

Beazer

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December 20, 2006

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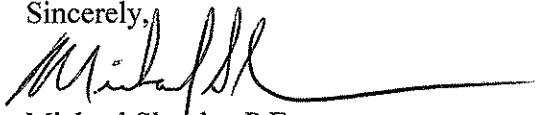
**RE: Screening Analysis of Surfactant Flushing Technologies
Cabot Carbon/Koppers Superfund Site in Gainesville, Florida**

Dear Ms. McLaughlin:

Enclosed please find the *Screening Analysis for Surfactant Flushing at Cabot Carbon/Koppers Site*, written by Dr. Tom Sale with the Colorado State University and dated December 20, 2006. This report was prepared as a follow-up to the June 15, 2005 project meeting in Gainesville, Florida, in which Beazer provided a presentation regarding surfactant flushing remediation technologies. On behalf of Beazer, Dr. Sale provided a presentation regarding surfactant flushing technologies that included an overview of the technology as well as a discussion regarding its potential applicability to the Koppers portion of the Cabot Carbon/Koppers Superfund Site located in Gainesville, Florida. The enclosed report is generally consistent with the information and assessment provided within that presentation.

If you should have any questions or require additional information, please contact me at 412-208-8867.

Sincerely,



Michael Slenska, P.E.
Environmental Manager

cc: Kelsey Helton, FDEP
John Mousa, ACEPD
Brett Goodman, GRU
Linda Paul, KI
Jim, Erickson, GeoTrans

Screening Analysis for Surfactant Flushing at Cabot Carbon/Koppers Site

Developed by Dr. Tom Sale

For

GeoTrans Inc. and Beazer East Inc.

December 20, 2006

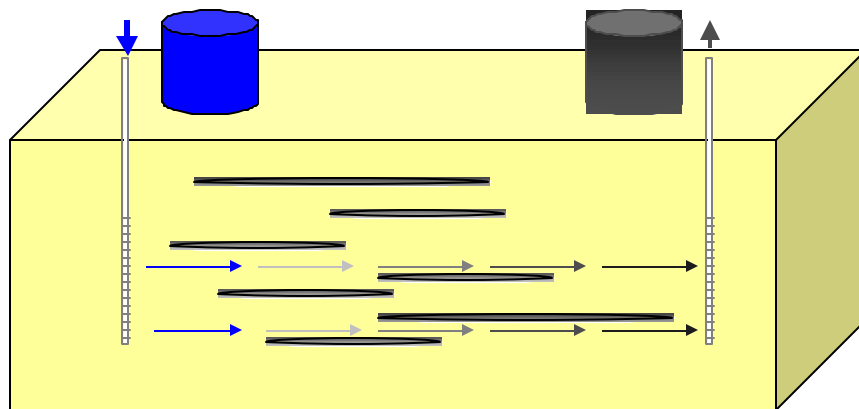


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1.0 Introduction

Over the last quarter century, the desire to clean up inadvertent releases of organic liquids has motivated the emergence of a host of innovative technologies. One of the first of these was surfactant flushing (e.g. API 1979; Sale et al., 1989; and Fountain et al., 1993). The underlying premise of surfactant flushing is that the same technology used to enhance production of oil from petroleum reservoirs can be adapted to recover nonaqueous phase liquids (NAPLs) from aquifers as an environmental remediation approach. To date, in excess of \$100,000,000 has been invested in this endeavor, including 37 field demonstrations. Of these, one project (Hill AFB OU2) is reported to have led to a large-scale application (Jackson 2005).

The objective of this report is to provide a screening-level analysis of the feasibility of using surfactant flushing at the Koppers, Inc. portion of the Cabot Carbon/Koppers Site, located in Gainesville, Florida (Site). The analysis of this potential application was conducted by Dr. Tom Sale, Colorado State University, at the request of GeoTrans Inc. and Beazer East, Inc. The report includes:

- Technology Description
 - o Mechanism of Enhanced Recovery
 - o Flushing Sequences
 - o Process Components
 - o History of Application
- Conceptual Application
 - o Design Basis
 - o Conceptual Design
 - o Estimated Cost
 - o Estimated Endpoint
- Conclusions

2.0 Technology Description

2.1 Mechanism of Enhanced Recovery

The primary target of surfactant flushing is NAPL trapped at residual saturations in porous media. NAPL entrapment is primarily a function of the size of the pores, the interfacial tension between the water and NAPL, and (with time) the degree of NAPL dissolution into the surrounding water. Figure 1 depicts a blob of residual NAPL trapped between soil grains.

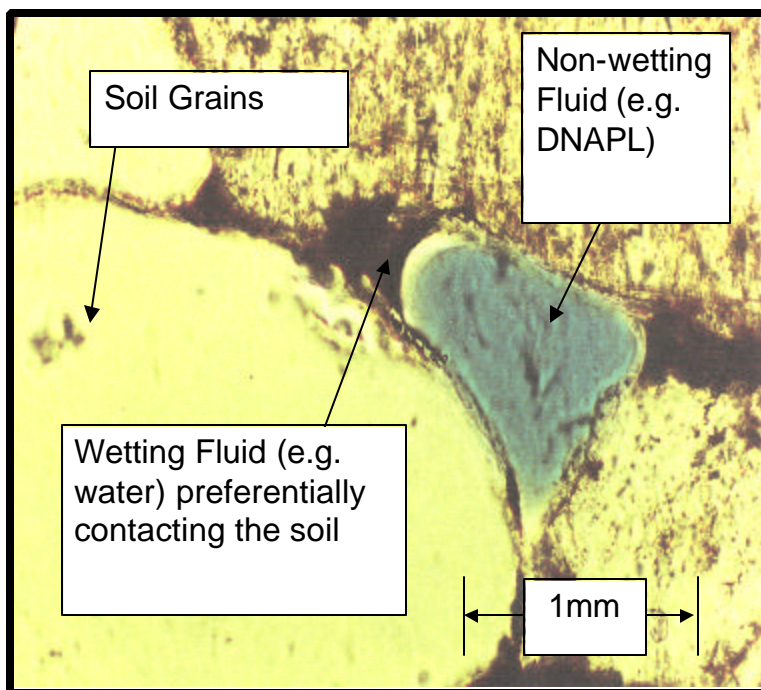


Figure 1 – Entrapped NAPL in porous media (After Wilson et al., 1990)

Surfactant flushing depletes entrapped NAPL through mobilization and/or enhanced dissolution. Compounds used to achieve these results are noted below.

2.1.1 Surfactants - Surfactant driven depletion of entrapped NAPL is achieved through reduction of interfacial tension (mobilization) and/or enhanced dissolution (solubilization). Reduction of interfacial tension is achieved through the addition of surface-active agents (surfactants) that accumulate at the interface between the NAPL and water. This is conceptualized in panel A of Figure 2. Reduced interfacial tension allows entrapped NAPL blobs to more easily distort and pass through narrow restrictions in the porous media. Unfortunately, this also has the potential to cause adverse vertical migration of Dense Nonaqueous Phase Liquids (DNAPL).

Enhanced solubilization occurs through the formation of surfactant micelles in the water. This is conceptualized in panels A and B of Figure 2. Dissolved NAPL constituents accumulate in the interior of the surfactant micelles enhancing the effective solubility of the NAPL constituents in water. The threshold surfactant concentration needed to form micelles is referred to as the critical micelle concentration (CMC).

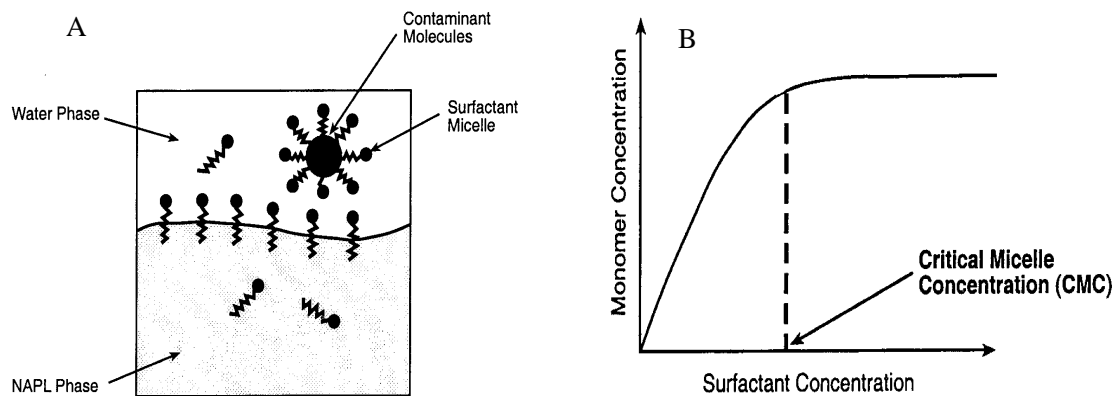


Figure 2 – A) Surfactant accumulation at the NAPL water interface and formation surfactant micelles in the aqueous phase. B) Critical concentration for formation of surfactant micelles in the aqueous phase. After Simpkin et al., (1966).

2.1.2 Alcohol - Alternatively, NAPL depletion can be accomplished by flushing alcohol (e.g. Falta 1996 and Lunn and Kueper 1996) or flushing combinations of surfactants and alcohol (Young et al., 2002) through the targeted media. Alcohol renders the water phase less polar, enhancing the solubility of the NAPL constituents in water, and modifies the density of the NAPL. Modified NAPL density is proposed as a means of reducing the potential for adverse downward migration of DNAPL.

2.1.3 Polymer - A primary challenge of delivering surfactants (and/or alcohol) to targeted media is the heterogeneous spatial distribution of permeability in aquifers. High permeability zones behave as preferred flow paths (“thief zones”) and frustrate efficient delivery of remedial fluids to target zones. A promising means of improving sweep efficiencies is the addition of polymers to increase the viscosity of the remedial fluids (e.g. Sale et al., 1989; Braun 1995; and Young et al., 2002).

Increasing the viscosity of the remedial fluids also improves pore-scale displacement of high viscosity NAPLs (Sale et al., 1989). This is particularly important when the NAPL has a high viscosity, as is the case with the DNAPL at the Site. Figure 3 presents a laboratory scale demonstration of improved sweep efficiency using polymer. Two important downsides of polymer addition are 1) it slows the rate of solution delivery and recovery, and 2) it makes post treatment displacement of the flushing solution and mobilized contaminants more difficult.

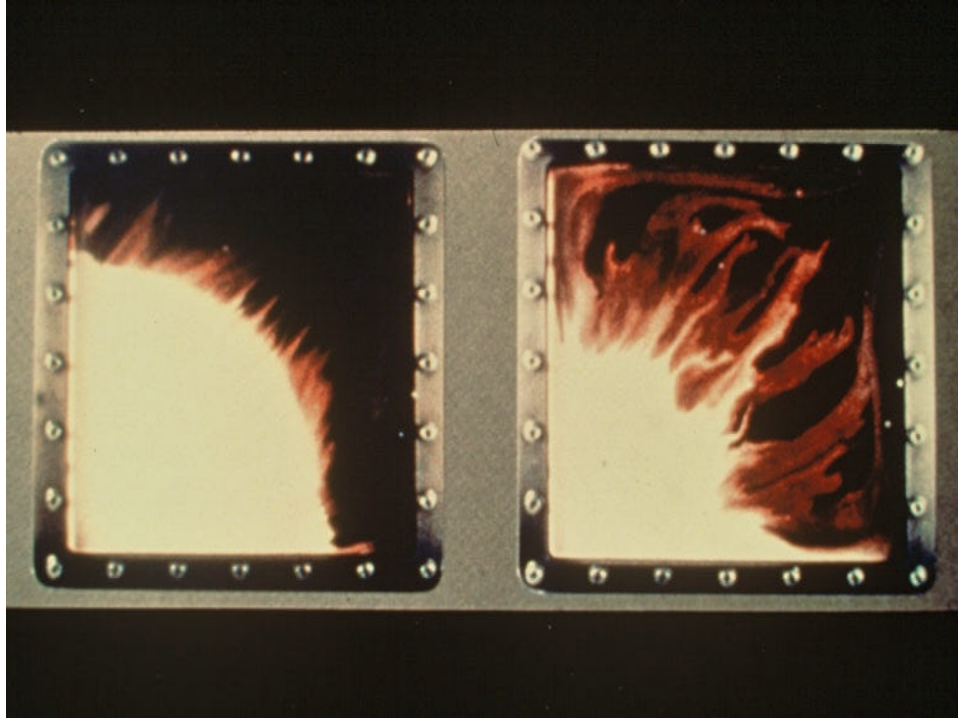


Figure 3 – Laboratory scale demonstration of improved sweep efficiency with addition of polymer to the displacing fluid. Left hand side with polymer, right hand side without polymer.

2.1.4 Salts - Surfactant systems can be optimized through the addition of salts, Two benefits can be achieved. First, reductions in interfacial tension can be optimized. Changes in ionic strength modify the degree to which the polar end of the surfactant is drawn into the aqueous phase and, correspondingly reduce interfacial tension between the fluids (Sale et al., 1989 and Simpkin et al., 1996). In addition, alkaline agents, such as sodium carbonate and sodium bicarbonate, increase solution pH. With select NAPLs, elevated pH can produce natural surfactants and beneficial reductions in interfacial tension.

The effect of the addition of surfactant, polymer, and salt is illustrated in Figure 4. The figure presents the cumulative percent of the initial NAPL saturation recovered from a laboratory radial flow core flood study as a function of the remedial fluids passing through the core. The largest increase in recovery comes with the addition of surfactant. The difference between total recovery and free phase (NAPL) recovery is the fraction of NAPL that was removed by solubilization.

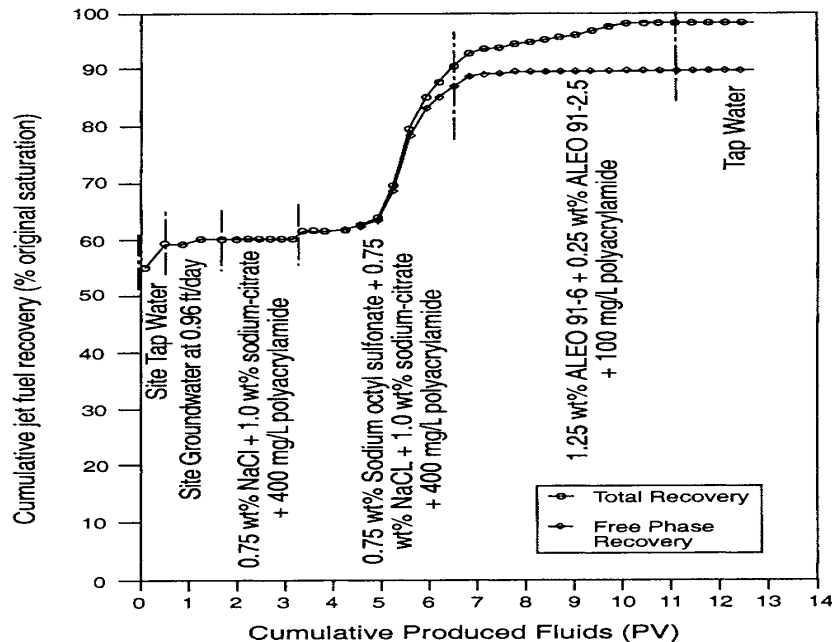


Figure 4 –Percent recovery of jet fuel from a laboratory scale radial core flood as a function of cumulative pore volumes and flushing solution. The sodium octyl sulfonate solution removes jet fuel primarily by displacement. The ALEO 91-6 solution removes jet fuel primarily by dissolution. Simpkin et al., (1996).

2.2 Flushing Sequences

As shown in Figure 4, surfactant flushing typically involves delivery of a sequence of solutions. Common steps include:

1. **Pre-flushing the target with water** – Initially, it is common to flush anywhere from one to tens of pore volume of water through the target as a pre-flush. Benefits can include recovering mobile NAPL, preconditioning the aquifer to optimize the effectiveness of the subsequent flushing, and/or testing of fluid delivery-recovery systems.
2. **Enhanced recovery of NAPL** – Typically one to four pore volumes of a chemical system containing combinations of surfactants, alcohols, polymers, and salts are delivered. This achieves the primary objective of depleting NAPL through mobilization and/or solubilization.
3. **Aquifer reconditioning** – After the treatment the target is full of mobilized NAPL and the chemicals employed to enhance NAPL recovery. This material is displaced by flushing water through the targeted volume. This can involve anywhere from a few to tens of pore volumes of water.

2.3 Process Components

Field implementation of surfactant flushing requires the following process components:

- 1) Facilities for storage of raw material (e.g., surfactants, alcohol, polymer, salts)
- 2) Systems to mix, filter, and meter remedial fluid solutions
- 3) Above ground transmission systems and below ground wells or drains for delivery of remedial fluid solutions to the subsurface target
- 4) Below ground wells or drains and above ground transmission systems for recovery of fluids from the subsurface target
- 5) Systems to treat recovered fluids
- 6) Facilities to manage process related waste streams

Figure 5, 6 and 7 provide illustrations of the above items. A key attribute of surfactant flushing is the substantial above and below grade infrastructure requirements. Operation and maintenance of the noted components require a corps of qualified operators. Process infrastructure and labor force are substantial cost drivers for the technology.

An important concept introduced in Figure 7 is the potential for reuse of portions of the recovered fluids. The primary purpose of reusing recovered fluids is to reduce raw material costs.

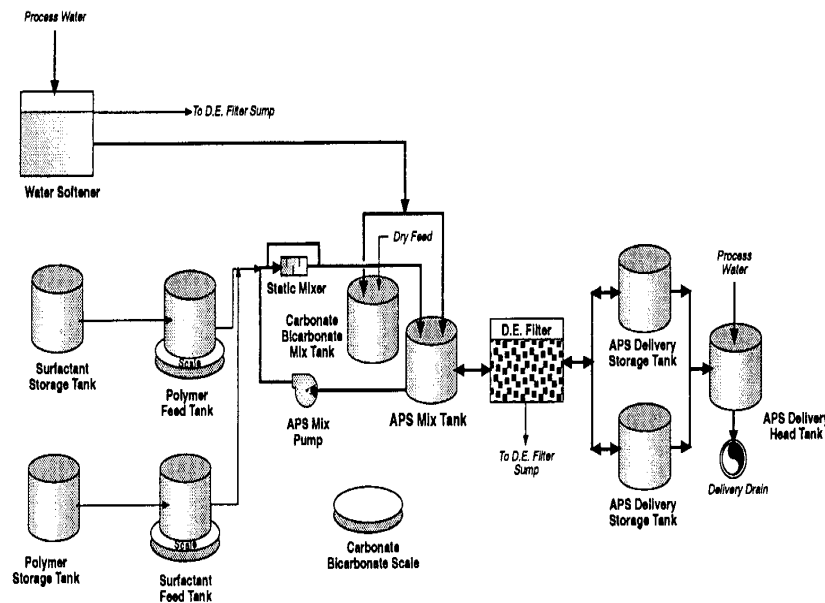
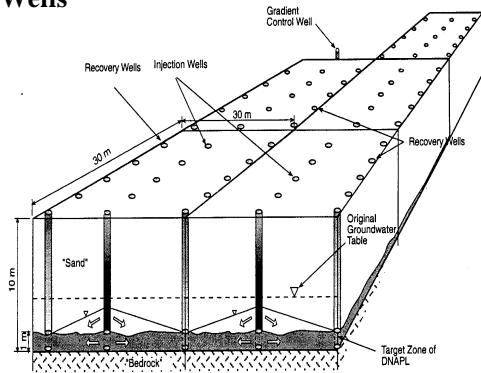


Figure 5 – Process diagram for storage and preparation of flushing solutions, Simpkin et al., (1996)

Wells



Drainlines

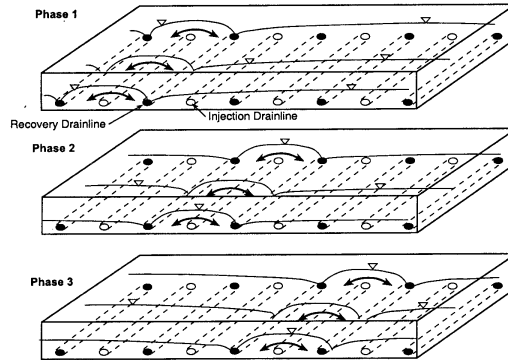


Figure 6 Subsurface approaches for delivery and recovery of flushing solutions, Simpkin et al., (1996)

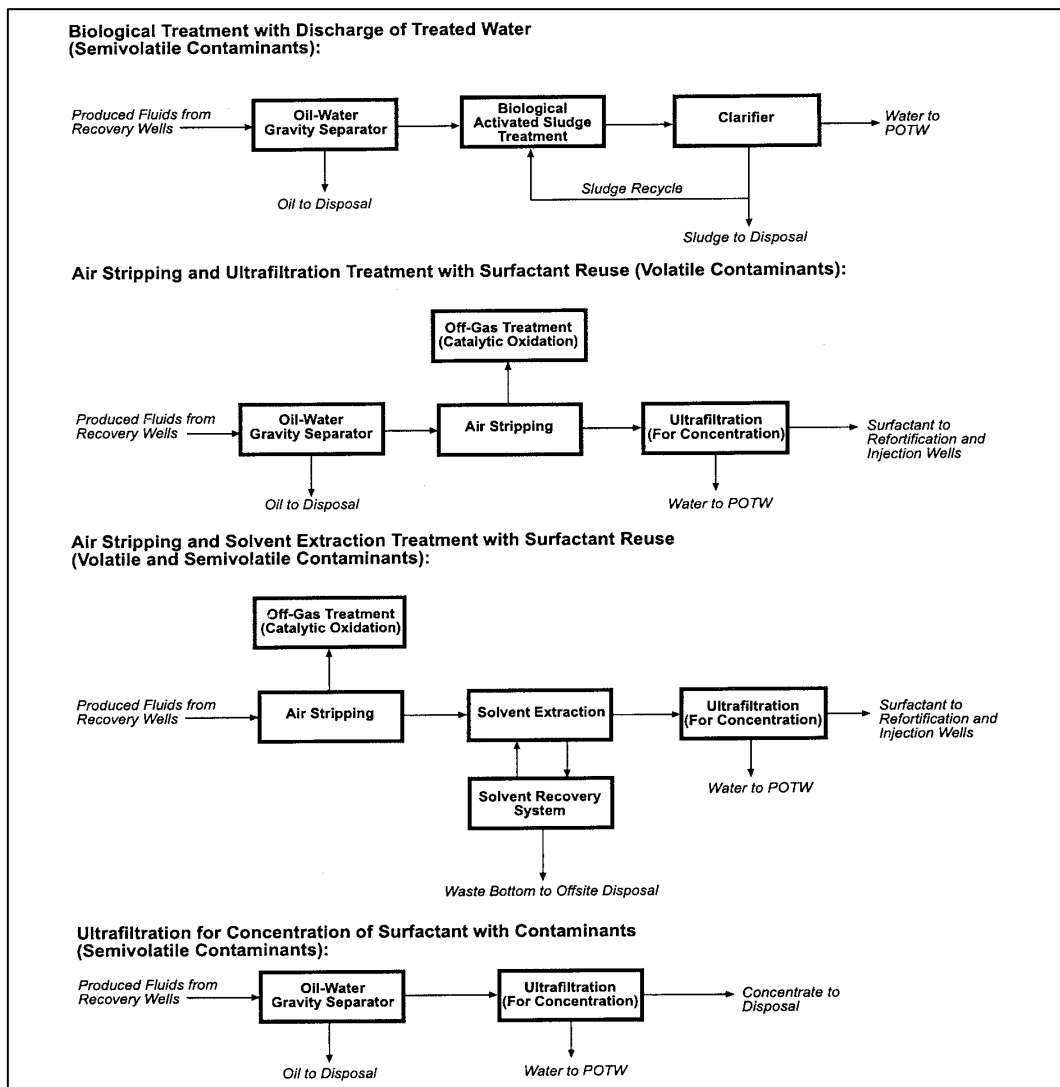


Figure 7 – Options for management of produced fluids, Simpkin et al., (1996)

2.4 History of Application

Primary references summarizing development and testing of surfactant enhanced aquifer remediation include Simpkin et al., (1996), NFESC (2002), and NRC (2005). Figure 8 lists field demonstrations identified in Simpkin et al., 1996. Figure 9 presents demonstrations described in NRC 2005. Figure 10 presents recent projects identified in other references. Based on these projects, the following presents a basis for evaluating the potential efficacy and cost of surfactant flushing at the Site.

<i>Project</i>	<i>Field Completion Date</i>
Laramie, Wyoming—Small-Scale Field Demonstration	9/88
Warren, Michigan	7/89
Laramie, Wyoming—Large-Scale Field Demonstration	12/89
Hialeah County, Florida	2/90
Canadian Forces Base, Borden, Ontario—3-Meter Cell—PCE	11/90
Fredricksburg, Virginia	12/90
Corpus Christi, Texas	2/93
Paducah, Kentucky	8/94
Quebec City, Quebec	10/94
L'Assomption, Quebec	12/94
Commercial Site, New Jersey	1/95
Delmont Station, Pennsylvania	1/95
Hill AFB, Utah—Ethanol OU 1	8/95
Traverse City, Michigan	8/95
Picatinny Arsenal, New Jersey	8/95
Canadian Forces Base Borden, Ontario—Gasoline	12/95
Saint Herblain, France	1/96
Hill AFB, Utah—Surfactant with Cosolvent OU 1, Cell No. 8	8/96
Hill AFB, Utah—Complexing Sugar OU 1, Cell No. 4	8/96
Hill AFB, Utah—Surfactant Mobilization, OU 1, Cell No. 6	8/96
Hill AFB, Utah—Surfactant Solubilization, OU 1, Cell No. 5	8/96
Hill AFB, Utah—OU 1, Cell No. 3	9/96
Hill AFB, Utah—OU 2, Micellar Flood	9/96
Shawnee, Oklahoma	9/96
Piketon, Ohio	10/96
Lake Charles, Louisiana	3/97
Hill AFB, Utah—OU 2 Foam Flood	5/97
Canadian Forces Base Borden, Ontario—0.76 m Cylinder—PCE	9/97
Oklahoma City, Oklahoma	10/97

Figure 8 – Surfactant cosolvent projects completed 1988-1997 (Simpkin et al., 1996)

TABLE 5-2 Summary of Well-Designed Field Tests of Surfactant and Cosolvent Flooding

Year	Location/Additive	Geology	NAPL	Swept Pore Volume (m ³)	Reduction in NAPL Mass (%)	Post-NAPL Saturation (%)	Reference
1991	Borden, Ontario 14 PV, 2% Surf.	Sand	PCE	9.1	77	0.2	Fountain et al., 1996
1994	L'Assomption, Quebec 0.9 PV, Surf./Alcohol/Solvent	Sandy Gravel	DNAPL	6.1	86	0.45	Martel et al., 1998
1995	Hill AFB, UT, OU1 9 PV, 82% Alcohol	Sandy Gravel	LNAPL ^a	4.5	85	0.9	Rao et al., 1997
1996	Hill AFB, UT, OU1 9.5 PV, 3% Surf. / 2.5% Alcohol	Sandy Gravel	LNAPL ^a	4.5	78	0.8	Jawitz et al., 1998
1996	Hill AFB, UT, OU1 6.5 PV, 4.3% Surf.	Sandy Gravel	LNAPL ^a	4.5	86	0.4	Knox et al., 1999
1996	Hill AFB, UT, OU2 2.4 PV, 8% Surf.	Sand	DNAPL	57	99	0.03	Brown et al., 1999
1996	Hill AFB, UT, OU1 4 PV, 95% Alcohol	Sandy Gravel	LNAPL ^a	4.5	80	0.4	Falta et al., 1999
1997	Hill AFB, UT, OU2 4% Surf. & Foam	Sand	DNAPL	31	90	0.03	Szafranski et al., 1998
1999	Camp Lejeune, NC 5 PV, 4% Surf.	Silt	PCE	18	72	0.5	Holzner et al., 2000
1999	Alameda Point, CA 6 PV, 7% Surf.	Sand	DNAPL	32	98	0.03	Hasegawa et al., 2000
1999	Pearl Harbor, HI 10 PV, 8% Surf.	Volcanic Tuff	Fuel Oil	7.5	86	0.35	Dwarakanath et al., 2000
2000	Hill AFB, UT, OU2 2.4 PV, 4% Surf.	Sand	DNAPL	188	94	0.07	Meimardus et al., 2002

NOTE: PV = pore volume; Surf = surfactant

^aLNAPL means an LNAPL with sufficient DNAPL components present, such that in the absence of the LNAPL, the waste would be a DNAPL.

Figure 9 – NRC (2005) list of “well-designed” field tests

Year	Site	NAPL	Cubic Yards	Reference
1997	Sages Dry Cleaner Site, FL	PCE	30	USEPA (2003)
2000 ¹	Bachman Road, MI	PCE	10	USEPA (2003)
2002 ¹	Viginia Beach, VA	TCA	Small	ESTCP CU-0113
2001 ¹	Bloomington, Ill	MGP	30	Young et al., 2002

1) Estimated

Figure 10 – Recent projects identified in other references

2.4.1 Characteristics of Demonstrations

Figure 11 describes the hydrogeologic setting and targeted contaminants for 29 of the 37 field demonstrations shown in Figures 8-10. As shown, the vast majority of the demonstrations occurred in sands and/or gravels. This reflects the need to be able to readily deliver and recover fluids from the targeted media. Of the remaining sites in Figure 11 (sites with sandy silts, silty clays, and fractured media) only one achieved significant recovery of the targeted contaminant (Camp

Lejeune 72% per Figure 9). This information demonstrates that transmissive sands and/or gravels are the most amenable to surfactant flushing.

Also shown in Figure 11 are the targeted contaminants. In all cases the target is a NAPL. Three of the sites, Laramie, Fredricksburg and Bloomington, involved high molecular weight dense DNAPL similar to those present at the Site.

An important limitation of the noted demonstrations is that they are not full-scale projects. As shown in Figure 12, the median size of the demonstration area is 37 cubic yards. This is equivalent to a 10 by 12 foot room with a standard ceiling. As a point of reference, this represents less than 0.01% of the site's estimated Surficial Aquifer target volume described in Section 3.1.1 of this report. Of the noted projects only Hill AFB OU2 (as reported by Jackson, 2005), has led to a significant large-scale application.

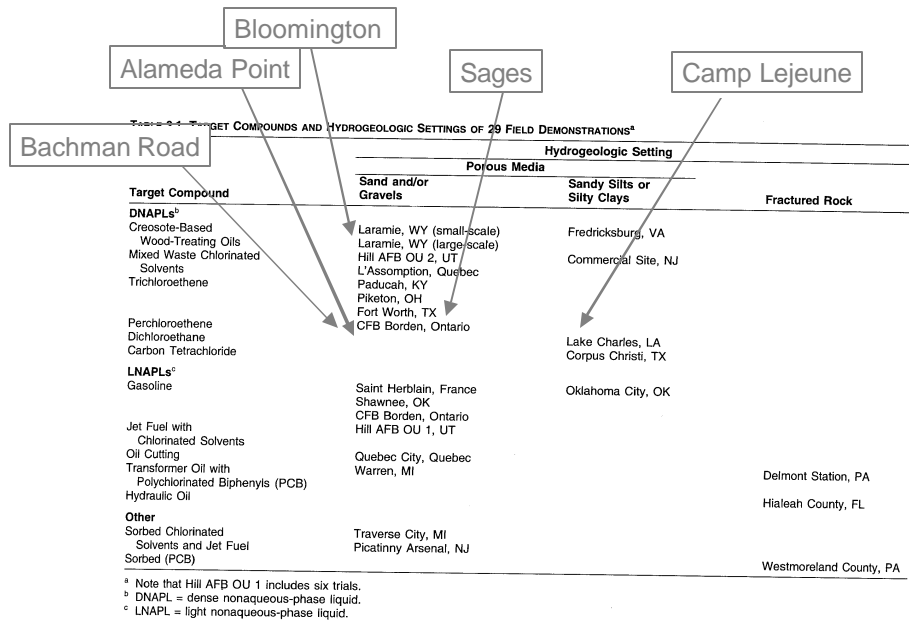


Figure 11 – Hydrogeologic settings and target contaminants from Simpkin et al., 1996. Site in the boxes were completed post 1996. Arrows point to the settings in which the demonstrations were conducted

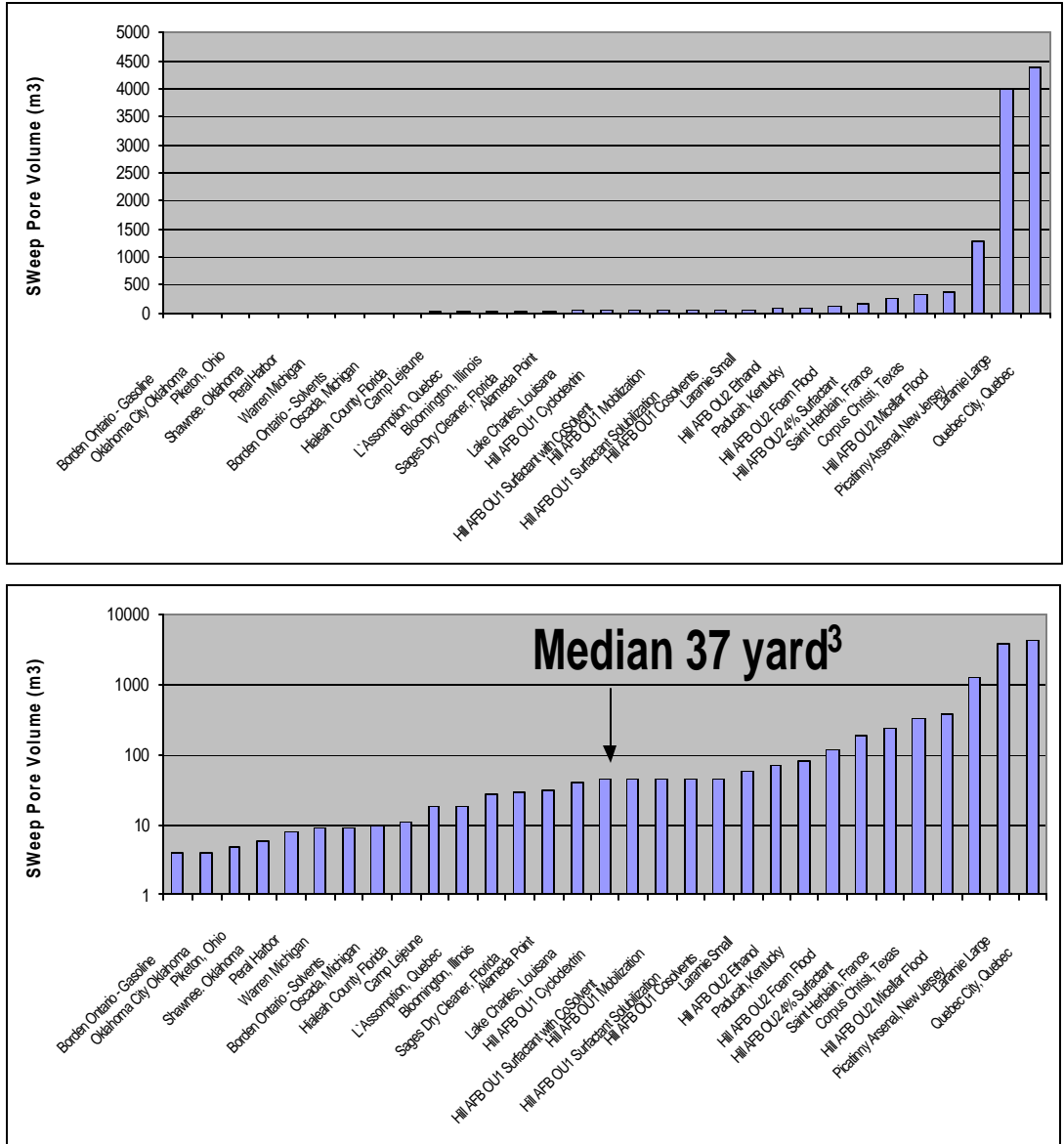


Figure 12 – Size of demonstrations

2.4.2 Efficacy

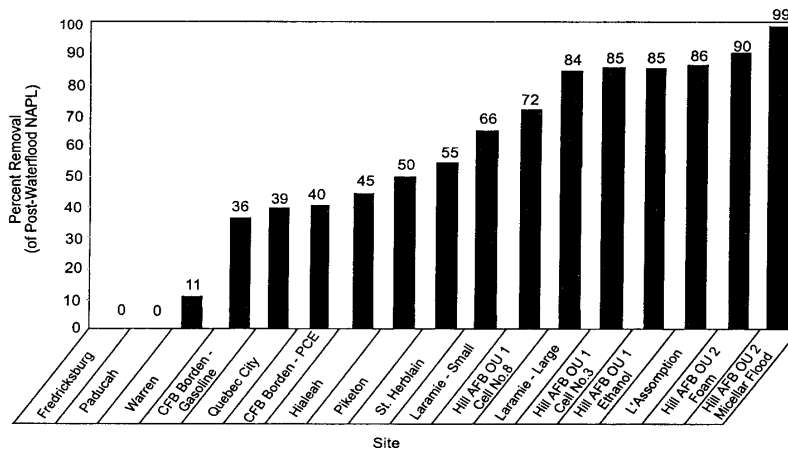
Performance metrics for surfactant flushing include:

- 1) Remaining contaminant mass or volume
- 2) Fractional depletion of the initial contaminant mass
- 3) Post-treatment contaminant concentrations in groundwater

- 4) Mass of flushing chemical (surfactant, polymer, and salt) remaining in the target post flushing
- 5) Redox state of the treated zone

Figure 9 and Figure 13 include estimates of fractional depletion of contaminant mass, remaining contaminant volume, and remaining contaminant mass. In Figure 9, the average depletion and remaining contaminant volume (NRC best projects) is 86% and 0.35% of pore space, respectively. Assuming 1% of pore space is ~ 1000 mg/kg, 0.35% of pore space is roughly equivalent to a concentration of 350 mg/kg.

A) Percent Removal of Targeted NAPL



B) Endpoint Soil Cocentrations

Project	Soil Concentrations
Laramie, Wyoming—Small-Scale Field Demonstration	Average 5,100 mg/kg
Laramie, Wyoming—Large-Scale Field Demonstration	Average 4,000 mg/kg Range 300 to 11,000 mg/kg
Quebec City, Quebec	Average 19,000 mg/kg
L'Assomption, Quebec	Average 4,500 mg/kg Range 10 to 10,000 mg/kg
Hill AFB, Utah: OU 2 Foam	Average 2,800 mg/kg Range 100 to 31,000 mg/kg
Hill AFB, Utah: OU 1 Ethanol	Average ~ 100 mg/kg ^a
Hill AFB, Utah: OU 1 Cosolvents, Cell No. 3	Average ~ 1,000 mg/kg ^a
Hill AFB, Utah: OU 1 Surfactant Mobilization, Cell No. 6	Average ~ 100 mg/kg ^a
Hill AFB, Utah: OU 1 Surfactant Solubilization, Cell No. 5	Average ~ 1,000 mg/kg ^a
Hill AFB, Utah: OU 1 Surfactant with Cosolvent, Cell No. 8	Average ~ 100 mg/kg ^a

^a Total concentrations were estimated using measurements of select analytes in soil and their overall mass fraction in the NAPL.

Figure 13 – A) Percent removal of targeted NAPL and B) Endpoint soil concentrations. After Simpkin et al., (1996).

Based on Figure 13 the average reported depletion is 55% and the average endpoint (excluding the Hill AFB OU2 data) is 7,000 mg/kg. Typically, concentrations of this magnitude indicate that substantial fractions of the pore space remains filled with NAPL post treatment. Far lower endpoint soil concentrations at Hill AFB OU2 reflect low initial contaminant levels (near zero NAPL).

In summary, while substantial depletion has been achieved, significant contaminant mass will remain. Data from Camp Lejeune suggests that 72% depletion could be achieved leaving 28% of the targeted NAPL in place. The most optimistic scenario using the remaining data suggests no higher than 90% depletion with 10% of the targeted NAPL left in place.

The remaining performance metrics are more difficult to evaluate. Concerning measurements of post-treatment contaminant concentrations in groundwater, there is no known published data supporting dramatic improvements in groundwater quality following surfactant flooding. Nevertheless, two general observations regarding groundwater can be drawn. First, as long as NAPL remains, concentrations of targeted contaminants will likely remain above drinking water standards. Secondly, residual flushing solution chemicals (e.g., surfactant, salts, and polymer) are likely to make the water unsuitable for potable use for an extended period.

Regarding remaining concentrations of flushing solutions, the only known data describing retained surfactant, polymer, and salt, comes from the Large-Scale Laramie Demonstration. This data (presented in Figure 14), indicates that post aquifer reconditioning (water flooding), thousands of pounds of reagent will remain per acre-foot of targeted media. Recognizing that much of this material is readily biodegradable, post treatment conditions are likely to be highly reduced. This raises two general concerns. First, the depletion of available electron acceptors may diminish the degree to which natural attenuation is limiting migration of dissolved phase contaminants. Secondly, naturally occurring metals can be mobilized under reduced conditions.

Table D-8
CHEMICAL CONSUMPTION/UNIT VOLUME TREATED

<u>Chemical</u>	<u>Total Consumption (lbs)</u>	<u>Consumption/ Unit Volume Treated (lbs/acre-foot)</u>
Polymer	2,294	1,604
Surfactant	13,498	9,439
Alkali (as total carbon)	4,944	3,457

Figure 14 – Large Scale Laramie Demonstration (CH2M HILL 1990)

2.4.3 Cost

Available cost estimates for surfactant flushing (field demonstrations and hypothetical scenarios) are presented in Figure 15 and McDade et al., (2005). Critical limitations of the cited cost information is that none of it comes from large-scale applications and, as noted below, conditions are generally more favorable than those at the Site.

The mean value from the Figure 15 data is \$314 per cubic yard of treated media. In terms of a target NAPL, the estimate of \$234 per cubic yard from the Laramie site is a potentially applicable value. Updating this 1990 cost to 2005 dollars, this cost equates to \$349 per cubic yard. Unfortunately, the Laramie site hydraulic conductivity values are three orders of magnitude greater than those of the Surficial Aquifer at the Cabot Carbon/Koppers site. Therefore, the Laramie site is not representative based on its hydrogeologic setting.

In terms of similar hydrogeologic settings, the estimate of \$500 per cubic yard from Camp Lejeune is more representative. Note the lower value of \$165 per cubic yard for Camp Lejeune reflects an optimized system based on a higher hydraulic conductivity.

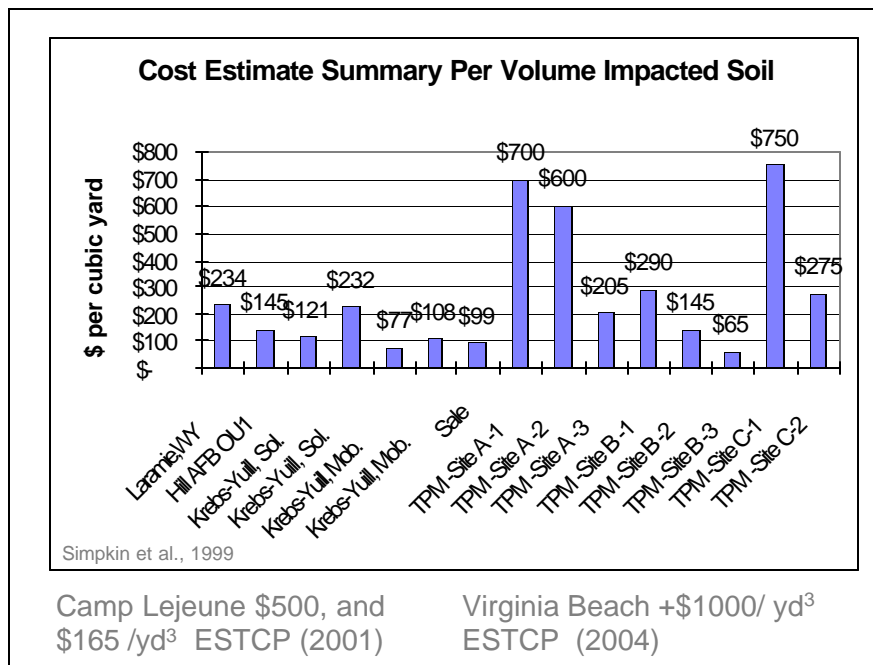


Figure 15 - Available cost data from Simpkin et al., 1996 and ESTCP projects

Additional cost estimates are presented in McDade et al., (2005). One of the projects cited in McDade et al., (2005), Hill AFB OU2, \$171 per cubic yard, is potentially reflective of full-scale application costs. Relative to the Site, this cost is biased low by the relative simplicity of treating chlorinated solvents and the presence of pre-existing systems for management of produced fluids.

From the above, the following cost basis is drawn:

- 1) The best case cost for surfactant flushing at the Site should be no lower than \$228 per cubic yard treated. This is the average of the Laramie, Low Camp Lejeune, and OU2 costs. Note each of these estimates are optimistic relative to the Cabot Carbon/Koppers site due to more favorable hydraulic conductivity values and/or contaminant type.
- 2) More conservative, the cost for surfactant flushing at the Cabot Carbon/Koppers site could be as high as \$500 per cubic yard treated. This reflects the full-scale cost estimate developed for the Camp Lejeune project.

2.4.4 Potential for Adverse Impacts

A primary tenet of any environment remediation approach is to not make conditions worse. Potential adverse impacts of surfactant flushing include:

Adverse vertical migration of DNAPL - This can be induced through reductions in interfacial tension and/or borings that breach barriers that perch DNAPL.

Adverse vertical migrations of dissolved phase DNAPL constituents – Introduction of borings through aquitards may create pathways for vertical migrations of dissolved DNAPL constituents.

Mobilized contaminants and residual flushing compounds – Following surfactant flushing, large amounts of delivered chemicals and mobilized NAPL will remain in the targeted sediments. These materials may pose environmental challenges equal to or greater than the initial NAPL in place.

3.0 Conceptual Application

Further analysis of the utility of applying surfactant flushing at the Site is achieved by developing a conceptual application for the Surficial Aquifer. This begins by developing a preliminary design based on pertinent site attributes. Then process components are identified. Finally, estimates of cost and performance are provided. As documented in Section 3.1.5, surfactant flushing in the Hawthorn Group is not feasible due to the low permeability of the formation. Therefore a development of surfactant flushing for the Hawthorn Group is not presented.

3.1 Design Basis

3.1.1 Target Volume

Figure 16 presents geologic data from the Site in a cross-section view. The estimated average thickness of the Surficial Aquifer that would be flushed is 25 feet. This assumes a vertical target of 20 feet plus an additional five feet (on average) of saturated zone that would be needed to drive the flushing solution through the target. Figure 17 presents the estimated target area for surfactant flushing in plan view for the Surficial Aquifer at the Site. The approximate area is 10 acres. Coupling both areal extent and depth, Table 1 presents an estimate of the volume of material that would be targeted in the Surficial Aquifer. Note these volumes are the same as those described in Haley and Aldrich, Inc. (2006). The only difference is the basis for the 25-foot vertical height of the target. In the case of Haley and Aldrich, Inc. (2006) a 20-foot target height is assumed and an additional 5 feet is added to reflect heating the upper Hawthorn Group.

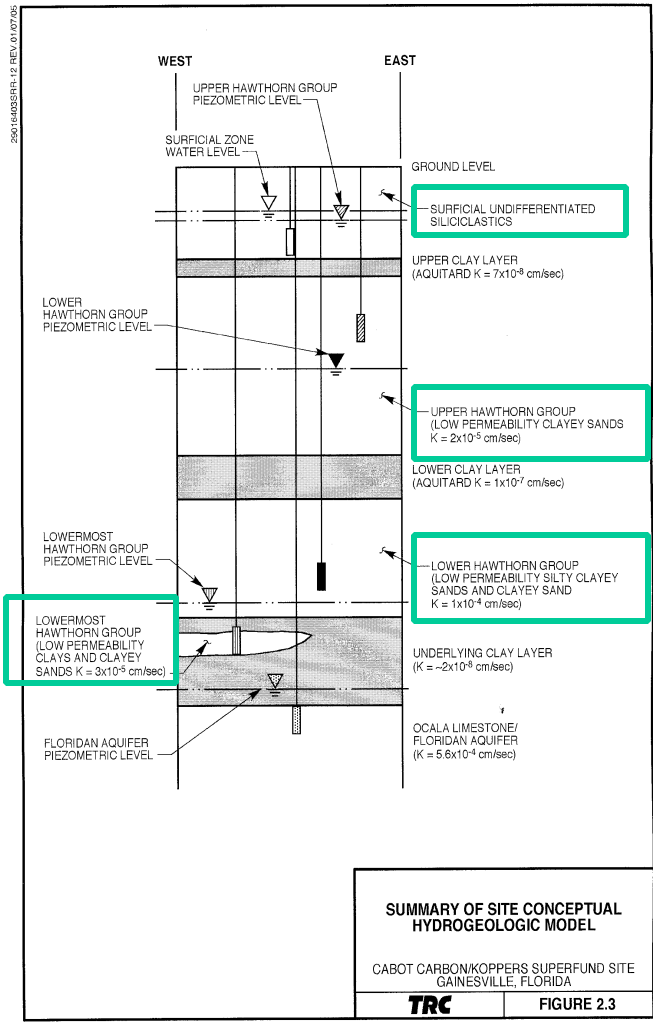


Figure 16 – Hydrostratigraphic units

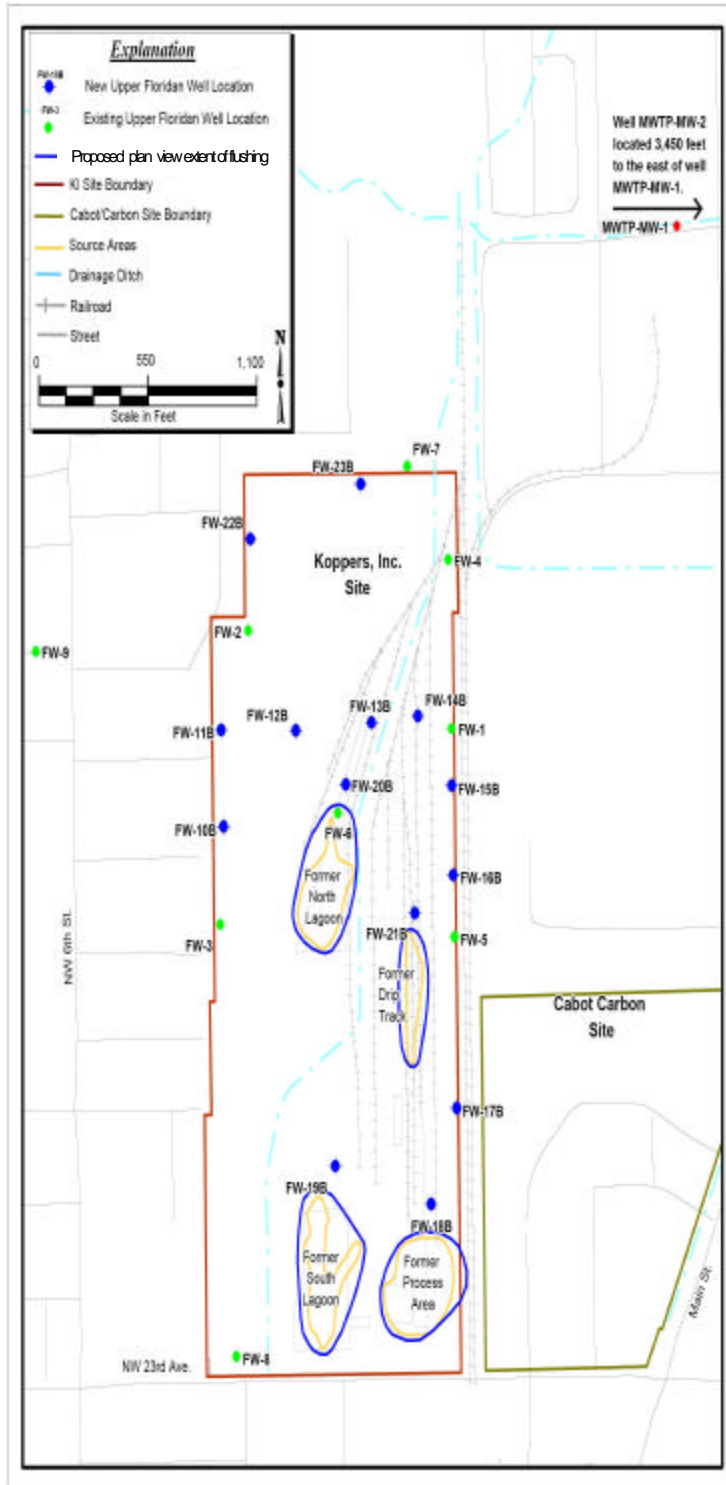


Figure 17 – Plan view extent of targeted areas

	Treatment Area (ft ²)	Thickness of sediments that would be addressed (ft)	Treatment Zone Volume (yards ³)
Former North Lagoon Area	117,000	25	110,000
Former South Lagoon Area	138,000	25	128,000
Former Process Area	122,000	25	113,000
Former Drip Track	56,000	25	52,000
Total			403,000

3.1.2 Flushing Solution Composition

Specific chemical solutions for surfactant flushing applications are typically designed through laboratory treatability studies. For the purpose of this analysis it is assumed that the chemical system developed for the Bloomington site (Young et al., 2002) would be appropriate for the Cabot Carbon/Koppers site. Specific chemical components are presented in Table 2. Selection of the chemical system of Young et al., (2002) reflects a similar target NAPL and the current, “up-to-date”, basis of their work.

Component	Fraction on a Weight Basis
Surfactant	0.04
Polymer	0.08
Alcohol	0.0013
Salt	0.0008

3.1.3 Pore Volume

The basis volume unit for surfactant floods is the volume of pore space in the sweep zone. Given a porosity of 0.2 (GeoTrans Inc., 2004) and the estimated target volume of 403,000 cubic yards, one pore volume is 16 million gallons.

3.1.4 Flushing Sequence

The following sequence of fluid delivery is assumed:

- A ten pore volume preflush with water to recover mobile DNAPL (if present) and to precondition the aquifer. This is predicated on the Large Scale Laramie Demonstration, CH2M HILL (1990).
- Three pore volumes of the Table 2 solution. This is based on Young et al., (2002).
- Ten pore volumes of post treatment aquifer reconditioning (After CH2M HILL 1990). Ideally this would involve a polymer concentration taper to optimize displacement of mobilized NAPL and flushing solution chemicals (CH2M 1990).

3.1.5 Time to Deliver One Pore Volume

The time to deliver one pore volume is primarily a function of permeability of the targeted materials, the driving head, spacing between delivery and recovery systems, and the viscosity of the flushing solutions. Appendix A presents the approach used to estimate the time to deliver one pore volume to a targeted volume using horizontal drainlines. Assumed inputs to the calculations are:

- Permeability values for the Surficial Aquifer and underlying units of the Hawthorn Group presented in Table 3. Note Hawthorn Group values are included for screening analysis.
- An assumption that the driving head would be limited to 10 feet. This is based on the approximate thickness of the unsaturated zone in the Surficial Aquifer.
- An assumed solution viscosity of 50 centipoise. This is based on the premise of needing a favorable mobility ratio between the flushing fluid and the DNAPL.

Building on this input, Figure 19 presents estimates of the time required to deliver one pore volume as a function of spacing between delivery and recovery systems. Given pragmatic spacings of 20–60 feet in the Surficial Aquifer, time to deliver one pore volume of flushing solution through the target falls in the range of 10 to 100 days¹. Given this, from a hydraulic perspective, the entire delivery

¹ Note: actual times may be significantly greater than those described above due to heterogeneous distributions of permeability and/or with use of wells.

sequence might be completed in a period of 100 to 1000 days. In this case, the time to complete surfactant flushing in the Surficial Aquifer is more likely to be defined by the capacities of system components (e.g., tanks, pumps, treatment systems).

In the case of the Hawthorn Group units, assuming a minimum practical spacing of 20 feet, the time to deliver one pore volume of flushing solution is in excess of 1,000 days (~ 3 years). The time to deliver three pore volumes of the flushing solution, plus the pre- and post- flushing solutions would likely be well in excess of 10 years. Operating a surfactant flushing system for this period of time is viewed as unfeasible. Also, a spacing of 20 feet between wells would require approximately 1,000 wells (10 acres/ 20ft x 20ft/well).

Time estimates alone determine that surfactant flushing is not a viable solution for DNAPL in the Hawthorn Group. Furthermore, breaching the varying layers in the Hawthorn Group that constrain downward migration to deeper aquifers at 1,000 locations (e.g. Figure 18) seems imprudent. Given the large vertical gradients, far more harm might be achieved from surfactant flushing in the Hawthorn Group than benefit.

Units	K - Hydraulic Conductivity (cm/sec)	k - Permeability (m ²)	Sediment Description
Surficial	7×10^{-3}	7×10^{-12}	Fine to medium-grained sand with thin layers of interbedded silts and clay
Upper Hawthorn Group	2×10^{-5}	2×10^{-14}	Clayey sands
Lower Hawthorn Group	1×10^{-4}	1×10^{-13}	Silty clayey sands and clayey sand
Lowermost Hawthorn Group	3×10^{-5}	3×10^{-14}	Clays and clayey sands

Table 3 – Estimated hydraulic conductivity and permeability values from TRC (2005)

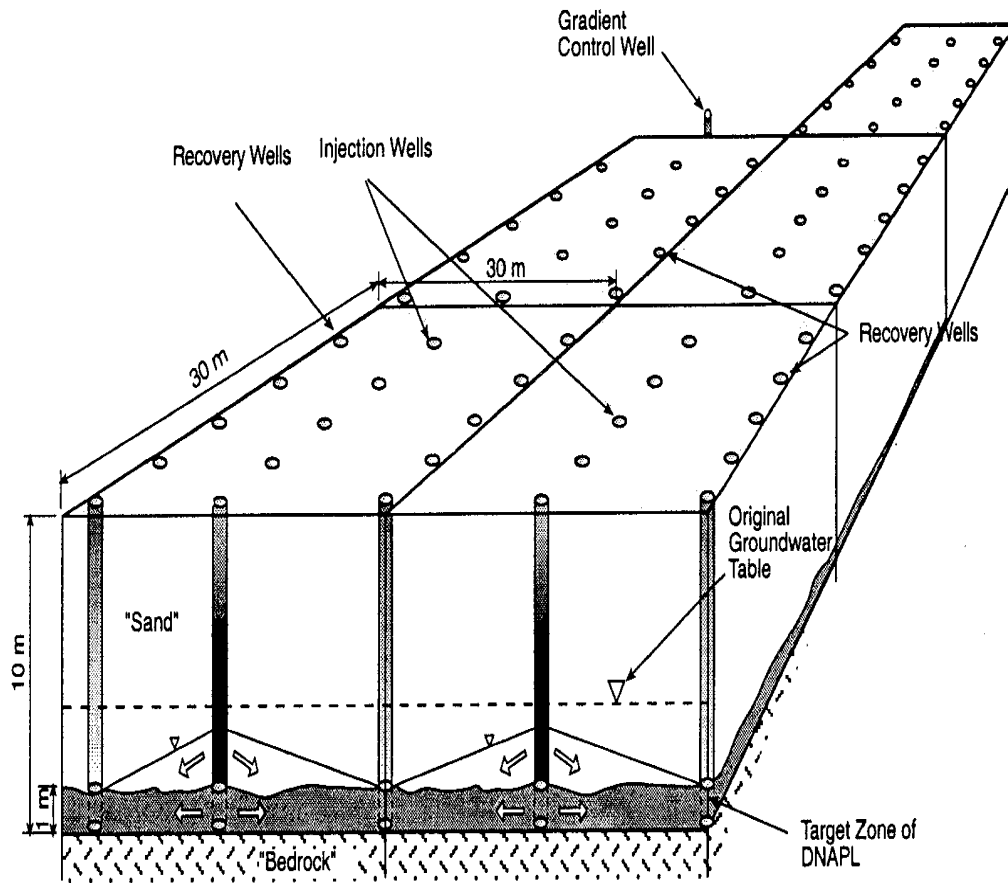


Figure 18 – Well based delivery recovery system

From Simpkin et al., 1999

$$\begin{aligned}
 c_p &:= \frac{1 \cdot \text{poise}}{100} & \mu_f &:= 50 \cdot c_p & \phi &:= 0.2 & \rho_f &:= 1 \cdot \frac{\text{gm}}{\text{cm}^3} \\
 S_p &:= 10 \cdot \text{ft}, 11 \cdot \text{ft}.. 90 \cdot \text{ft} & t_p(k, \Delta h, S_p) &:= \frac{\phi \cdot S_p^2 \cdot \mu_f}{k \cdot \rho_f \cdot g \cdot \Delta h}
 \end{aligned}$$

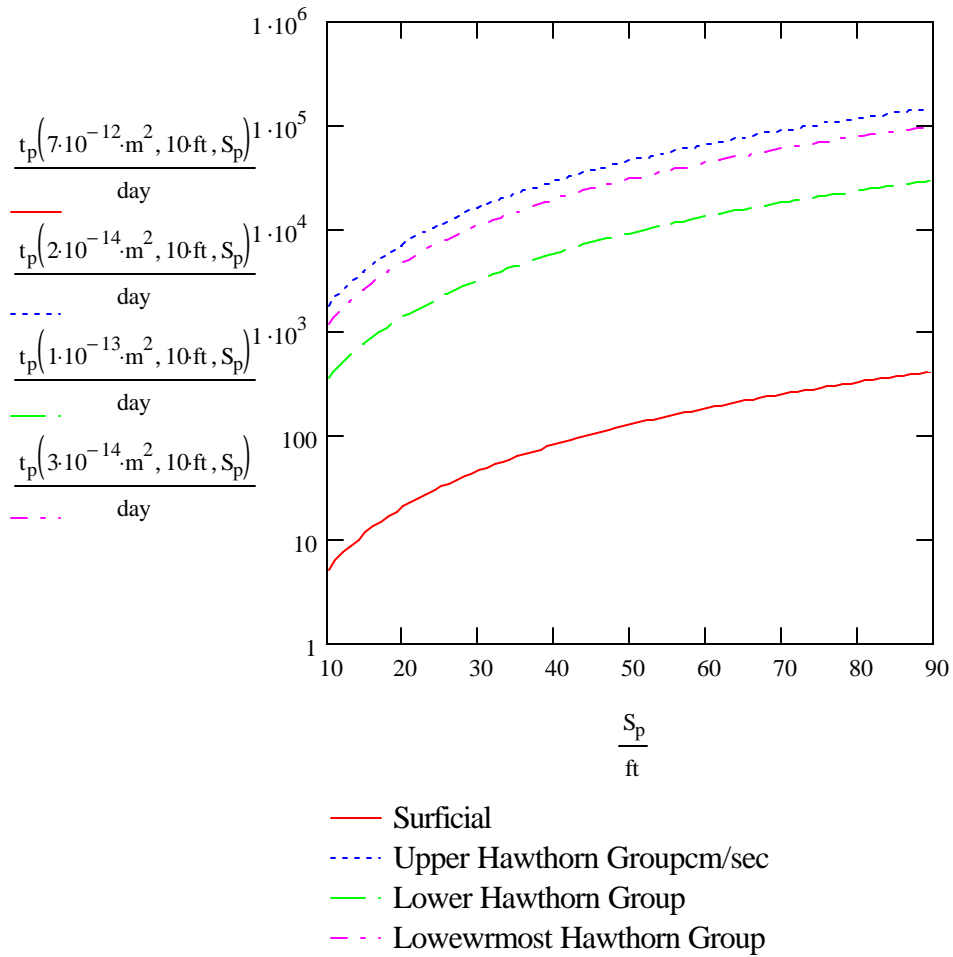


Figure 19 – Idealized time to flush one pore volume through a targeted section of an aquifer using horizontal drainlines (per Appendix A)

3.1.6 Masses and Capacities

Figure 20 presents estimated masses of chemicals and the volume of fluids potentially required for a full-scale application of surfactant flushing in the Surficial Aquifer at the Site. This indicates that a total of 25,000 tons (50 million lbs) of chemical would need to be delivered into the Surficial Aquifer. This would include 8,000 tons of surfactant, 16,000 tons of alcohol, 265 tons of polymer and 163 tons of calcium chloride. In total, approximately 212 million gallons of fluid would need to be prepared, delivered, recovered, treated and appropriately discharged. Given targets for completion of 1 and 10 years, capacities of all process components would be on the order of 0.6 to 0.06 million gallons per day (mgd). (To put this in perspective, a 0.6 million gallon per day wastewater treatment plant typically serves ~ 6,000 people.)

Basis Calculations

Inputs Values reflect Bloomington Site (Young et al., 2002)

SurfactantFrac := 0.04 BuytlAlcoholFrac := 0.08 PolymerFrac := 0.0013 CaCl2Frac := 0.0008

PreflushPV := 10 TreatmentPV := 3 PostTreatmentPV := 10

Site characteristics reflect TRS (2005)

$f := 0.2$ $K_w := 7 \cdot 10^{-3} \cdot \frac{\text{cm}}{\text{sec}}$ TargetVolume := 403000 · yd³ $r_w := 1 \cdot \frac{\text{gm}}{\text{cm}^3}$

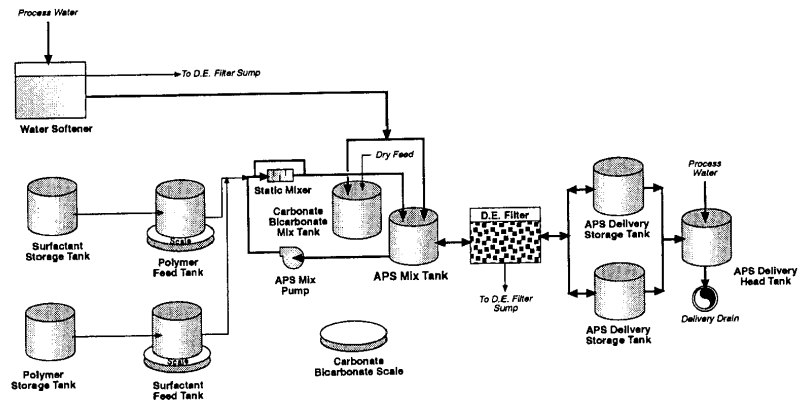
Calculations

PoreVolume := TargetVolume · f	PoreVolume = 16 × 10 ⁶ gal
WtSurfactant := TreatmentPV · PoreVolume · r _w · SurfactantFrac	WtSurfactant = 8 × 10 ³ ton
WtBuytlAlcohol := TreatmentPV · PoreVolume · r _w · BuytlAlcoholFrac	WtBuytlAlcohol = 16 × 10 ³ ton
WtPolymer := TreatmentPV · PoreVolume · r _w · PolymerFrac	WtPolymer = 265 ton
WtCaCl2 := TreatmentPV · PoreVolume · r _w · CaCl2Frac	WtCaCl2 = 163 ton
WtTotal := WtSurfactant + WtBuytlAlcohol + WtPolymer + WtCaCl2	WtTotal = 25 × 10 ³ ton
ProducedFluidsVol := PoreVolume · (TreatmentPV + PostTreatmentPV)	ProducedFluidsVol = 212 × 10 ⁶ gal

Figure 20 – Masses and volumes for full-scale application in the Surficial Aquifer

3.1.7 Process Components

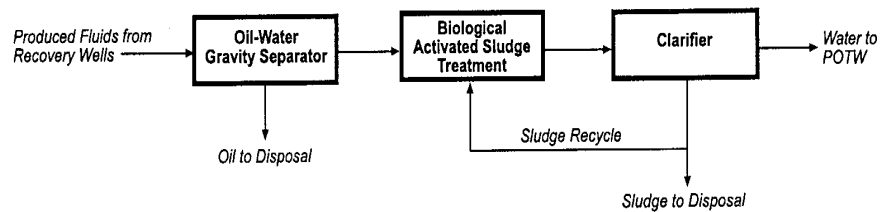
Per Simpkin et al., (1996) likely treatment components for delivery and treatment of produced fluids are presented in Figure 21 and Figure 22. Systems such as these, with capacities of 0.06 to 0.6 mgd would have large physical footprints and would require a large staff for operations and maintenance.



Plus a train for buytl alcohol, Replace carbonate with CaCl2

Figure 21 - Process for preparation flushing solutions (after Simpkin et al., 1996)

Biological Treatment with Discharge of Treated Water (Semivolatile Contaminants):



Ultrafiltration for Concentration of Surfactant with Contaminants (Semivolatile Contaminants):

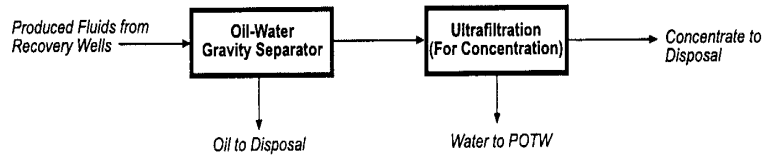


Figure 22 - Process for treatment of produced fluids (after Simpkin et al., 1996)

3.2 Cost for Surfactant Flushing in the Surficial Aquifer

Based on the prior review of available cost data:

- 1) The best-case (optimistic) scenario for treatment costs is \$228 per cubic yard. Given the target of 403,000 cubic yards this suggests a total cost of \$92 million.
- 2) More conservative treatment costs could be as high as \$500 per cubic yard. Given the target of 403,000 cubic yards this suggests a total cost of \$ 202 million.

Due to lower cost for excavation, described in TRC 2005, further refinement of cost for surfactant flushing is not seen as being warranted.

3.3 Estimated Endpoint

The following endpoint seems likely:

- Given a “well designed” and “well executed” project, anywhere from 72 to 90 percent of the DNAPL in the Surficial Aquifer could be depleted.
- Anywhere from 28 to 10 percent of the DNAPL currently in place would likely remain. This would result in exceedances of groundwater standards in the targeted areas for very long periods.
- Some of the chemicals used to mobilize the DNAPL will remain in the targeted zones. Assuming that the remainder is 10 percent of the total introduced, approximately 2,500 tons of chemicals (5 million lbs) would be emplaced in the Surficial Aquifer through a surfactant flushing remedy.
- Reductions in water-DNAPL interfacial tension and enhanced concentrations of DNAPL constituents in groundwater will introduce new potential mechanisms for adverse migration of site related contaminants.
- Natural degradation of polymer and surfactants will create highly reduced conditions in the aquifer. This will deplete available electron acceptors that are likely to be limiting migration of dissolved phase contaminants via natural attenuation processes. Reduced natural attenuation may have the adverse result of expanding plumes of dissolved phase DNAPL constituents. Also, the mobility of metals could be enhanced by low redox conditions.

4.0 Conclusions

Surfactant flushing has been under consideration for more than 20 years as a means of addressing NAPL in soil. Over this period in excess of \$100,000,000 has been invested in developing the technology. Unfortunately, the technology has not become a widely adopted solution. At best it has only been taken to a large-scale application at Hill AFB OU2 (Jackson, 2005).

The analysis presented herein has a similar result. Use of the technology does not appear to be warranted. By each hydrogeologic unit, the basis for this conclusion is that:

- Surfactant flushing in the Surficial Aquifer appears to be more expensive than excavation as described in TRC (2005). Furthermore, there are substantial issues related to effectiveness and adverse impacts. Given these issues, surfactant flushing is not a promising remedy for the Surficial Aquifer.
- The feasibility of using surfactant flushing in the Hawthorn Group is limited by the low permeability and the resultant impracticability of delivering and recovering flushing solutions to and from the target. Based on this fact alone, surfactant flushing is not a viable remedy for the Hawthorn Group. Furthermore, the large number of borings that would be required, through a unit with large downward gradients, would pose a substantial risk to the deeper aquifer.

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Appendix A – Idealized Approach for Analysis of Time to Deliver and Recover Fluids (after Simpkin et al 1996)

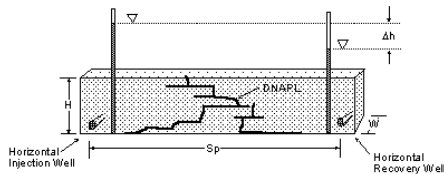


Figure 6-2
Hypothetical scenario

$$t_p = \frac{P_v}{Q_{sol}}$$

$$t_p = \frac{f S_p^2 m_f}{k r_f g \Delta h}$$

From Simpkin et al., 1999

$$c_p := \frac{1 \text{ poise}}{100}$$

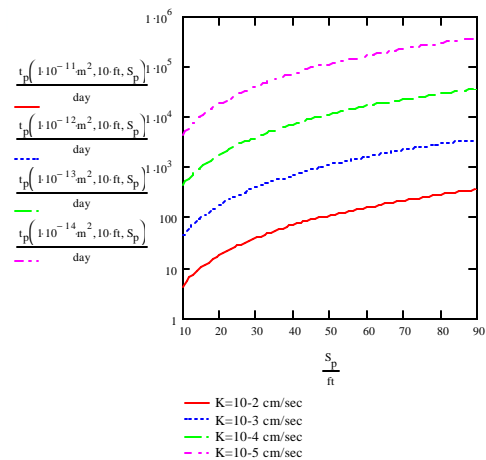
$$\mu_f := 50 \text{ cp}$$

$$\phi := 0.25$$

$$\rho_f := 1 \frac{\text{gm}}{\text{cm}^3}$$

$$S_p := 10 \text{ ft}, 11 \text{ ft}, 90 \text{ ft}$$

$$t_p(k, \Delta h, S_p) := \frac{\phi S_p^2 \mu_f}{k \rho_f g \Delta h}$$



Simpkin et al., 1999

Appendix B - Resume for Tom Sale

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Engineering Research Center, Room B-01
Fort Collins, Colorado 80523
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TSale@Engr.ColoState.Edu

Goal

Advance subsurface water resource engineering through teaching, research, and community outreach.

Education

Colorado State University 1994-1998

Ph.D. Agricultural Engineering, May 1998 - Course work included multiphase-flow, chemical equilibria in soils, contaminant transport in porous media, and upper level math. Working under the guidance of Dr. David McWhorter, Dr. Sale's dissertation focused on quantification of mass transfer from nonaqueous phase liquids (NAPLs) in field settings and the benefits of NAPL source zone remediation. The Solvents in Groundwater Research Consortium (University of Waterloo) and the Boeing Contaminant Hydrology Fund (Colorado State University) funded this research.

University of Arizona 1983-1984

MS Watershed Hydrology, December 1984 - Interdisciplinary course work included groundwater hydrology, unsaturated flow, surface water hydrology, and water quality. Working under the guidance of Dr. John Thames, Dr. Sale's thesis research focused on measuring and modeling seepage losses from reservoirs in southeastern Arizona. The Salt River Project and the US Forest Service provided funding.

Miami University (Ohio) 1976-1980

BA Chemistry, May 1980 - An accelerated chemistry curriculum designed for students planning careers in chemistry.

BA Geology, September 1980 - Broad geology curriculum with specific emphasis in hydrogeology.

Professional Positions

Director of the Center for Contaminant Hydrology in Civil and Environmental Engineering at Colorado State University (2005-Present)

Dr. Sale has been the primary force behind the development of the Center for Contaminant Hydrology in the Department of Civil and Environmental Engineering at Colorado State University. Currently, the Center conducts approximately \$700,000/year in research and supports 7 graduate and undergraduate students. Current funding comes from the University Consortium for Field-Focused Groundwater Contamination Research, DuPont, US DoD - Environmental Securities Testing and Certification Program, Suncor Energy, American Petroleum Institute, ExxonMobil, and CH2M HILL. In the last 6 years the Center has acquired four complete and two pending patents.

Colorado State University - Research Scientist / Assistant Professor (1999 – Present)

Since receiving his PhD Dr. Sale has been conducting groundwater research and teaching at Colorado State University. To date, Dr. Sale has been integral in gaining funding for and completing around \$3,000,000 in funded research. Through this Dr. Sale has been able to provide financial support to a total of 23 graduate and 13 undergraduate students. Since 2000 Dr. Sale has advised 12 students and served on 24 graduate student committees. In addition, Dr. Sale has taught five graduate levels courses over the past five years.

Independent Consulting Hydrologist (1995-Present)

Dr. Sale has been working as an independent consulting hydrologist since 1995. Dr. Sale is currently reviewing the sustainability of groundwater production from the Denver Basin Aquifer for the City of Castle Rock, Colorado. In addition, Dr. Sale, in conjunction with Drs. Allan Freeze and Jim Mercer provided peer review of remedial measures at DOE's Rocky Flats Facility near Golden, Colorado. Dr. Sale is currently supporting efforts to manage subsurface hydrocarbons at 3 major US refineries. Key issues at these facilities include natural attenuation of petroleum hydrocarbons, technical practicability of LNAPL recovery, and appropriate endpoints for mobile LNAPL recovery systems. Dr. Sale has provided technical support to a number of field demonstrations of remedial technologies. This includes projects in Melbourne, Australia; Commerce City, Colorado; Marietta, Georgia; and Ogden, Utah.

CH2M HILL (1985-1995)

Upon graduation from the University of Arizona Dr. Sale was employed by CH2M HILL in Denver, Colorado. Over 10 years with CH2M HILL Dr. Sale's responsibilities evolved through positions as a project hydrologist, project manager, department manager, and senior technical resource. Throughout Dr.

Sale's career with CH2M HILL his primary focus was development of groundwater resources and mitigation of risks posed by subsurface contaminants. Highlights of Dr. Sale's career with CH2M HILL are described below.

Project Hydrologist/Project Manager - As a project hydrologist and project manager Dr. Sale planned, implemented, and reported on a wide variety of hydrogeologic investigations conducted at locations across the western United States. Through this work Dr. Sale became familiar with a wide variety of hydrogeologic settings including the Columbia Lava Plateau, alluvial basins of the Southwest, fluvial systems of the western and central plains, alpine glacial deposits of the Rocky Mountains, Permian Formations of central Oklahoma, and bedrock aquifers of the Denver Basin. In addition, Dr. Sale gained extensive experience in the collection, evaluation, and documentation of hydrogeologic and water quality data.

Department Manager - In 1989 Dr. Sale became the manager of CH2M HILL's Denver Groundwater Resources Department. As a complement to project work Dr. Sale was responsible for hiring, maintaining workload, staff career development, marketing, strategic planning, and overall department profitability. In this role Dr. Sale increased the department staff from 6 to 18 and diversified the department's workload to include site characterization, remedial design, water supply, and modeling projects. Through these efforts and extensive training provided by CH2M HILL, Dr. Sale gained the skills needed to successfully develop and manage diverse groups of people. Dr. Sale's responsibilities as department manager were concluded in 1994 after successfully training his replacement.

Technical Resource - Through the later half of his career with CH2M HILL Dr. Sale's efforts focused on technical support for projects involving groundwater contamination resulting from Nonaqueous Phase Liquids (NAPLs). In this role Dr. Sale assisted with development of new business, technology transfer within CH2M HILL, and mentoring junior staff. In recognition of Dr. Sale's abilities was invited to speak at a large number of workshops, conferences, short courses, and seminars.

After ten years with CH2M HILL Dr. Sale enrolled in the Ph.D. program at Colorado State University under the direction of Dr. David McWhorter. Dr. Sale's goals in this endeavor were to expand his technical/research skills and to position himself for a career in academia.

Engineering Enterprises Inc. (1981-1982)

Upon completion of his undergraduate course work, Dr. Sale was employed as hydrogeologist and geochemist by Engineering Enterprises Inc. (EEI), Norman, Oklahoma. During Dr. Sale's two years with EEI his activities focused on development of larger water supply wells, product recovery in refineries, and soil and groundwater monitoring systems for land treatment systems. Dr. Sale

gained extensive experience with aquifer tests, geologic logging, geophysical logging, soils and groundwater sampling, design, operation, and repair of pumping systems, well drilling techniques, well construction techniques, and engineering consulting practices. After two years with EEI Dr. Sale enrolled at the University of Arizona with the goal of expanding his technical background in hydrology and water quality.

Prior to Undergraduate Graduation (1980)

From an early age Dr. Sale worked for his father's civil engineering firm. Experience included rodman, instrumentman, and draftsman. Dr. Sale gained broad exposure to fundamental engineering practices.

Research Interests

Denver Basin Groundwater Resources (1998-Present)

Explosive population growth along the front range of Colorado has led to the rapid development of the groundwater resources of the Denver Basin. Over the last ten years, working with Hemenway Groundwater Engineering, Dr. Sale has visually logged in excess of 120,000 linear feet of Denver Basin sediments. Coupling this information with geophysical logs and pump test data, Dr. Sale and Mr. Hemenway are accumulating data that will advance the current state of knowledge regarding the sustainability of groundwater production in the Denver Basin. Building on this, Dr. Sale was hired by the City of Castle Rock, Colorado in the fall of 2006 to advise them on the long term sustainability of groundwater production from the Denver Basin Aquifers.

ZVI-Clay (2002-Present)

In 2002 DuPont donated patents to Colorado State University (CSU) regarding treatment of spills of chlorinated compounds using reactive media, stabilizing agents, and soil mixing techniques. This technology holds the promise of being more effective and less costly than competing options for management of chlorinated compounds in soil and groundwater. Presently, funds supporting related research and development are approaching \$650,000 per year and formal agreements are being developed with industry partners. In January 2005, CSU issued its first license for commercial use of the technology to CH2M HILL for a site at Marine Corps Base Camp Lejeune, North Carolina. In February of 2005, 7,000 yards of soil containing 10 tons of perchloroethene (PCE) were treated at Camp Lejeune. This was accomplished by admixing 200 tons of granular iron and 100 tons of bentonite clay with the impacted soils using crane mounted soil mixing equipment. The treated PCE is associated with a former Marine Base dry cleaner. Since 2005 three other site licenses have been issued. Issuance of 5 additional site licenses is anticipated in 2006. The long term vision for this project is that it will provide innumerable research opportunities for students and substantial revenue for salaries and equipment.

Electrically Induced Redox Barriers (1998 - Present)

A primary focus of Dr. Sale's research is the use of electrically induced redox barriers for in-situ treatment of contaminated groundwater, Sale and Gilbert (2002). This concept involves closely spaced (e.g. 0.01 – 0.01 m) permeable electrodes installed in a trench that intercepts a plume of contaminated groundwater. Application of an electrical potential to the aqueous media results in oxidation at the positive electrode and reduction at the negative electrode. To date treatment efficacy has been demonstrated for chlorinated ethenes, chlorinated ethanes, energetics, and arsenic. Laboratory studies have led to field demonstrations at Canadian Forces Base, Borden, Ontario (November, 2001), F.E. Warren Air Force Base, Wyoming (August 2002), and Pueblo Chemical Depot, Colorado (January 2006). Results from our laboratory studies are described in Gilbert and Sale (2002), Petersen et al., (2006) and Gilbert et al., (2006). Support on the order of \$1,100,000 has been obtained from the University Consortium for Field-Focused Groundwater Contamination Research, National Science Foundation, Environmental Security Technology Certification (ESTCP), Strategic Environmental Research Development Program (SERDP), and United Technologies Corporation.

Mass Transfer from Field-Scale NAPL Sources and the Benefits of Partial NAPL Source Zone Remediation (1996-Present)

For his dissertation, Dr. Sale and Dr. David McWhorter (Colorado State University) worked to resolve the benefits of partial mass removal from subsurface NAPL zones. This involved laboratory studies, analysis of field data, and assistance with the development of a Multiple Analytical Source Superposition Technique (MASST). Through application of MASST it has been shown that very high NAPL mass removal efficiencies are required to achieve significant near term exposure reductions. This research is described in Sale (1998) and Sale and McWhorter (2001). The significance of the results led to comments on results (P.S. Rao and J.W. Jawtiz) and response to comments (Sale and McWhorter) that were published in Water Resource Research Fall 2002. Building on this work Dr. Sale was awarded \$425,000 by the Air Force Center for Environmental Excellence (AFCEE) in October 2002. This funding has been the seed project for developing a decision guide for the US DoD regarding when to invest in NAPL source remediation. The value of this document will be avoidance of high cost remedies with low potential for risk reduction.

Reflecting the relevance of this research, Dr. Sale has been an invited speaker at the following conferences: National Research Council (NRC), San Diego, February (2001); Battelle Conference, San Diego, May (2001); Solvents Focus Meeting, Chicago October (2001); EPA DNAPL Workshop, Dallas, October (2001); SERDP/ESTCP Partners Conference, Washington, D.C. November (2001); AFCEE Remediation Workshop, San Antonio, March (2002); Battelle Conference, Monterey, May (2002); NRC, Washington D.C August (2002),

Battelle Conference, Monterey, May (2004), ESTCP/SERDP Baltimore February 2006) and Battelle Conference, Monterey, May (2006). In addition, Dr. Sale was a member of an expert panels funded by the USEPA. A white paper presenting findings was released in 2005 (UESPA600/R-03/143). Dr. Sale was also a member of a NRC panel addressing benefits of subsurface remediation. This was released in 2005. Lastly, Dr. Sale has been funded to provide technical engineering reviews for the Air Force, Navy, NASA, and numerous petroleum companies regarding the efficacy of proposed NAPL remediation projects.

Recovery of Mobile Product (1981-Present)

In the early 1980s Dr. Sale worked on the design, construction, and operation of Light Nonaqueous Phase Liquid (free product) recovery systems at petroleum refineries in the U.S. At a facility in Tulsa, peak production of 90,000 gallons of gasoline/day was achieved from an alluvial aquifer. Building on this Dr. Sale has worked at 21 different petroleum refineries in the US and Puerto Rico. In the mid 1980s Dr. Sale developed the concept of Dense Nonaqueous Phase Liquid (DNAPL) recovery using waterflooding and horizontal drains (Sale and Applegate, 1997). In Laramie, Wyoming, this technology achieved a record recovery of 1,800,000 gallons of DNAPL. Variations of this technology have been applied at two US refineries, two wood-treating facility, and a former manufactured gas plant.

Reflecting his experience with managing releases of fuel hydrocarbons, the American Petroleum Institute (API) funded Dr. Sale to work on Pump and Treat: The Petroleum Industry Perspective, Glass et al., (1992); An Evaluation of Field Methods for Intrinsic Bioremediation Measurements, Piontek et al., (1994); Methods for Determining Inputs to Environmental Petroleum Hydrocarbon Mobility and Recovery Models, Sale (2001); and Frequently Asked Questions About Managing Risk at LNAPL Sites, Sale (2002). API and its sponsors are now using the latter two documents for training. Their value will be to build a common understanding of technical issues and pragmatic constraints.

Building on results from Dr. Sale 's most recent API publications, he has embarked on a new research initiative focused on *in situ* measurement of LNAPL seepage velocities. Following well bore dilution techniques, the disappearance of a tracer in LNAPL (in a well) is being used to estimate formation LNAPL seepage velocity, Sale et al., (2006). Results to date are promising. Given success, the tools developed through this research will play a major role in resolving the potential mobility of subsurface LNAPL, appropriate endpoints for NAPL deletion, and a potential means of long term monitoring.

Surfactant and Cosolvent Flushing (1986-1998)

In the early 1980's Dr. Sale was funded by Sun Oil Company to study the potential for surfactant-enhanced recovery of NAPL. From 1986-1989 Dr. Sale was the technical lead of a project team that developed the first field demonstration of Surfactant Flushing (Sale et al., 1988) and the largest (to date) surfactant flood Sale (1996). Building on this Dr. Sale was successful in a proposal for \$250,000 to Rice University (Advanced Applied Technology

Demonstration Facility) for development of a Technical Practices Manual for Surfactant and Cosolvent Flushing. Coauthors of the published book (Simpkin et al., 1999) were Dr. Bernard Kueper, Queens University; Dr. Tom Simpkin, CH2M HILL; and Dr. Malcolm Pitts, SURTEK INC. This comprehensive analysis includes: 1) review of surfactant/cosolvent field demonstrations, 2) surfactant/cosolvent enhanced recovery processes, 3) a step-wise approach for implementation of surfactants/cosolvent flushing projects, and 4) screening tools for analysis of the applicability including rigorous consideration of cost.

Natural Attenuation of Dissolved Hydrocarbons (1993-Present)

Dr. Sale worked with Phillips Petroleum and CH2M HILL to evaluate natural attenuation of fuel hydrocarbons at a former natural gas plant. Work at this site led to one of the earliest demonstrations of 1) the use of sulfate as an electron acceptor and 2) increases in alkalinity attributable to anaerobic degradation of petroleum hydrocarbons. Results were published in the Society of Petroleum Engineering's Advanced Technologies Series, Health, Safety, and Environmental Issues (Admire, 1996).

***In Situ* Treatment Process Development Program (1987-1990)**

While working for CH2M HILL Dr. Sale was a lead in proposing, and subsequently conducting, a four year \$15 million insitu treatment technology development program. Work was conducted for Union Pacific Railroad at their former tie-treating plant in Laramie, Wyoming. The focus of the effort was to find remedial alternatives to incineration. Activities focused on design, implementation, and evaluation of small and large-scale field demonstrations. Technologies considered included waterflood DNAPL recovery, surfactant enhanced DNAPL recovery, and in-situ bioremediation. Through this pioneering effort a number of significant breakthroughs were achieved including:

- Development of a dual drainline waterflood DNAPL recovery technology. Full-scale application of this technology has resulted in the production of 1.8 million gallons of DNAPL (Sale and Applegate, 1997).
- The first (Sale et al., 1989) and the largest (Sale et al., 1994) field demonstrations of surfactant flushing.
- Identification of the limitations of oxygen cycling for enhanced bioremediation of NAPL zones (Simpkin et al., 1991).
- Documentation of the technical impracticability of restoring DNAPL zones to drinking water standards (Sale and Piontek, 1992).

Model for Prediction of Seepage Losses from Small Unlined Water Impoundments (1983-1984)

As a research assistant at the University of Arizona Dr. Sale developed a model that estimates seepage losses from unlined reservoirs in southeastern Arizona.

Finite difference techniques were applied to the Green-Ampt equation. Model validation was accomplished through comparison with historical data obtained from the Walnut Gulch Experimental Watershed, Tombstone, Arizona. Results of this effort were documented in Dr. Sale's Master's Thesis (Sale, 1985).

Teaching Experience

Dr. Sale's teaching experience includes two undergraduate classes, three graduate classes, and multiple short courses. These are reviewed below.

Courses - Colorado State University, Colorado

CE - 423 Groundwater Engineering (Spring 2005 and 2006) – This is an undergraduate level introduction to groundwater hydrology. Topics addressed include the role of groundwater in the hydrologic cycle, morphology of aquifers, groundwater movement, elastic properties, flow equations, hydraulic testing, groundwater as a resource, well design /construction, and groundwater in the basin hydrologic cycle. Examples from Colorado based groundwater projects are highlighted to help students appreciate the utility of the presented material.

CE – 658 Subsurface Remediation (Spring 2004) - This course carries students through the steps of developing engineered solutions for anthropogenic releases of hazardous compounds. Fundamentals of engineering are applied including application of first principles learned in earlier coursework, conducting design calculations, and analysis of project costs. A pre-release draft of Contaminants in the Subsurface: Source Zone Assessment and Remediation, a National Research Council Book on which I was a co-author (NRC 2005) was the course text.

CE – 680 - Solutions to Subsurface Releases (Spring 2003) - This was the first version of CE658 as described above.

CE – 531 Groundwater Hydrology (Fall 2001) – This is a graduate level introduction to groundwater hydrology. This is similar to CE 423 (described above) but with more rigor. Topics addressed included role of groundwater in the hydrologic cycle, morphology of aquifers, groundwater movement, elastic properties, flow equations, hydraulic testing, groundwater as a resource, well design/construction, and groundwater in the basin hydrologic cycle.

Seminars and Short Courses

Air Force Center for Environmental Excellence - Technology Transfer Workshop, Pragmatic Expectation of NAPL Source Zones, One to two lecture presented in 1999, 2001, and 2002.

Conoco Inc, Houston, Texas - Pragmatic Expectations for Management of NAPL Sources – A 6-hour short course presented to the Conoco Remediation Technology staff and Conoco alliance contractors, November of 1999.

USEPA - Pragmatic Expectations for Remediation of NAPL Source Zone – A 4-hour lecture presented as part of a 3-day USEPA short course on NAPLs, Helena Montana, September 1998.

University of Wisconsin, Madison – *In Situ* Treatment of Soil and Groundwater: Methods for Mitigation of Risk - A 4-hour lecture given as part of a 3-day short course, 1992 , 1993, and 1994.

University of California Berkley - Enhanced Recovery of DNAPLs and Mechanics of DNAPL Transport - An invited lecture given to graduate students and faculty, November 1991.

CH2M Hill Technology Transfer Seminars --- Emerging perspective for Source Zones and Plumes, 1-hour lecture August 2006, --- Pragmatic Expectations for NAPL Source Zones – A 1-hour lecture given 5 times, October 2000, ---Insitu Bioremediation, Denver, Colorado - A 1-hour lecture, October 1990. --- Characterization of Porous Media Characteristic, Phoenix, Arizona - A 1-hour introduction to identification and management of NAPL source zones, December 1991.

Awards - Recognition

Member of the 2003-2005 National Research Council Committee addressing Contaminants in the Subsurface – Source Zone Assessment and Remediation

Member of the 2003-2005 USEPA Advisory Panel Addressing The DNAPL Remediation Challenge: Is There a Case for Source Depletion?

Research Faculty Award for Excellence – Colorado State University - 2003

American Geophysical Union - Best Ph.D. Presentation - Seventh Annual Hydrology Days Conference, Fort Collins, Colorado. April 1997.

Colorado Ground Water Association - Harlan Erker Scholarship 1996.

CH2M HILL Office of Innovation - Innovation Award for the Union Pacific Railroad *In Situ* Treatment Process Development Program 1992.

Professional Affiliations

American Geophysical Union
National Ground Water Association

Professional Registrations

Professional Geologist Wyoming, No. PG-1954 (Since 1992)

Peer Reviewed Publications

Pending

Sale, T., G. Taylor, G. Iltis, and M. Lyverse, (2006), Measurement of LNAPL Flow Using Single Well Tracer Dilution Techniques. Submitted to Journal of Groundwater 7/06, Accepted for publication with minor revisions 10/06.

Sale, T.C., G.R. Taylor, and M. Lyverse (2005), Measurement of Non-Aqueous Phase Liquid Flow in Porous Media by Tracer Dilution. Patent Pending.

Gilbert, D., T. Sale, and M. Petersen, (2006), Electrolytic Reactive Barriers (e-barriers), Chapter Section of ESTCP/SERDP Remediation Technology Monograph. In Review.

Sale, T. and C. Newell, (2006), Chlorinated Solvent Releases – The Nature of the Problem. Chapter Section of ESTCP/SERDP Remediation Technology Monograph. In Review.

Sale, T.C., J.A. Zimbron, D.S. Dandy (2006). Storage and Release of Contaminants in Hydraulically Stagnant Zones in Aquifers. In final preparation for submission to the Journal of Contaminant Hydrology.

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Petersen, M., T. Sale, and K. Reardon, (2006), Electrolytic Trichloroethene Degradation Using Mixed Metal Oxide Coated Titanium Mesh Electrodes. Chemosphere, Accepted for publication 11/27/06, In Press.

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Sale. T., C. Newell, H. Stroo, R. Hinchee, and P. Johnson. (2006) Guides for Selecting Remedies for Chlorinated Solvents Releases (ER-0530). ESTCP/SERDP Partners in Remediation Conference, Washington D.C., November 27-30, 2006.

Sale. T., M.Olson, T. Simpkin, and C. Bozzini. (2006). In Situ Remediation of Chlorinated Solvents via Admixing Reactive Media and Stabilizing Agents (ZVI-Clay). ESTCP/SERDP Partners in Remediation Conference, Washington D.C., November 27-30, 2006.

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Sale. T. (2006). Surfactants Status after 18 Years of Field Studies. ESTCP/SERDP DNAPL Workshop, Baltimore, Maryland, March 7, 2006.

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- Sale, T., G. Amato, M. Olson, and J. Grant. (2006). ZVI-Clay - Driving technology use University Consortium for Field-Focused Groundwater Contamination Research 2006 Annual Progress Meeting, Orangeville, Ontario, May 9-12, 2006.
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- Sale, T. and G. Amato. (2006). Advancing Innovative Remediation Technologies to Broad Commercial Use. American Geophysical Union, Hydrology Days, Colorado State University, March 22, 2006.
- Sale, T. and M. Olson. (2006). In Situ Remediation of Chlorinated Solvents via Admixing Reactive Media and Stabilizing Agents. Groundwater Resource Association of California – DNAPL Source Zone Characterization and Remediation, December 7-8, 2005, San Francisco, California.
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