a packed column air stripper and hollow fiber membrane air strippers with removal efficiencies in excess of 85% without foam production was demonstrated. Also demonstrated was effective operation of micellar enhanced ultrafiltration for surfactant stream concentration, and surfactant injection and recovery in a low yield formation (less than 0.2 gpm/well)

Elevated contaminant concentrations of up to 20 times the baseline groundwater concentration were observed in the recovered groundwater. Surfactant recovery was observed to exceed 85%. Packed column and hollow fiber membrane column air strippers were demonstrated to operate without the generation of foam. Contaminant separation efficiencies of the columns were reduced by 15%- 30% when surfactant was present above the Critical Micelle Concentration. Surfactant recovery using MEUF was varied with the maximum observed recovery exceeding 80%. Finally, a tray stripper was operated to recovery monomers and strip remaining contaminants from the MEUF permeate.

The results of this pilot scale demonstration are positive and provide valuable information for future application of the technology. The significant points demonstrated as part of this project include:

A high level of surfactant recovery from the subsurface in a low permeable formation (over 85%);
Enhanced contaminant recovery in a low permeable formation (between 1 and 2 orders of magnitude over baseline concentrations).
Vacuum enhanced groundwater extraction can be used in conjunction with surfactant flushing to increase surfactant recovery and reduce flushing duration.
The continuous operation of packed column air strippers without foaming
or other operational difficulties.
The degree surfactants affect contaminant removal in air strippers.

Sensitivity analysis on air stripper removal performance.
Effective application of MEUF operation for surfactant recovery and the performance of extensive sensitivity analysis.

The overall value of the technology is significantly enhanced if it can be demonstrated to be effective under various subsurface conditions. The demonstration of elevated contaminant recovery and a high percentage of surfactant recovery in this low yield aquifer is an important step in demonstrating "broad" application potential. Also, key in the future application of this technology is the effective demonstration of surfactant-contaminant separation and surfactant recovery for re-use. These aspects of the technology were also demonstrated to be viable for the conditions present at this site.

Tables, Figures and Appendices available but not shown in this project summary:

Table 1 - Surfactant Recovery Results
Table 2 - Baseline Contaminant Removal
Table 3 - Stripper Performance at 0.5 wt% Dowfax
Table 4 - Hollow Fiber Performance Operating in Parallel
Table 5 - Stripper Removal Efficiencies for TPH Operating at Elevated Air to Water Ratios
Table 6 - MEUF at 43-44 psi Back Pressure
Table 7 - MEUF at 51-54 psi Back Pressure
Table 8 - Tray Stripper Removal Efficiency

Figure 1 - Schematic of Surfactant Enhanced Remediation
Figure 2 - Well Location Diagram

Appendix A - Bench Scale Results
Appendix B - Well Logs
Appendix C - Laboratory Analysis and Test Results
Appendix D - Site Map and Photographs

Report(s)/Publication(s) (Additional Information Sources):

Draft report from Surbec Environmental Services, Norman, OK, phone (405) 364-9726.

GWRTAC ID: FLSH0075

Project Name: U.S. DOE Paducah Gaseous Diffusion Plant

City: Paducah **State/Province:** KY

Primary GWRTAC Personal Communication Source (Name/Organization): Mark Hasegawa
Surbec Environmental Services

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text was excerpted from marketing information provided by Surbec Environmental, Norman, Oklahoma, in October 1998:

The primary purpose of this project is to utilize bench scale testing to screen surfactant systems for remediation application at the subject site. The treatability study will focus on three primary systems: 1) the best surfactant solubilization system, 2) the best surfactant/cosolvent solubilization system and 3) the best mobilization system in which vertical migration can be mitigated. One potential method of mitigating vertical migration is to develop a mobilization system with an ultra high solubilization potential so that any mobilized DNAPL is solubilized into solution before significant vertical migration can occur.

Conceptual and pilot scale design of the surfactant injection and recovery system included predesign analysis, Modflow analysis, surfactant selection and optimization, surfactant recovery design, and fate transport analysis. Over 50 surfactants will be screened for evaluation under the treatability study. Included in the testing will be two dimensional sand tank studies to evaluate vertical migration potential. The estimate for project completion is December 1998.

Report(s)/Publication(s) (Additional Information Sources):

None

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0076

Project Name: UST Site, Shawnee, OK

City: Shawnee **State/Province:** OK

Primary GWRTAC Personal Communication Source (Name/Organization): Mark Hasegawa
Surbec Environmental Services

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text was excerpted from marketing information provided by Surbec Environmental, Norman, Oklahoma, in October 1998:

Surface remediation can be a cost effective method for removal of residual subsurface petroleum hydrocarbons. When used in conjunction with Risk Based Corrective Action (RBCA) this technology can be used to remediate to Site Specific Target Levels (SSTLs). In order to quantify the potential cost of this application, a pilot test is being conducted in Shawnee, Oklahoma. Results of the flush will be used for future design and cost analysis purposes.

Predesign analysis, Modflow analysis, tracer test analysis, surfactant selection and optimization, surfactant recovery design, fate transport analysis, and process design were conducted by Surbec. A treatability study was conducted to evaluate surfactant-enhanced recovery of BTEX and TPH. This study focused on separating the contaminant from the waste stream and Micellar Enhanced Ultrafiltration (MEUF) for surfactant reconcentration. Numerical 3-D flow and 2-D fate and transport modeling to identify injection/capture zones was also conducted.

Surfactant injection/recovery project included re-injection of treated surfactant. Demonstrated 92% recovery of injected surfactant. A surfactant-contaminant separation process and surfactant re-concentration system (MEUF) was designed and implemented. The effective application of foam fractionation for tertiary surfactant recovery was demonstrated.

Report(s)/Publication(s) (Additional Information Sources):

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0077

Project Name: Coast Guard Facility, Elizabeth City, NC

City: Elizabeth City **State/Province:** NC

Primary GWRTAC Personal Communication Source (Name/Organization): Mark Hasegawa
Surbec Environmental Services

Report(s)/Publication(s) (GWRTAC Source):

None

Project Summary:

The following text was excerpted from marketing information provided by Surbec Environmental, Norman, Oklahoma, in October 1998:

Surbec supervised and conducted field screening to determine the feasibility of surfactant-enhanced removal of chromium and chlorinated solvents. A surfactant screening analysis was conducted for removal of chromium from the subsurface at the Coast Guard Facility in Elizabeth City, NC. The project included a predesign analysis, Moc analysis, tracer test analysis, surfactant selection and optimization, surfactant recovery design, and fate transport analysis. Treatability studies were conducted to evaluate surfactant-enhanced recovery of chromium. The results indicated that the addition of surfactant and a complexing agent increased chromium (chromate ion) removal by over 1 order of magnitude over water flushing alone.

Report(s)/Publication(s) (Additional Information Sources):

GWRTAC ID: FLSH0078

Project Name: PPG Plant, Lake Charles, LA

City: Lake Charles **State/Province:** LA

Primary GWRTAC Personal Communication Source (Name/Organization):

Report(s)/Publication(s) (GWRTAC Source):

"Surfactant-Enhanced DNAPL Remediation at a Highly Heterogeneous Site", John Fountain, Geology Department, State University of New York at Buffalo, presented May 6, 1998 at GWRTAC/U.S. EPA TIO "Advances in Ground-Water Remedation Conference", San Francisco, CA

Project Summary:

The following text was excerpted from "Surfactant-Enhanced DNAPL Remediation at a Highly Heterogeneous Site", John Fountain, Geology Department, State University of New York at Buffalo, presented May 6, 1998 at GWRTAC/U.S. EPA TIO "Advances in Ground-Water Remedation Conference", San Francisco, CA:

At the PPG Plant in Lake Charles, Louisiana, a site with known DNAPL (primarily dichloroethane - EDC) contamination, a pilot test was undertaken to effect DNAPL source zone remediation. The site is underlain by a thick sequence of interbedded clays and thin sands of fluvial-deltaic and marine origin (Holocene and Pleistocene aged Beaumont or Prarie Formation). The site hydrostratigraphy is thus complex, and a regional aquifer (Chicot Aquifer) is present at depth.

The surfactant field test was conducted in 1997-1998, only in the shallowest water-bearing unit, the "10 foot sand", which had been consistently found beneath the site at about 10 feet bgs. DNAPL was likely present in the sand layer based on cone penetrometer testing and analysis of groundwater samples collected from monitoring wells. The DNAPL primarily consists on dichloroethane, or EDC. A sand layer at 20 feet was also contaminated. Grain size analysis showed that a one foot sand zone was present at 10.5 feet bgs, and another foot of silty sand was present beneath this one foot sand zone. Permeameter tests on core samples revealed hydraulic conductivities ranging from 6 x 10-3 cm/sec in sand to <10-7 cm/sec in clays. The clays were smectitie, and contained total organic carbon of much less than 1%. The EDC concentration was highest in the sand zone immmediately above the clay, although several cores also found elevated levels of EDC within the clay units, which remains an important issue at this site. A decision was made to test surfactant-enhanced remediation at the site, with the realization that the contamination in the clay would not be treated by this method of remediation.

A pumping test conducted in the "10 foot sand" produced a large response in the "20 foot sand", indicating a hydraulic connection between the two sand units. From the pumping tests, it was determined that the hydraulic head in the 20 foot sand should be maintained above that in the 10 foot sand to minimize downward migration, and that a high interfacial tension should be maintained to minimize mobilization potential.

The surfactant field test was conducted in a 12 x 15 foot sheet piling cell. The 20 foot sand zone was pressurized to minimize the potential for DNAPL mobilization. Three injection wells and three withdrawl wells were installed within the test cell in a line-drive pattern. A partioning tracer test conducted indicated tht only 50% of the test cell was swept in the 30 day duration of the test, suggesting that the low permeability zones apparently occupied about half of the target zones. DNAPL satuaration was oonly about 0.4% at the conclusion of the tracer test, indicating approximately 6 gallons of EDC were present within the test cell.

Surfactant blending was undertaken by considering the following: An anionic surfactant would be needed to minimize sorption by the clay; The high (8,700 mg/L) solubility of EDC; and, Low interfacial tension systems were not desired. The surfactant linear alkylbenzene sulfonate was selected as surfactant sorption batch and column tests showed low sorption. Interfacial tension was 1.3 dynes/cm, and the critical micelle concentration was 0.044%.

The surfactant was injected from February through June 1997, and water circulation continued through December 1997. The injection rates dropped dramatically soon after surfactant injection began; this was believed to be due to a clay plug formed around the injection well. A total of approximately 2,500 gallons was injected, which was less than one total pore volume, and equivalent to about two "effective pore volumes". Based on breakthrough curve analysis for the surfactant and a conservative tracer, nearly all of the flow through the test cells was through high permeability paths near the center of the cell. Breakthrough curves potted by volume were nearly identical for the surfactant and a conservative tracer, indicating limited sorption effects occurred. Soil cores were taken near monitoring and extraction wells. In high permeability zones, cores revealed low EDC concentrations to the top of the clay. Cores from the corners of the test cell, in low permeability zones, revealed higher EDC. The highest EDC levels in otherwise "clean" cores occurred at the top of the clay unit, signifying apparent diffusion into the clay. Significant EDC was found at all levels in the base clay.

Conclusions made from this project include the following: Other than well development problems, surfactant system worked well in clayey units; Apparently all units where breakthrough occurred were cleaned of DNAPL; EDC was persistent in clay, reflecting a combination of diffusion and flow (strong downward gradient exists at site); The significance of fractures at the site within the clay is to be determined. Also, it was concluded that: Heterogeneities slow the remediation process; Behavior in complex systems waas as predicted from model based on tracers; The persistance of EDC in the clay units suggest significant residual would always be present; and Clear definition of objectives are required to determine if this technology will be appropriate for a given site.

Report(s)/Publication(s) (Additional Information Sources):

"Surfactant-Enhanced DNAPL Remediation at a Highly Heterogeneous Site", John Fountain, Geology Department, State University of New York at Buffalo, presented May 6, 1998 at GWRTAC/U.S. EPA TIO "Advances in Ground-Water Remedation Conference", San Francisco, CA

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0079

Project Name: University of North Carolina - Bank Formation in Surfactant R

City: Chapel Hill **State/Province:** NC

Primary GWRTAC Personal Communication Source (Name/Organization): Joy Hall
Black & Veatch

Report(s)/Publication(s) (GWRTAC Source):

Hall, Joy L., and Cass T. Miller, 1998: "Bank Formation During Surfactant Flushing of Porous Media", ESENotes, Spring 1998, Vol. 33, Issue 1, University of North Carolina, Chapel Hill, NC, available at http://www.sph.unc.edu/envr/esenotes/spring98/hall.htm.

Hall, Joy L., Paul T. Imhoff, Clinton S. Wilson, and Cass T. Miller, 1997: "Surfactant-Enhanced Mobilization of Dense Nonaqueous Phase Liquids in Groundwater Remediation", Center for Multiphase Research News Reprint, Vol. 3, No. 1, Fall/Winter 1997, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, available at http://cmr.sph.unc.edu/CMR/home.html.

Project Summary:

At the University of North Carolina at Chapel Hill, reseachers associated with the Center for Multiphase Research (CMR) have conducted laboratory experiments to quantify the dynamics of surfactant enhanced mobilization of DNAPL, including factors leading to bank formation. The following two articles are available on the internet, and the 1998 article is printed below.

Hall, Joy L., and Cass T. Miller, 1998: "Bank Formation During Surfactant Flushing of Porous Media", ESENotes, Spring 1998, Vol. 33, Issue 1, University of North Carolina, Chapel Hill, NC, available at http://www.sph.unc.edu/envr/esenotes/spring98/hall.htm.

Hall, Joy L., Paul T. Imhoff, Clinton S. Wilson, and Cass T. Miller, 1997: "Surfactant-Enhanced Mobilization of Dense Nonaqueous Phase Liquids in Groundwater Remediation", Center for Multiphase Research News Reprint, Vol. 3, No. 1, Fall/Winter 1997, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, available at http://cmr.sph.unc.edu/CMR/home.html.

Hall and Miller 1998 Reprinted below with written permission from author Joy Hall:

Bank Formation During Surfactant Flushing of Porous Media
Joy L. Hall and Cass T. Miller

As surface sources of drinking water are less able to meet growing demands, the dependence on groundwater has continued to increase in the United States and all over the world. Groundwater is the primary source of drinking water for over 50% of Americans, with over 75% of American cities relying on groundwater for at least part of their drinking water supplies (1). The most common types of groundwater pollutants are organic compounds that are highly immiscible in water (2), often referred to as nonaqueous phase liquids. Denser-than-water nonaqueous phase liquids (DNAPLs) frequently enter the subsurface as a separate phase and migrate downward due to gravity. After the bulk of the DNAPL migrates through the aquifer, discrete "blobs" or ganglia of DNAPL are entrapped, held in the pore spaces by capillary forces. Under low flow conditions typical in aquifers, these blobs of residual DNAPL are immobile and dissolve very slowly, thereby creating long-term sources of contamination (3).

Surfactants can be used to dramatically reduce remediation times via increased solubilization through micellar partitioning, increased mobilization through reductions in interfacial tension, or a combination of both. Mobilization has a greater potential to increase remediation efficiency over solubilization alone, but, if uncontrolled, the mobilized DNAPL may sink deeper into the aquifer where it is more difficult to remediate and may contaminate previously pristine portions of the aquifer. Particular mobilization regimes are more easily controlled and thus preferred during surfactant flushing. Bank formation, the creation of a continuous phase of DNAPL at the surfactant front, can lead to increased efficiency in DNAPL removal and may be used to control migration of mobilized DNAPL (4, 5).

The purpose of this investigation was to examine the mobilization of residual DNAPL in well-characterized, two-dimensional homogeneous porous media during surfactant flushing to 1) determine the critical conditions that lead to different mobilization regimes, 2) quantify the factors leading to DNAPL bank formation, and 3) examine the use of a dimensionless grouping for predicting DNAPL bank formation as a function of viscous and buoyancy forces. For all experiments, a 1:1 mixture of two food-grade, anionic surfactants, sodium diamyl sulfosuccinate (Aerosol AY) and sodium dioctyl sulfosuccinate (Aerosol OT) were selected for the surfactant flushing solution. Tetrachloroethylene, a representative groundwater pollutant, was selected as the DNAPL. Experiments were conducted in two well-characterized cells packed with glass beads. Explanations of the mobilization regimes are given using a dimensionless grouping of system parameters defined as the bank number. The bank number was defined as the total force acting on a DNAPL ganglion in the flow direction divided by the force acting on the same ganglion in a direction perpendicular to the flow. A bank number of 1 indicates a balance in viscous and buoyancy forces. Different bank numbers were achieved by varying the angle of the cell (i.e., the angle of flow) and the surfactant injection rate.

For each experiment, an aqueous solution of 1% Aerosol AY/OT was injected into the cell. Upon contact with the surfactant solution, the vast majority of the PCE was immediately mobilized as a separate phase for all experiments.

In five experiments, PCE was immediately mobilized downward upon contact with the surfactant solution, forming a PCE pool at the bottom of the cell. This mobilization regime was termed "downward mobilization." As the experiments progressed, the pool grew, moved through the cell, and finally exited the cell. Bank numbers for these experiments ranged from 0.41 to 1.34. Nearly complete downward mobilization in these experiments was expected due to the dominating effect of the gravitational force on the mobilized DNAPL ganglia. Figure 1 is a representative set of images taken at three separate times during a surfactant experiment where downward mobilization was observed, resulting in the formation of a DNAPL pool.

Figure 1. Downward mobilization with DNAPL pool formation (Refer to internet source to view)

In two experiments, distinct DNAPL banks were formed. For these experiments, the bank numbers were 0.96 and 1.05. Upon contact with the surfactant solution, PCE was immediately mobilized downward, forming a pool at the bottom of the cell. The surfactant solution flowed preferentially along the top of the micro-cell as the mobilized PCE migrated downward, leaving a less permeable region at the bottom of the cell. Because the PCE pool was less viscous than the aqueous phase, the pool moved faster than the aqueous phase and began climbing up the surfactant front. As the PCE climbed up the surfactant front, a bank of PCE formed at this front, i.e., a DNAPL bank formed. Figure 2 is a representative set of images taken from a surfactant experiment with "DNAPL bank formation."

Figure 2. Distinct DNAPL bank formation (Refer to internet source to view)

In four experiments, less distinct DNAPL banks were formed. PCE was mobilized upon contact with the surfactant front, forming a DNAPL pool at the surfactant/clean water front. As the surfactant mobilized DNAPL, some of the DNAPL moved ahead of the surfactant front, where the interfacial tension increased, retrapping the DNAPL until the front reached it once again. This process resulted in the formation of a DNAPL bank at the leading edge of the surfactant front. This process has been reported elsewhere, by Constantinides and Payatakes (5) and Pennell et al. (6). As shown in the series of images in Figure 3 below, these banks were not as distinct as the banks formed in the two experiments depicted in Figure 2.

Figure 3. Diffuse DNAPL bank formation (Refer to internet source to view)

In the experiments depicted in Figures 2 and 3, PCE was mobilized in the directions of flow, not in the direction of gravity (as in the downward mobilization experiments depicted in Figure 1). This behavior was expected because of the dominant viscous forces (compared to the buoyancy forces) and because the displaced fluid was less viscous than the flushing fluid.

At bank numbers less than 0.8 and greater than 2, the macroscopic flow behavior (i.e., whether downward mobilization or DNAPL bank formation occurs) is easily explained by examination of the relative magnitude and direction of the viscous and buoyancy forces. However, the data suggest that a DNAPL bank may or may not form around a bank number of 1. This is a critical region, where the DNAPL must "climb" up the surfactant/clean water front to form a bank. If the surfactant solution lowers the IFT sufficiently on the upgradient side of the front, then the DNAPL moves down this front and a DNAPL bank does not form. At bank numbers of 2 and greater, though, the force acting on the DNAPL in the direction of flow is sufficiently large that a DNAPL bank always forms. Because the bank number relies on general physical and chemical properties, it should be applicable to flushing of any homogeneous porous media. Further testing is required to verify this hypothesis.

References

1. Patrick, R., Ford, E., and Quarles, J., Groundwater Contamination in the United States, Second Edition, University of Pennsylvania Press, 1987.

2. Mackay, D. M. and Cherry, J. A., Groundwater contamination: pump-and-treat remediation, Environmental Science and Technology, 23(6), 630-636, 1989.

3. Pankow, J. F. and Cherry, J. A., Dense Chlorinated Solvents and other DNAPLs in Groundwater, Waterloo Press, Portland, 1996.

4. Hawthorne, R. G., Two-phase flow in two-dimensional systems—effects of rate, viscosity, and density on fluid displacement in porous media, Petroleum Transactions AIME, 219, 81-87, 1960.

5. Constantinides, G. N. and Payatakes, A. C., A theoretical model of collision and coalescence of ganglia in porous media, Journal of Colloid and Interface Science, 141(2), 486-504, 1991.

6. Pennell, K. D., Pope, G. A., and Abriola, L. M., Influence of viscous and buoyancy forces on the mobilization of residual tetrachloroethylene during surfactant flushing, Environmental Science and Technology, 30(4), 1328-1335, 1996.

Report(s)/Publication(s) (Additional Information Sources):

Hall, Joy L., and Cass T. Miller, 1998: "Bank Formation During Surfactant Flushing of Porous Media", ESENotes, Spring 1998, Vol. 33, Issue 1, University of North Carolina, Chapel Hill, NC, available at http://www.sph.unc.edu/envr/esenotes/spring98/hall.htm.

Hall, Joy L., Paul T. Imhoff, Clinton S. Wilson, and Cass T. Miller, 1997: "Surfactant-Enhanced Mobilization of Dense Nonaqueous Phase Liquids in Groundwater Remediation", Center for Multiphase Research News Reprint, Vol. 3, No. 1, Fall/Winter 1997, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, available at http://cmr.sph.unc.edu/CMR/home.html.

GWRTAC ID: FLSH0080

Project Name: University of Oklahoma - Remediation of Chlorinated Solvents

City: Norman **State/Province:** OK

Primary GWRTAC Personal Communication Source (Name/Organization): None

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 111-112

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 111-112:

Surfactant enhanced subsurface remediation is being evaluated as an innovative technology to expedite contaminant extraction from the subsurface. Regulatory approval of this technology will likely be enhanced by use of surfactants with FDA direct food additive status ('edible' surfactants). This research establishes edible surfactant systems capable of solubilizing (via micellar partioning) and microemulsifying (via middle phase microemulsions) chlorinated solvents (PCE, TCE, and trans 1,2-DCE). Micellar partition coefficients with edible surfactants are observed to be comparable to values previously reported for other surfactants, with solubilization increasing aqueous concentrations by one to two orders of magnitude for the chlorinated organics. Middle phase microemulsion formation is dependent on surfactant structure and cosurfactant concentration. Solubility enhancement in the middle phase systems (microemulsification) is at least one to two orders of magnitude higher than solubilization for the same sufactant concentration, but is much more sensitive to the surfactant system and the contaminant. IN addition, successful microemulsion formation is seen to be a function of ground-water temperature and hardness, indicating the need to consider these and additional factors for successful design and implementation of surfactant enhanced subsurface remediation. This research thus establishes a variety of edible surfactant systems that can significantly expedite subsurface remediation of chlorinated solvents, and illustrates the importance of proper selection and design of surfactant systems.

Report(s)/Publication(s) (Additional Information Sources):

Shiau, Bor-Jier, David A. Sabatini, and Jeffrey H. Harwell, Univ. of Oklahoma, Norman, OK, 1994: "Solubilization and Microemulsifcation of Chlorinated Solvents Using Direct Food Additive (Edible) Surfactants", in Groundwater, Vol. 32, No. 4, Jul-Aug 1994, pp. 561--569.

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water

GWRTAC ID: FLSH0081

Project Name: University of Illinois - Impact of Surfactant of Configuration of

City: Carbondale **State/Province:** IL

Primary GWRTAC Personal Communication Source (Name/Organization): None None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Sept. 1-15, 1998, page 6.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Sept. 1-15, 1998, page 6:

A parallel-plate glass tank filled with Ottawa sand was used to create a laboratory-scale physical model for visual analysis of the fundamental 2-D flow characteristics of a gasoline spill moving through an unconfined aquifer. It was subsequently used to evaluate treatment of the contaminant plume with a surfactant. When samples of gasoline were introduced into the model at a point source located in the vadose zone, the gasoline was found to pool above the water saturated pores of the tension saturated zone of water. Reductions in the height of the capillary fringe beyond the gasoline lens was attributed to capillary pollution.

Report(s)/Publication(s) (Additional Information Sources):

Chevalier, Lizette R., Roger B. Wallace, and David C. Wiggert, 1998: "Impact of Surfactant on Configuration of Petroleum Hydrocarbon Lens", Journal of Soil Contamination, Vol. 7, No. 3, May 1998, page 395.

GWRTAC ID: FLSH0082

Project Name: University of Florida - Two-Dimensional Flow Experiments and

City: Gainesville **State/Province:** FL

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8:

A laboratory study was designed to investigate how density and viscosity contrasts affected cosolvent displacements in unconfined porous media characterized by the presence of a capillary fringe. Two-dimensional flow experiments were conducted to determine potential implications of flow instabilities in homogeneous sand packs, and numerical simulations were conducted to investigate the differential impact of fluid property contrasts in confined and unconfined systems. Test results indicated that the presence of a capillary fringe was an important factor in displacement efficiency. Buoyancy forces can act to carry a lighter-than-water cosolvent into the capillary fringe during displacement of the resident groundwater. During subsequent water flooding, buoyancy forces can trap the cosolvent in the capillary fringe, contributing to the inefficient removal of cosolvent from the aquifer.

Report(s)/Publication(s) (Additional Information Sources):

Jawitz, J.W., M.D. Annable, P.S.C. Rao, Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, "Two-Dimensional Flow Experiments and Simulations", in Journal of Contaminant Hydrology, 31:3-4, p. 211-230, 1998

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8.

GWRTAC ID: FLSH0083

Project Name: University of Arizona - HC Solubilzation and Mobilization by Bi

City: Tucson **State/Province:** AZ

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8:

The effect of cation type, ionic strength, and pH on the ability of an anionic biosurfactant to solubilize and remove residual nonaqueous phase liquid (NAPL) from sand was examined. Na+, Mg2+, and Ca2+ were used in the experiments, and hexadecane was selected as a representative NAPL less dense than water. Hexadecane solubility in rhamnolipid solution was significantly increased by the addition of Na+ and Mg2+. Addition of up to 0.2 mM Ca2+ also increased hexadecane solubility, although for concentrations greater than 0.2 mM there was little effect on solubility due to competing effects of calcium-induced rhamnolipid precipitation and enhanced hexadecane solubilization. Molar solubilization ratios (MSR) values for hexadecane in rhamnolipid solutions were 7.5 times higher in the presence of 500 mM Na+, and were 25 times greater in the presence of 1 mM Mg2+. The presence of cations also reduced the interfacial tension between rhamnolipid solutions and hexadecane. Decreasing pH caused a reduction in interfacial tension, and lowering interfacial tension value was found to be optimal for removal of hexadecane residual from sand columns, with 58% of residual NAPL removed within three pore volumes. Residual NAPL was removed from the packed columns through mobilization primarily, though solubilization was significantly increased in the presence of Na+.

Report(s)/Publication(s) (Additional Information Sources):

Bai, Guiyun, M.L. Brusseau, R.M. Miller, Soil, Water and Environmental Science Department, University of Arizona, Tucson, AZ, "Influence of Cation Type, Ionic Strength, and pH on Solubilization and Mobilization of Residual Hydrocarbon by a Biosurfactant", in Journal of Contaminant Hydrology, 30:3-4, p. 265-279, 1998

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 8.

In Situ Flushing Project Summaries
GWRTAC Case Study Database

GWRTAC ID: FLSH0084

Project Name: Georessources - Aquifer Washing by Micellar Solutions

City: Sainte-Foy **State/Province:** QC

Primary GWRTAC Personal Communication Source (Name/Organization): None
None

Report(s)/Publication(s) (GWRTAC Source):

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 10.

Project Summary:

The following text was excerpted from U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 10:

Phase diagrams were used to identify dense nonaqueous phase liquid (DNAPL) extraction zones and for alcohol-surfactant-solvent formulation. Although four potential extraction zones of Mercier DNAPL, a mixture of heavy aliphatics, aromatics and chlorinated hydrocarbons, were identified, only one microemulsion zone showed satisfactory DNAPL recovery in sand columns. More than 90 sand column experiments were performed. Among the researchers' findings: (1) only combined alcohol- surfactant-solvent solutions effectively recovered DNAPLS; and (2) washing solution formulations seemed to be site specific and had to be modified if the surface properties of the solids (mineralogy) changed locally, or if the interfacial behavior of liquids (type of oil) changed. The optimal washing solution of n-butanol-SAS-toluene-D-limonene in water recovered up to 95% of Mercier DNAPL in sand columns.

Report(s)/Publication(s) (Additional Information Sources):

R. Martel, P.J. Gelinas, J.E. Desnoyers, INRS-Georessources, 2535 boul. Laurier, C.P. 7500, Sainte-Foy, QC, G1V 4C7, Canada, "Aquifer Washing by Micellar Solutions: 1. Optimization of Alcohol-Surfactant-Solvent Solutions", in Journal of Contaminant Hydrology, 29:4, pp. 319-346, 1998.

U.S. EPA Technology Innovation Office Technology Information Summary Report, Oct. 16-31, 1998, page 10.