The In-Situ Decontamination Of Sand And Gravel Aquifers By Chemically Enhanced Solubilization Of Multiple-Component DNAPLS With Surfactant Solutions

**Topical Report
January 1995**

Work Performed Under Contract No.: DE-AC21-92MC29111

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
1000 Independence Avenue
Washington, DC 20585

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
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Acknowledgement

INTERA Inc. is very grateful to the personnel of Martin Marietta Energy Systems, Inc. for their friendly collaboration and their tireless assistance with site characterization, waste-water treatment, and permitting, and during the field test. Special thanks are owed to Ken Davis and Jeff Douthitt for their effort, ideas, and enthusiasm.

Abstract

Laboratory, numerical simulation, and field studies have been conducted to assess the potential use of micellar-surfactant solutions to solubilize chlorinated solvents contaminating sand and gravel aquifers. Laboratory studies were conducted at the State University of New York at Buffalo (SUNY) while numerical simulation and field work were undertaken by INTERA Inc. in collaboration with Martin Marietta Energy Systems Inc. at the Paducah Gaseous Diffusion Plant (PGDP) in Kentucky.

Ninety-nine surfactants were screened for their ability to solubilize trichloroethene (TCE), perchloroethylene (PCE), and carbon tetrachloride (CTET). Ten of these were capable of solubilizing TCE to concentrations greater than 15,000 mg/L, compared to its aqueous solubility of 1,100 mg/L. Four surfactants were identified as good solubilizers of all three chlorinated solvents. Of these, a secondary alcohol ethoxylate was the first choice for *in situ* testing because of its excellent solubilizing ability and its low propensity to sorb. However, this surfactant did not meet the Commonwealth of Kentucky's acceptance criteria. Consequently, it was decided to use a surfactant approved for use by the Food and Drug Administration as a food-grade additive. As a 1% micellar-surfactant solution, this sorbitan monooleate has a solubilization capacity of 16,000 mg TCE/L, but has a higher propensity to sorb to clays than has the alcohol ethoxylate.

Constraints beyond INTERA's control prevented the assessment of the potentially suitable surfactants in the laboratory with cores and ground waters from the site. These constraints, which could not be resolved before the field test, meant the surfactant solution had to be injected without laboratory testing of the surfactant's compatibility with the aquifer materials.

The field test was conducted in the alluvial aquifer which is located 20 to 30 meters beneath a vapor degreasing operation at PGDP. This aquifer has become contaminated with TCE due to leakage of perhaps 40,000 liters of TCE, which has generated a plume of dissolved TCE extending throughout an area of approximately

3 km² in the aquifer. Most of the TCE is believed to be present in the overlying lacustrine deposits and in the aquifer itself as a dense, non-aqueous phase liquid, or DNAPL.

The objective of the field test was to assess the efficacy of the surfactant for *in situ* TCE solubilization. This involved the injection and subsequent extraction of the surfactant solution through a single well. The aqueous concentrations of TCE in this well have consistently been measured at 300 to 550 mg TCE/L over a period of three years. Capillary and bond numbers were calculated and evaluated to confirm the improbability of mobilization of DNAPL due to the lowering of the interfacial tension by the surfactant solution. The injection phase lasted 3.75 days at 3.8 liters per minute (1 gpm), while the extraction phase lasted 16 days at 3.8 liters per minute (1 gpm). The extraction operation, which removed four times the injected volume, recovered only 34% of the surfactant, probably due to sorption, precipitation, or liquid crystal formation of the surfactant, or some combination of these processes. Due to this loss of surfactant *in situ*, there was no enhancement of aqueous TCE concentrations in the recovered ground waters. TCE behaved nonconservatively during the early stages of extraction, suggesting that it may have been sorbed to the immobilized surfactants.

Although the test demonstrated that sorbitan monooleate was unsuitable as a solubilizer in this aquifer, the single-well test was demonstrated to be a viable method for the *in situ* testing of surfactants or cosolvents prior to proceeding to full-scale remediation. It is probable that this result could have been identified in the SUNY laboratory beforehand and an alternative surfactant chosen and tested with core materials, had it been possible to transfer core off site.

It is recommended that (1) detailed core analyses to screen surfactants meeting the Commonwealth of Kentucky's acceptance criteria be conducted, (2) the field studies at C-400 planned by PGDP for next spring be complemented with computational studies of DNAPL migration to assist in the design of the drilling program, and (3) an inter-well DNAPL solubilization test be undertaken over a distance of at least 10 meters to test the efficacy of DNAPL solubilization by micellar surfactant solution.

1.0 INTRODUCTION

1.1 Surfactant-Enhanced Aquifer Remediation

Dense, non-aqueous phase liquids or DNAPLs, in particular chlorinated solvents such as trichloroethene (TCE), pose an as-yet unresolved ground-water contamination problem at DOE facilities across the nation. Figure 1.1 shows the migration of DNAPL in a sand and gravel aquifer system and the development of a DNAPL zone, comprising several vertical fingers and horizontal pools. Also shown are two dissolved-phase plumes, one partially due to vapor migration to the water table, the other due solely to DNAPL dissolution beneath the water table. The mobility of DNAPLs in the subsurface, their low aqueous solubility, and the heterogeneity of typical aquifer systems combine to create conditions that inhibit rapid *in situ* remediation by traditional pump-and-treat methods. Thus, tens to hundreds of liters of DNAPL may require tens to hundreds of years to be dissolved by ground-water extraction (Johnson and Pankow, 1992).

Such long remediation times mean that short-term remediation target dates will not be met. The hazardous waste clean-up program presently being undertaken by the U.S. Department of Energy is committed to the decontamination of the Weapons Complex facilities in 30 years (i.e., by the year 2019). As Mackay and Cherry (1989) have noted about DNAPLs in general, "... very little success has been achieved in even locating the subsurface sources, let alone removing them." Thus, it is essential that methods be developed to permit the rapid location, characterization, and remediation of such DNAPL sources if DOE's deadline is to be met.

A particularly attractive approach to the characterization and remediation of DNAPL sites involves the use of surfactants to enhance the dissolution of DNAPLs by a process known as solubilization. Surfactant-enhanced aquifer remediation (SEAR) is the generic name given to the process of *in situ* DNAPL remediation employing micellar surfactant solutions (Jackson, 1993).

The mechanism of solubilization displayed by nonionic and anionic surfactants arises from the formation of micelles by the surfactant in aqueous solutions (Rosen, 1989). Surfactants, or surface-active solutes, have polar and nonpolar groups that exhibit hydrophilic and hydrophobic properties, respectively. At certain characteristic concentrations, surfactants exhibit marked changes in several physical and chemical properties, e.g., electrical conductivity, interfacial tension and detergency. The concentration of the surfactant at which these phenomena occur is known as the critical micelle concentration, or CMC. At this concentration, the polar and nonpolar

groups become oriented such that they form colloidal clusters of molecules in solution. The clusters are characterized by the interfacing of the hydrophilic groups with the water molecules on the outside of the cluster, while the hydrophobic groups are arranged pointing toward the interior of the cluster.

At the CMC, aqueous solutions of surfactants show a greatly enhanced ability to dissolve compounds that are otherwise sparingly soluble in aqueous solution. The hydrophobic interior of the micelles creates a nonpolar environment in the center of the cell which is capable of accommodating nonpolar molecules, effectively bringing the contaminants into solution. This process of solubilization has been defined by Rosen (1989) as "... the spontaneous dissolving of a substance (solid, liquid, or gas) by reversible interaction with the micelles of a surfactant in activity of the solubilized material." Figure 1.2 shows a schematic interpretation of solubilization.

It is well known in the petroleum industry that extremely high effective aqueous solubilities for organic compounds can be obtained by lowering the interfacial tensions of oil/surfactant mixtures to values less than 0.1 dynes/cm (Lake, 1989). By this method, it is possible to mobilize and displace petroleum hydrocarbons as an "oil bank." However, when remediating contaminated sites, such mobilization of DNAPLs could well result in their vertical displacement through permeable windows in sedimentary aquitards and through fractures in rock, resulting in deeper contamination. This has necessitated a different approach for surfactant-enhanced aquifer remediation. The alternative approach seeks to maintain the interfacial tensions above 1 dyne/cm to minimize the possibility of vertical and horizontal mobilization while striving for maximum effective solubility. Fountain et al. (1991) demonstrate that dilute (1%) surfactant solutions may have interfacial tensions exceeding 1 dyne/cm with respect to perchloroethylene (PCE) with a solubilization capacity of 1 g PCE / g surfactant, where the aqueous solubility of PCE is 0.0002 g PCE/g water.

1.2 Objectives

This project is composed of two phases and has the final objective of demonstrating SEAR as a practical remediation technology in sand and gravel aquifers with ground water contaminated by DNAPLs such as chlorinated solvents. The first phase of this project, *Laboratory and Pilot Field Scale Testing*, which is the subject of the work so far, had two specific objectives:

1. to identify surfactants or blends of surfactants in the laboratory that will efficiently extract PCE and TCE from a sand aquifer by micellar solubilization; and

2. to test the efficacy of the surfactant or surfactant blend(s) to solubilize the DNAPLs, perchloroethylene (PCE) and trichloroethylene (TCE), *in situ* by injection and then withdrawal of a surfactant solution through an existing well within the sand aquifer at a government-owned contaminated site.

(The underlined parts reflect changes to these specific objectives proposed by INTERA in its Cost to Complete proposal of September 28, 1994, in order to remove inconsistencies between the specific objectives listed above and the tasks set out by the Morgantown Energy Technology Center (METC) in the Statement of Work.)

These specific objectives became tasks in the Phase 1 project. The task structure is as follows:

- Task 1.1: Information required for the National Environmental Policy Act (NEPA);
- Task 1.2: Laboratory experiments to identify and characterize surfactants and their solubilization activity;
- Task 1.3: Single-well, injection-withdrawal test for DNAPL solubilization;
- Task 1.4: Phase 1 topical report.

1.3 Site Selection

The Statement of Work prepared for this contract by METC indicated that the field work would be conducted at a government-owned plant. A number of issues arose which indicated that it would be advantageous to conduct the field test at the Paducah Gaseous Diffusion Plant [PGDP] in Kentucky (see Figure 1.3). Most important of these was the possibility that the test might be conducted in a shallow aquifer (20 to 30 feet deep) at the "Drop Test" site at PGDP, which had been used for drop-testing UF₆ cylinders and at which site TCE had leaked into the subsurface. Because PGDP was already committed to characterizing the Drop Test site by drilling numerous boreholes into the shallow aquifer, there was a significant cost advantage to using a shallow contaminated aquifer system rather than a deeper one. The decision to conduct the field test at PGDP with Martin Marietta Energy Services was endorsed by Mr. Jeff Walker of EM-50 (Germantown, MD) during a telephone discussion on February 17, 1993.

However, on December 3, 1993, after one full year of field testing at the Drop Test site, PGDP decided to abandon the site because it had become clear that the shallow formation was not the high permeability sand and gravel PGDP first thought it to be. Rather, analysis of a core sample from the Drop Test Site at the State University of New York at Buffalo (SUNY-Buffalo) indicated that it was a poorly sorted material composed of clays and silts (10%), sands (24%), and gravel (63%). (Cores from the Drop Test Site could be shipped to Buffalo because they were not radioactively contaminated; this was not the case with the C-400 cores.) This soil material had a hydraulic conductivity of much less than 0.001 cm/s, which is the minimum acceptable hydraulic conductivity for the Phase 1 test. In a ground-water system with a hydraulic conductivity of less than 0.001 cm/s, the period of surfactant injection would be of the order of months—not days—for the surfactant solution to migrate out 10 feet from the injection well, and an equally long period of extraction. Because the Statement of Work clearly indicated that the test should be in a sand aquifer and therefore only a week of field work had been budgeted, the Drop Test site was clearly unsuitable for use for this test (see Progress Report dated January 12, 1994, ISD 15).

A second site at PGDP, the C-400 site, was chosen because a particular well at the site (MW-156) had a sufficiently high hydraulic conductivity and had TCE concentrations greater than 100 mg/L, which suggested a nearby TCE DNAPL zone. Thus, as the Statement of Work indicated, an existing well could be employed. Consequently, a Work Plan for this new site was prepared in January and February 1994.

1.4 Scope Limitations

Three issues arose prior to the test which affected the original scope of the field test. First, Sandia National Laboratories was not able to subcontract with INTERA to test the effectiveness of the surfactant in the laboratory. Second, Martin Marietta Energy Systems' policy prevented INTERA from having cores of the RGA sent to SUNY-Buffalo for testing with the surfactants deemed suitable for injection. Third, the original preferred surfactant for the field test did not meet the State of Kentucky's acceptance criteria. Because these issues affected testing the efficacy of micellar-surfactant solutions prior to injection, it is necessary to discuss their importance in the hope that they might be resolved before the commencement of Phase 2.

1.4.1 Difficulties in Contracting with Sandia National Laboratories

The original Statement of Work (SOW) of the contract included provision for work to be undertaken at the Sandia National Laboratories. The proposed role of Sandia in the Phase 1 study was identified in paragraph 2 of Task 1.2 of the SOW. The tests at Sandia concerned laboratory-scale and bench-scale solubilization experiments

employing single- and multiple-component DNAPLs with the surfactant blend identified by Dr. Fountain at the State University of New York at Buffalo (SUNY-Buffalo).

DOE Albuquerque and DOE/METC were unable to reach agreement on the issue of the permissibility of Sandia National Laboratories being a subcontractor to INTERA for this work (J. Harness, METC, personal communication). This disagreement was noted in each monthly progress report submitted by INTERA to METC, beginning with that of June 18, 1993 (ISD 8). Therefore INTERA recommended to DOE (see Cost-to-Complete Proposal dated September 28, 1994) that the Phase 1 SOW should be changed to reflect the fact that these tests cannot be included in the Contract. The inability of Sandia to assist in the assessment of the surfactant was a considerable disadvantage to the project.

1.4.2 Difficulties in Transfer of RGA Cores to SUNY-Buffalo

During 1993, when the focus of the field work was on the Drop Test site, PGDP sent a core to SUNY-Buffalo for use in surfactant screening and hydrogeological characterization of the HU2 formation (see Figure 3.2). During the spring of 1994, there were prolonged and ultimately unsuccessful discussions between Martin Marietta Energy Systems at Oak Ridge, SUNY-Buffalo, DOE/METC, and INTERA over the shipping of a second core to SUNY for testing with surfactants which appeared to be suitable for employment in the RGA (HU4-5). This second core was to be taken from the PGDP core archives representing aquifer materials from the RGA near MW-156.

The difficulty in transferring this second core appears to have arisen from the presence of alpha and beta emitters in the aquifer samples (gross alpha = 3-5 pCi/g; gross beta = 6-10 pCi/g). The alpha emitters might include U, Pu, or other actinides, while the beta emitter would likely be ⁹⁹Tc. Lawyers for Martin at Oak Ridge wrote SUNY-Buffalo requesting changes to SUNY's Radioactive Materials License to allow for (1) the presence of tritium in these samples, (2) an extension of the license to include elements with atomic numbers 84 through 98 (i.e., the actinide series, radium etc.) and (3) concentrations of up to 100 mCi for isotopes with atomic numbers 84 to 98. SUNY responded that tritium was already covered and that the requirement for a 100 mCi quantity of each radioisotope with atomic number 84 to 98 was unreasonable in the light of the measured contamination, but that SUNY nevertheless was willing to explore changes to its license. Unfortunately, these changes could not be implemented before the test was undertaken in August 1994.

PGDP assisted in determining the nature of the aquifer materials by submitting a sample to the Oak Ridge National Laboratory for x-ray diffraction analysis. This testing

revealed that more than 90% of the clay-sized fraction of this sample (~ 0.7% of the total sample, i.e., boring H007, 63-69 ft, sample #4382) was composed of quartz, with lesser amounts of kaolinite, smectite and hematite (memorandum from Dr. Mark Elless, Oak Ridge National Laboratory, to K.R. Davis, PGDP, dated 2.18.94). Therefore, it appears probable that the total concentration of smectite, an expandable clay mineral which could readily sorb surfactants, would be about 0.02% of the total sample. Such a concentration would be unlikely to exert a pronounced negative effect on surfactant injection within the RGA.

1.4.3 Difficulties with Employment of the Preferred Surfactant

On March 24, PGDP and INTERA made a presentation to the Division of Waste Management, Environmental Protection Cabinet, of the Commonwealth of Kentucky concerning the proposed field test. The state representatives agreed to allow the test to go forward provided that:

1. additional scoping calculations were made using higher hydraulic conductivities in estimating the bond number (see Section 4) than had been used initially by INTERA; and
2. an alternative surfactant be chosen which did not contain reagent chemicals prohibited in Kentucky ground waters (Tergitol, an alcohol ethoxylate, contains unreacted reagent chemicals such as 1,4-dioxane and glycol ether which are prohibited in Kentucky ground waters).

Tergitol had been shown to perform excellently during the *in situ* solubilization of carbon tetrachloride at the DuPont chlorocarbon facility near Corpus Christi, Texas, by Dr. John Fountain of SUNY-Buffalo (Fountain, 1993). Tergitol was replaced with a sorbitan monooleate surfactant (T-MAZ 80K) which had sorbed appreciably during the Corpus Christi test but was chosen on the basis of the expected low clay content of the RGA and its FDA-approved status as a food-grade additive with good biodegradation properties and very low toxicity.

Later, the state of Kentucky indicated to PGDP that it would like to see the majority of the surfactant recovered. Consequently, by agreement with PGDP, the extraction period was lengthened to four times the injection period. This resulted in the length of the field test being extended from 49 man-days in the proposal to 90 days in the field, adding considerably to the cost of the field test. Final approval to conduct the field test was granted by the Commonwealth of Kentucky in June (letter of Caroline Haight, June 3, 1994).

2.0 LABORATORY EXPERIMENTS TO IDENTIFY AND CHARACTERIZE SURFACTANTS AND THEIR SOLUBILIZATION ACTIVITY

A significant factor in selecting a surfactant for the field test is its ability to solubilize TCE, PCE, and CTET. Toxicity, sorption, interfacial tension, and viscosity must also be evaluated before a final selection can be made. The following sections detail the analyses performed by SUNY to determine an appropriate surfactant for the C-400 site at PGDP.

2.1 Aquifer Characterization

Aquifer characterization data is critical in the selection of an appropriate surfactant for the field test. Grain size distribution, clay chemistry, and total organic carbon content determine the sorption of the surfactant to the soils (see Section 2.4). A knowledge of site water chemistry is critical because many surfactants are intolerant of high cation concentrations. No samples were made available to SUNY for characterization of the aquifer sediments or water from the C-400 site; therefore, no core characterization studies could be conducted. As a result, several assumptions had to be made to assure a reasonable choice of surfactants. Surfactant sorption is proportional to the smectite clay content and total organic carbon (TOC) content. Clay percentages have been reported to be considerably less than 1%, so clay adsorption was not expected to be significant. Because this aquifer is well below the surface, it was reasonable to assume that TOC values will be low and thus sorption will also be low. Because the water chemistry was unknown, the selected surfactant must be tolerant of a wide range of conditions to minimize potential problems resulting from variations in aquifer, soil, and water chemistry.

2.2 Solubilization

Examination of solubilization results for TCE, PCE (perchloroethylene), and CTET (carbon tetrachloride) suggest that sorbitan derivatives, ethoxylated amide derivatives, secondary alcohol ethoxylates, castor oil derivatives, and alkylaryl sulfonate derivatives are the best solubilizers. The results and experiments are discussed in detail below.

2.2.1 HLB Determination

Any organic liquid, such as a surfactant or a chlorinated solvent, can be ascribed an HLB number, i.e., a hydrophilic-lipophilic balance number. In order to form a microemulsion of a chlorinated solvent in a surfactant solution, it is best to match the HLB number of the surfactant solution with the HLB number of the chlorinated solvent.

Therefore, an initial task was to identify the HLBs of the three chlorinated solvents of concern: TCE, PCE, and CTET. Knowing these values, potentially suitable surfactants could be identified from previously reported values.

The HLB was determined for TCE, PCE, and CTET using the Tergitol secondary alcohol ethoxylates by gas chromatograph (GC) analysis of surfactant contaminant mixtures. Solutions of 25 ml of 1% surfactant in distilled water plus excess (>0.5 ml) TCE, PCE or CTET were prepared and stirred for a minimum of 24 hours. The TCE was dyed red with Sudan IV to enhance visibility. The solutions were then centrifuged at 3,500 rpm for one hour and analyzed.

The Tergitol with the highest solubilized concentration represents the HLB of the contaminant. An HLB of 14.7 was determined for TCE and CTET, and an HLB of 13.3 for PCE (see Table 2.1 and Figure 2.1). Once the HLB was established, quantitative gas chromatograph (GC) screening of nonionic and anionic surfactants was undertaken.

2.2.2 Solubilization of TCE

The ability of a 1% surfactant solution to solubilize TCE was determined by GC analysis of surfactant contaminant mixtures using a test parameter known as the maximum additive concentration (MAC). The MAC represents the maximum concentration of TCE or other contaminant which can be solubilized by a given volume. To determine the MAC, 25 ml solutions of 1% surfactant in distilled water plus excess (0.5 ml) TCE were prepared and stirred for a minimum of 24 hours. The TCE was dyed red with Sudan IV to enhance visibility. The solutions were then centrifuged at 3,500 rpm for one hour and analyzed. Additional volumes of TCE were added, stirred, and analyzed until a limit was achieved above which solubilization no longer occurred—the MAC. Initial screening of nonionic surfactants proceeded using 1% solutions of surfactants with HLBs ranging from 14 to 17. A total of 99 surfactants was screened, including 25 nonionics and 74 anionics (see Tables 2.2 and 2.3). The results are discussed below.

Examination of the data indicates that 10 of the 99 surfactants tested to date solubilize TCE at greater than 15,000 ppm (5 nonionics, 5 anionics) (see Tables 2.2 and 2.3). Among the nonionics, sorbitan monooleates and castor oil derivatives are the most promising, since they are food grade additives and have high solubilization values (>16,000 ppm). In addition, the soya sterol, with a solubilization value of about 29,000 ppm, is also promising. Within the anionics, alkylaryl sulfonates, sulfonate/nonionic blends, and phosphate esters show the best solubilization (>15,000 ppm). Castor oil sulfates and sulfonates are also good solubilizers, with solubilities ranging from 10,000 ppm to approximately 15,000 ppm.

2.2.3 Solubilization of Other Contaminants

In addition to TCE, PCE and CTET are other contaminants of concern. To determine if the other contaminants could be remediated efficiently using the same surfactants, 25 ml solutions of 1% surfactant plus 0.5 ml of PCE or CTET were prepared for GC analysis. The solutions were stirred for a minimum of two days and then centrifuged at 3,500 rpm for one hour before analysis.

Examination of the data indicates that the surfactants that are good solubilizers of TCE will also solubilize the PCE and CTET. Generally, PCE solubilizes less than TCE and the solubility of CTET showed more variation (see Tables 2.2 and 2.3). For example, the solubilization of TCE in the sorbitan derivatives is generally greater than 13,000 ppm, whereas the solubilization of PCE is generally less than 6,000 ppm and the solubilization for CTET ranged from 10,500 to 12,500 ppm. Four surfactants are good general solubilizers of all contaminants. These are no. 60 (a Sorbitan monooleate), no. 119 (an Alkylaryl sulfonate isopropylamine), no. 135 (C11-C15 secondary alcohol ethoxylate) and no. 154 (POE 7 Oleamide).

Comparison of the MAC to aqueous solubility of the various contaminants suggests that the increase in solubility of the contaminant is a function of the aqueous solubility. PCE with a solubility of 150 ppm attains 135 times the aqueous solubility. TCE with a solubility of 1,100 ppm attains a maximum of 23 times aqueous solubility.

2.2.4 Solubilization of Mixtures

Most of the tests were done using one component DNAPLs (TCE or PCE) because it eliminates possible complications arising from their interaction; however, mixtures are more typical of actual DNAPL contamination found in the field. To study whether co-solvent effects (i.e., the enhancement of DNAPL solubility due to the presence of dissolved components of another DNAPL) occur between the components of a DNAPL mixture, mixtures of PCE and TCE were prepared in the following proportions (TCE:PCE) for each surfactant under consideration (#18, #135, and #154): 90:10, 75:25, 50:50, and 25:75 (see Table 2.4).

Examination of the results indicates that the percent of TCE and PCE solubilized is approximately equal to the percent of TCE and PCE present in the DNAPL mixture. This indicates that co-solvent effects are insignificant.

2.3 Toxicity

The toxicity of any compound that will be injected into water-bearing zones is of concern since remediation is supposed to solve contamination problems, not exacerbate them. The surfactants under consideration are either food grade additives or food usage additives, which means that small amounts are not toxic. Surfactants in general have very low toxicity to mammals. Their LD50s (lethal dosage at which 50 percent of test animals are killed) are in the same range as sodium chloride (Swisher, 1987). Several types of surfactants, including many of the sorbitan derivatives (i.e. surfactants nos. 18, 60, 64 and 161) and the sodium lauryl sulfate are classified as food grade additives by the FDA (CFR 21.172). Many others are classified as suitable for use on food and food processing equipment, including the alcohol ethoxylates like surfactant no. 135. One major use of surfactants is in dish-washing soaps; thus, it is likely that small amounts of surfactants are ingested regularly by large segments of the population. Surfactants, however, have higher toxicities to aquatic life and thus the discharge levels to fresh water must be regulated.

All the surfactants currently under consideration are non-toxic to humans, especially at concentrations of 1% or 2%.

2.4 Sorption

Sorption refers to the combination of adsorption and absorption since they can seldom be independently evaluated in ground-water systems. Because surfactants are organic compounds, their sorption on clay and organic aquifer materials may be significant and thus may be an important factor in determining the cost of remediation. Sorption isotherms are typically Langmuirian with a steep slope prior to the critical micellar concentration (CMC) and then a nearly flat slope above the CMC. The shape of the isotherm has been explained by two different models: (1) the site model, and (2) the micelle model. The site model is a conventional interpretation in which it is assumed that by the time the CMC is reached, all sites on the surface have received a mono layer of surfactants. Sorption is minimal above this point. The micelle model is based on the distribution of surfactants in the aqueous phase. Below the CMC, surfactant molecules are present as monomers; their concentration in the aqueous phase is the same as the total surfactant concentration up to the CMC. Above the concentrations where micelles form, the concentration of the monomers remains at the CMC concentration. Any additional surfactant added to the system forms micelles and thus the aqueous monomer phase concentration does not change. Since micelles are not believed to be sorbed (they have strongly polar outer shells), sorption is controlled by

the monomer concentration up to the CMC and is flat above it as the monomer concentration stays constant. Data are consistent with either model.

Sorption varies with mineralogy of the aquifer, organic content, and water chemistry. In the target zone, there was assumed to be little organic carbon and minor amounts of smectitic clays (<< 1% reported; see Section 1.4.2). It is highly probable that these smectites control the sorption of the surfactants. Because smectite clays have large surface areas (Grim, 1968), surfactants as surface active agents should be expected to react strongly with them. Thus, in the presence of these clays, it is expected their percentage controls the sorption of the surfactants. Examination of sorption on smectite-rich sediments suggest that this is true. In fact, sorption in these soils is considerably higher than sorption on 3% organic soils tested in our laboratory. The results of the batch tests are discussed below.

2.4.1 Batch Tests

The clay mineralogy of the core sample received in September 1993 for the Drop Test site indicated that there was a maximum of 3% interlayered illite/smectite clay, with approximately 50% of the clay being smectites. Based on these data, batch tests were prepared using a mixture of 3% illite/smectite clay (40% smectite) and 97% sand for the following four surfactants:

- no. 60 (Sorbitan monooleate)
- no. 119 (Alkylaryl sulfonate isopropylamine)
- no. 135 (C11-C15 secondary alcohol ethoxylate)
- no. 154 (POE 7 oleamide).

Eight grams of soil were added to 40 ml of 1% surfactant prepared in water with a total dissolved solid content of 2,612 mg/L. The flasks were shaken for 24 hours to ensure that equilibrium had been reached. The solutions were then analyzed using either UV analysis or the cobalt thiocyanate dye method for nonionics (Greff et al., 1965). The difference between the initial and final concentrations of surfactant were used to calculate the retardation factor. The retardation factor (R) is a ratio of the velocity of water through a soil system to the velocity of a solute (such as a surfactant) through the same system. This ratio is a function of the sorption of the compound on the soil. Examination of the data suggests all surfactants under consideration have retardation factors lower than 5 in 3% clay soils with brackish water (see Table 2.5). Surfactant no. 119 was not tested because the solution was cloudy, making it unsuitable for use.

Subsequent analysis of similar aquifer material from borehole H007 (see Figure 3.1 for location) by Oak Ridge Laboratories indicates that there is only 0.02% clay in the target formation. Retardation decreases with decreasing clay (see Table 2.5) and thus the actual retardation values should be less than 2, making them acceptable for use.

In addition, the batch studies were conducted using water with a total dissolved solid content (TDS) of 2,612 mg/L, which is considered brackish water (Freeze and Cherry, 1979). Although the ground water in the Paducah aquifer is expected to be fresh water, no site water analyses were available to us and thus this composition represents a probable upper limit. Many surfactants are sensitive to ionic strength, and using brackish water ensures that the chosen surfactant will be tolerant of a wide range of water chemistry.

2.5 Surfactant Physical Properties

The physical properties of surfactant solutions, such as interfacial tension, critical micellar concentration, and viscosity affect their transport through the subsurface and their ability to solubilize contaminants. The interfacial tension between the surfactant and the contaminant determines whether the contaminant will be mobilized horizontally or vertically during surfactant flushing. The critical micellar concentration determines the point at which a surfactant can solubilize the contaminant through the formation of micelles. The solutions used during remediation must exceed this concentration to maximize contaminant solubilization. The viscosity of the surfactant solution partly determines whether it can flow easily through the subsurface. Examination of these properties suggests that surfactants nos. 18, 135, and 154 are viable for use at Paducah.

2.5.1 Interfacial Tension

Surfactants have the ability to lower the interfacial tension of the DNAPLs by several orders of magnitude, which in theory would allow horizontal movement of the DNAPL through traction of pumped ground water. However, reducing the interfacial tension of the contaminant sufficiently to mobilize the contaminant horizontally may also induce unwanted vertical mobility (Fountain, 1992; Palmer and Fish, 1992), making the task of DNAPL retrieval that much more difficult. Laboratory and field tests suggest that no vertical movement occurs if the IFT is at least 1 dyne/cm.

The IFT between TCE, PCE, and CTET and several 1% surfactant solutions were measured (see Table 2.6). Obtaining IFT values between TCE and the surfactant solutions proved to be problematic because emulsions formed on the interface, leading

to apparently elevated IFT values. However, comparison of IFT values between the surfactant solutions and the DNAPL compounds where emulsions did not form suggests that IFT values between the surfactant solutions and TCE should be similar to IFT values between the surfactant solutions and PCE or CTET. Thus, IFT values between a particular surfactant solution and TCE can be estimated from the IFT values between the surfactant solution and PCE or CTET. Using such an estimation, a 1% solution of surfactant no. 135, for example, has an IFT with TCE of between 5 and 7 dynes/cm. Examination of the results suggests that most of the surfactant types of interest at 1% solution have IFTs greater than 1 dyne/cm with respect to TCE, PCE, and CTET, and may be suitable for use.

2.5.2 Critical Micellar Concentration

Determination of the critical micellar concentration (CMC) is essential to the determination of the percent surfactant that can be used in the field test. The CMC value represents the minimum volume percentage of surfactant that can be used in solution and maintain the micellar structure necessary for contaminant solubilization. The CMC for surfactant no. 135 (linear alcohol ethoxylate) is reported as 0.011%, and for surfactant no. 18 (sorbitan monooleate) it is 0.012% (PPG Corporation communication to R.E. Jackson). Surface tension measurements confirm that the critical micellar concentration is considerably less than 1% for both surfactants (see Table 2.7). Thus, use of a minimum of a 1% surfactant solution ensures the presence of micelles during remediation.

2.5.3 Viscosity

Viscosity measurements were made on 1% and 2% solutions of surfactants nos. 18, 135, and 154 to ensure that the solutions have a low enough viscosity to permit movement through the aquifer. Examination of the data indicates that the viscosity of the 1% and 2% solutions is similar to that of water (see Table 2.8) and thus the solutions should flow at approximately the same rate as the ground water.

2.6 Solubilization Kinetics

Column studies were conducted to determine the relative solubilization kinetics between TCE and surfactants nos. 18, 135, and 154. The maximum concentration obtained and the number of pore volumes required to reach the maximum concentration were used to measure the solubilization kinetics between the contaminant and the surfactant.

Examination of the data in Table 2.9 suggests that, of the three target surfactants, no. 18 exhibits the best kinetics. It produced effluent containing 13,600 ppm of dissolved TCE within one pore volume, which is 84% of the MAC determined in vial tests (@ 16,000 ppm). Surfactant 154 reached 10,000 ppm TCE after 1 pore volume, which is 55% of the vial MAC (@ 18,000 ppm). Surfactant 135 had a thick layer of emulsion at the base of the column and there appeared to be some drainage of TCE from the column. Number 135 only attained 3,111 ppm after several pore volumes, which is only 24% of the vial MAC (@ 13,000 ppm). There are several possible reasons for this. The mobilization of the TCE to the bottom of the column may have resulted in reduced contact time and area for the surfactant, which would lead to lower solubilization. In addition, the presence of an immobile emulsion may have inhibited the solubilization process.

2.7 Surfactant Selection

The solubilization data suggest that the following surfactants have solubilization values that exceed 10,000 ppm for TCE and are thus possible candidates for use in the field test:

Surfactant No.	18 = POE20 Sorbitan Monooleate
	119 = Alkyl Aryl Sulfonate Isopropylamine
	121 = PEG 25 Soya Sterol
	128 = Aliphatic Phosphate Ester
	135 = C11-C15 Secondary Alcohol
	154 = POE 7 Oleamide
	213 = PEG 1100 Castor Oil
	249 = Na Sulfated Ester
	250 = Sulfated Castor Oil
	271 = 12 POE Nonylphenol

Examination of the sorption and toxicity data suggested that the best choice for the Paducah field test was a secondary alcohol ethoxylate (surfactant no. 135, commercial name: Tergitol 15-S-12). However, this surfactant proved unsatisfactory to the Commonwealth of Kentucky because of the possibility of its containing unreacted reagent chemicals which are prohibited in Kentucky ground waters. The second choice for the surfactant was a sorbitan monooleate (surfactant no. 18, commercial name: T-MAZ-80). It combines excellent solubilization ability with extremely low toxicity but can have a problem with sorption if the soils contain clays and organic materials. Tables 2.10 through 2.13 summarize the solubilization, IFT, viscosity and retardation factor data for surfactant no. 18 and the other sorbitan monooleates in the study.

Surfactant no. 18 increases TCE solubility to approximately 16,000 ppm in a 1% surfactant solution from an aqueous solubility for TCE of 1,100 ppm (see Table 2.10). Table 2.11 shows the interfacial tension between a 1% solution of surfactant no. 18 and TCE is 11.67 dynes/cm which is an order of magnitude greater than the 1 dyne/cm cut-off used in the study. Viscosity measurements made on 1% and 2% solutions of surfactant no. 18 are similar to that of water (see Table 2.12). It is a better performer than Tergitol 15-S-12 (surfactant no. 135) in these respects. It is also tolerant of a wide range of water chemistries ranging from brines to fresh water. It was not initially recommended because its sorption is higher than Tergitol; however, studies indicate that the sorption remains low on sediments if clay and organic contents remain low (see Table 2.13). If the characterization data supplied to SUNY is correct and the clay content is indeed below 1%, sorption should be minimal. Analysis of sorbitan monooleate concentration in solution is also easy, since it may be measured directly by UV adsorption. It is a chromophore, so no dye is required. Finally, the deciding factor in view of the objections raised to Tergitol by the State regulators (see Section 1.4.3), sorbitan monooleates are food grade additives as per CFR 21.172.840 and thus have very low toxicity and high biodegradability.

Surfactant no. 154 was our first alternate. It is a good general solubilizer and is tolerant of a wide range of water chemistry. Its sorption should be low if clay contents are < 1% and it has low toxicity.

The remaining surfactants are unlikely candidates for a variety of reasons. The soya sterol (no. 121) was eliminated because it is a specialty surfactant and its cost is prohibitive. Surfactants no. 119, 213, 249, and 250 precipitate in ground waters with high ionic strengths making them unsuitable for use where water chemistry is unknown. Nonylphenol ethoxylate (surfactant no. 271) may persist for extended periods in the subsurface due to low biodegradability, making them unsuitable for remediation efforts. Phosphate esters such as surfactant no. 128 hydrolyze rapidly, making them unsuitable.

3.0 THE FIELD TEST SITE

3.1 Contaminant Hydrogeology of WMU-11

The field test site is known as Waste Management Unit 11 (WMU-11) and is centered on monitor well MW-156, which is located at the southwestern edge of Building C-400 (Figure 3.1). Large volumes of TCE were used in C-400 to degrease electrical equipment. During an excavation in 1986, it was discovered that substantial amounts of TCE had escaped into the subsurface through a broken connection between the C-400 sump line and a concrete sewer. Estimates reported by Clausen et al. (1992) indicate that some 10,000 gallons (40,000 L) of TCE may have leaked through the broken connection. MW-156 is one of a nest of monitor wells installed at WMU-11 to monitor the concentrations of TCE in the ground-water zone beneath Building C-400.

The hydrostratigraphic profile for MW-155, which is adjacent to and somewhat deeper than MW-156, is shown in Figure 3.2 and summarized in Table 3.1. The well screen for MW-156 is plotted on Figure 3.2 and indicates that it is screened over a distance of 2 m at 19 to 21 m (63 to 70 ft) below grade in a zone of gravelly, fine to medium sand. A mean hydraulic conductivity equal to 3×10^{-3} cm/s has been measured by CH2M Hill (1992). The sand pack for MW-156 extends over 4 m from 18.5 to 22.5 m (61 to 75 ft) below grade. MW-155 monitors the lower part of the Regional Gravel Aquifer (RGA or HU5) and has a measured hydraulic conductivity of 4.4×10^{-3} cm/s. MW-156 monitors the upper part of the RGA, while MW-157 is screened in HU2 and has a measured hydraulic conductivity of 2.5×10^{-5} cm/s. Beneath the RGA is the McNairy formation, which, according to the MW-155 borehole log, is composed of sandy clay that would act as a capillary barrier to penetration of the TCE DNAPL.

The hydrostratigraphy of the surficial sediments beneath C-400 has been analyzed by Phillips (1992) using a number of boreholes (shown in Figure 3.3) together with cross section F-G. The hydrostratigraphic model along the cross section of the subsurface beneath C-400 is shown in Figure 3.4. The basal McNairy formation is overlain by the RGA, which appears to fine upwards. However, the hydraulic conductivities of MW-155 and MW-156, as determined by slug testing, are similar, which suggests that fine- and medium-grained sands are abundant within the RGA and dictate the measured hydraulic and capillary properties. The lacustrine deposits above the RGA contain interbeds of sand and gravel which may provide part of the vertical pathway for DNAPL migration, although PGDP staff have noted fractures in these deposits which provide a more plausible and direct pathway to the RGA.

Clausen et al. (1992) have presented a conceptual model of DNAPL distribution beneath C-400 which is reproduced as Figure 3.5. The concentrations of TCE observed beneath WMU-11 are shown in Table 3.2. They indicate significant contamination to the bottom of the RGA. However, both HU 2 and the upper RGA are especially contaminated. The level of contamination in these two zones, being greater than 10% of the aqueous solubility of TCE, is strongly indicative of the presence of TCE DNAPL zones (EPA, 1992) surrounding the wells. This zone probably is comprised of vertical fingers and horizontal pools of TCE, as shown in Figures 1.1 and 3.5, with the pools perched on capillary barriers and containing large amounts of residual DNAPL and, possibly, some free-phase TCE. Monitor wells indicate that the RGA is also contaminated with some PCE, indicating that the DNAPL is a multicomponent mixture.

3.2 Scenarios of TCE in the Regional Gravel Aquifer

The conceptual model of DNAPL migration beneath C-400 shown in Figure 3.5 appears to be derived from that proposed by Kueper (1991) in a review of the C-400 DNAPL problem. He noted that:

The volumes of DNAPL released at PGDP have the potential to migrate to significant depths below ground surface. The ultimate depth of penetration is dependent upon many factors, most of which cannot be practically determined.

Kueper concluded that "... it must be assumed that DNAPL has entered the McNairy formation unless it can be proven otherwise," and that DNAPL may be pooled in the RGA above the McNairy.

This does not appear to be the case at the C-400 site. Assuming that the McNairy is indeed a sandy clay as the MW-155 log indicates, the entry of DNAPL into the McNairy would require a DNAPL pool height of at least 4 meters, assuming (very conservatively) a maximum pore throat radius of the sandy clay of 1 μm and a TCE/ground-water interfacial tension of 10 dynes/cm (0.01 N/m). Such a pool would inevitably manifest its presence as free-phase TCE in MW-155. As it is, MW-155, at the base of the RGA, exhibits aqueous TCE concentrations of 2 mg TCE/L, which is too low to allow the nearby presence of substantial amounts of residual TCE DNAPL, let alone a pool of such thickness.

A scenario similar to that of Kueper's was described by McConnell et al. (1994) based on numerical simulation of the C-400 TCE release. McConnell et al. concluded that "... residual TCE in the RGA averages about 5% and is fairly uniform; however, a

large pool of TCE which is only a few centimeters thick is formed at the RGA-McNairy interface." Similar objections must be made to this scenario as to that of Kueper.

Figure 3.6 shows a schematic of the subsurface beneath C-400 which assumes that the pathway of ground-water recharge and DNAPL migration to the RGA is via a network of interconnected fractures. This aspect of the scenario is consistent with the observations made at the nearby PGDP landfill of deep fractures in the silts and clays extending all the way through the Upper Continental Deposits to the top of the RGA (Clausen et al., 1992, p.106) and with the measurement of dissolved oxygen and below neutral pH in MW-155 ground-water samples (see Section 5.8).

Scenario A of Figure 3.6 shows the distribution of TCE DNAPL within the RGA as a zone located upgradient of MW-156 and limited to the upper RGA. Scenario B in Figure 3.6 is that predicted by McConnell et al. (1994). These two scenarios have been simulated using INTERA's version of the UTCHEM multiphase, multicomponent simulator developed by G.A. Pope, K. Sepehrnoori, and colleagues of the Department of Petroleum and Geosystems Engineering of the University of Texas at Austin.

3.3 Simulation of TCE Scenarios in the Regional Gravel Aquifer

All the scenarios in this section were performed using UTCHEM (the University of Texas Chemical Flood Simulator (Saad, 1989)) a three-dimensional, multi-phase, multi-component, finite difference simulator originally designed to model enhanced-oil recovery.

Two scenarios were modeled in an effort to match the aqueous TCE concentration data in MW-155, 156, and 178. Both involved an area of residual TCE saturation that was allowed to dissolve into the surrounding water until steady state was achieved. Figure 3.7 is a schematic of the cross section that was simulated in both scenarios. The only differences between the two scenarios are the location of the DNAPL source and the size of the grid blocks. The cross section consists of four different stratigraphic layers representing the ground-water zone beneath building C-400 in the vicinity of wells MW-155, 156 and 178. The cross section has a length of 229 m (750 ft) and a depth of 16.5 m (54 ft). The upper 2.4 m represent the bottom of the Lacustrine units consisting of sandy clay. The next 5.5 m represent the upper half of the RGA consisting of sand. The next 6.1 m (20 ft) represent the bottom half of the RGA consisting of gravel. The bottom 2.4 m (8 ft) represent the top of the McNairy Formation, consisting of sandy clay. Three 5-cm (2-inch) diameter wells are completed within this cross section: MW-155, 156, and 178. The first well, MW-156, is screened from -19.2 to -21.3 m (-62 to -70 ft). The next well, MW-155, located 9 m to the north, is screened

from -26 to -28 m (-86 to -92 ft). The final well, MW-178, located 64 m to the north, is screened from -18.9 to -20.7 m (-62 to -68 ft). The locations of these wells are shown on Figure 3.3. The DNAPL source for Scenario A is represented by the dark horizontal rectangle within the cross section. Its center is located 27.4 m (90 ft) south of the first well and just within the Upper RGA. Its length is 27.4 m and its height was 0.6 m. This source consists of DNAPL at a residual saturation of 0.15 (i.e., 15% of the pore space is occupied by TCE DNAPL), which means there are 268 liters (71 gallons) of TCE present in this DNAPL zone. The DNAPL source for Scenario B is represented by the dark vertical rectangle at the south of the schematic. Its center is located 45.7 m south of the first well and spans the entire RGA. All blocks within this source are at 0.05 residual saturation TCE DNAPL, except for the bottom one, representing a pool 7.6 cm high, with a residual saturation of 0.40, containing 591 liters (156 gallons) of TCE. This scenario is similar to that of McConnell et al. (1994).

The 25 x 27 block simulation grid for Scenario A is shown in Figure 3.8. The 25 x 32 block simulation grid and schematic for Scenario B is shown in Figure 3.9. The model parameters are the same for both scenarios and are shown in Table 3.3. The left and the right boundaries of the model are constant-pressure boundaries which establish a ground-water gradient of 0.00175 m/m. Ground water entering the boundaries is uncontaminated. The dispersion values were determined by changing the model dispersivities until the aqueous TCE concentrations of the model and the field data were similar.

Both scenarios involved the same simulation, that is, the dissolution of residual or pooled TCE and then the transport through advection and dispersion of the aqueous TCE, creating a plume. When the flow achieved steady state and the plume was no longer growing, the simulation was stopped. The concentration plumes of the two scenarios are shown in Figures 3.10 and 3.11 in units of volume of TCE per unit volume of water. The concentrations at the wells of both scenarios and the field sample concentrations are shown in Table 3.4. Since the well screens covered more than one cell block, the concentrations of all cell blocks used in the well were averaged. As can be seen from Table 3.4, the concentrations of Scenario A are much closer to the measured values than Scenario B's values are, indicating that it is a more likely occurrence. In fact the simulated MW-155 aqueous TCE concentration for Scenario B is two orders of magnitude larger than measured.

It was also determined by numerical simulation that these aqueous TCE concentrations could be simulated with a DNAPL source confined to the Upper Continental Deposits above the RGA. This finding underlines the uncertainty of the knowledge of the DNAPL zone, although Scenario A of Figure 3.6 is the most likely scenario because of the probable presence of through-going fractures in the Upper Continental Deposits.

4.0 DESIGN OF FIELD TEST

The field test that INTERA undertook for DOE at PGDP is based on the concept (Jackson and Pickens, 1994) that DNAPLs can be identified in the subsurface by contacting the DNAPL with a micellar-surfactant solution. This occurs through the enhancement of the effective solubility of the DNAPL chemical by incorporating the DNAPL molecules within surfactant micelles, which are colloidal aggregates of surfactant molecules (see Figure 1.2). By the injection and extraction of micellar-surfactant solutions into a geologic formation, the DNAPL zone is contacted by the solution and the aqueous concentrations of the DNAPL chemicals are raised above their aqueous solubilities. This allows the positive identification of the DNAPL zone around the injection well and also allows the identification of other components in the DNAPL—in this case, PCE, which is suspected of being present in the DNAPL with TCE. This test also provides an excellent means of testing the efficacy of the surfactant for solubilizing the DNAPL, which was the primary purpose of the field test.

The particular configuration chosen for the field test at PGDP was a single-well injection-extraction test using MW-156, i.e., surfactants were first injected into the subsurface through MW-156, pushed out 10 feet into the aquifer, and then extracted by back production through the same well. The rate of surfactant injection is a critical issue in that the rate should not cause mobilization of the TCE DNAPL while, at the same time, the surfactant front should migrate a significant distance into the aquifer over a reasonably short period of time. The concern with DNAPL mobilization is that it may result in more DNAPL seeping into the lower RGA than most probably is already present. While this would not seem to make matters much worse than they already are, it was not the intention of the test to promote deeper migration of the DNAPL, and the State of Kentucky demanded assurance that the McNairy formation would not be jeopardized further. Thus, the potential for DNAPL mobilization was addressed before the test.

Computations of DNAPL mobility require the computation of the interfacial, advective, and buoyancy forces affecting the fate of the DNAPL in the porous media. The two dimensionless numbers which measure these three forces are the bond (N_b) and capillary (N_c) numbers, which are (Pennell et al., 1984):

$$N_b = \frac{\Delta \rho g k k_{rw}}{\sigma}$$

$$N_C = \frac{k \rho g i}{\sigma} = \frac{q \mu_w}{\sigma}$$

where:

- k = intrinsic permeability of aquifer (cm^2);
- k_{rw} = relative permeability of aquifer to water (dimensionless);
- ρ = density of the aqueous phase (g/cm^3);
- σ = interfacial tension (dynes/cm or $\text{g cm/s}^2 \text{ cm}$);
- g = acceleration due to gravity (cm/s^2);
- $\Delta \rho$ = density difference between DNAPL and water (g/cm^3);
- i = hydraulic gradient (dimensionless);
- q = Darcy velocity (cm/s); and
- μ_w = absolute viscosity of water in centipoise (g/s cm).

Assuming an injection rate of 1 gpm, which will produce a Darcy velocity of 530 cm/day at MW-156, and an interfacial tension of TCE (vs. ground water) of 10 dynes/cm, one obtains $N_C = 6.2 \times 10^{-6}$. Assuming a density difference between TCE and ground water of 0.46 g/cm^3 , an intrinsic permeability of $3 \times 10^{-8} \text{ cm}^2$ ($K = 3 \times 10^{-3} \text{ cm/s}$), and a relative permeability of 0.1, one obtains $N_B = 0.2 \times 10^{-5}$. The introduction of a surfactant solution might change the interfacial tension (IFT) between micellar-surfactant solution and the DNAPL. However, a sorbitan monooleate surfactant solution (T-MAZ 80K) with an IFT of 11 dynes/cm (vs. TCE) was injected, consequently no pronounced changes in either dimensionless number were expected. Even if the IFT had decreased to only 3 dynes/cm, values of $N_C = 2.0 \times 10^{-5}$ and $N_B = 0.6 \times 10^{-5}$ would have been obtained.

Abriola et al. (1993) have shown that PCE, a chlorinated solvent with similar properties to TCE, is initially mobilized in the vertical direction when the sum of the capillary and bond numbers is approximately 2×10^{-4} (see Figure 4.1). For coarse sand (i.e., 20-30 mesh), the critical number could be as low as 4×10^{-5} . Since the sum of the capillary and bond numbers for the 1 gpm surfactant injection-extraction test was approximately 0.8×10^{-5} , there was a safety factor of about twenty inhibiting vertical mobilization. If it was assumed that the logs of MW-156 were incorrect and that the sand adjacent to the well screen was coarse-grained rather than fine- to medium-grained (as reported and as indicated by the hydraulic conductivity value), then the factor of safety was about ten. Furthermore, it should be appreciated that the most probable consequence of vertical mobilization is the partial desaturation of pores and the redistribution of DNAPL elsewhere in the same formation, not a catastrophic cascading of DNAPL to greater depths.

Assuming the hydraulic conductivity of the RGA is of the order of 10^{-5} m/s, the aquifer thickness is 2.1 m (set equal to the length of the well screen), and an injection rate of ~1 gpm (3.8 L/min), it takes approximately 4 days for a dilute surfactant solution to migrate 3 m radially from MW-156, assuming no significant surfactant sorption. Thus, the volume of injectate was estimated to be 96 hrs x 3.8 L/min x 60 min/hr = 21,800 L. Employing a 1% surfactant solution, approximately 60 gallons of pure surfactant would be injected.

The arrival time of 96 hours was computed using the GTFM code by the equation:

$$t = \frac{\pi r^2 b \theta}{Q}$$

where $b = 2.1$ m, $\theta = 0.35$, $Q = 3.8$ L/min, and $r = 3.1$ m. The injection pressure was computed using the GTFM code as 1.7 m using a specific storage of 10^{-5} m⁻¹ and a constant pressure boundary set at 1,500 m.

Two conditions were considered which could contribute to a situation by which the surfactant front would not migrate as far as 3.1 m radially. In the first case, surfactant sorption and/or precipitation could retard surfactant migration. However, the high dissolved TCE concentrations recorded at MW-156 indicate that DNAPL is quite close to the well. Consequently, should the surfactant have a retardation factor = 1.2, a migration distance of over 2.4 m would be attained, which was deemed sufficient for the purposes of this test. In the second case, because the screen length was approximately half the length of the sand pack, it was possible that injected surfactant might not enter the aquifer adjacent to the well screen. However, because of the low injection rate used, this was not deemed particularly likely.

To recover as much injected surfactant as possible for regulatory purposes, it was planned to extract a volume of ground water four times the injected volume, i.e., about 90,840 L.

5.0 THE FIELD TEST

5.1 The Injection/Extraction System

The test (see Section 4.0) consisted of a surfactant injection phase followed by an extraction phase in a single well, MW-156. As such, an equipment configuration versatile enough to accommodate both circumstances was required. The function of the injection system was to transfer a surfactant mix stored in tanks at the surface to the well. The function of the extraction system was to back produce the surfactant solution injected and any DNAPL which had been solubilized. Work began on setting up the injection/extraction system on July 27, and continued through August 1, 1994.

Figure 5.1 is a schematic showing the injection configuration. Reference to the figure shows that the surfactant mix was pumped from the tanks by a centrifugal pump located on the surface. Reinforced Teflon hose connected the pump to a drain at the base of each tank. Multiple valves installed in line provided for control of flow and divided the system into segments that could be sealed and individually drained upon disassembly, minimizing the risk of spillage. The surfactant mix was transferred into the well by means of a brass drop pipe installed to a depth of 18 m below grade, near the top of the screened interval.

Figure 5.2 is a schematic of the extraction system. Reference to the figure shows that the centrifugal pump at the surface of the injection system was replaced by an electric submersible pump downhole and that the metering system (i.e. rotameter and totalizing meter) has been reversed due to the change in direction of flow. The system discharge lines were connected to the top of the discharge tanks. Drop pipes were utilized in the tanks to minimize foaming of the surfactant solution as it was pumped in.

The area immediately around the well head and tank storage area was divided into the exclusion and contaminant reduction zones shown on Figure 5.3. The exclusion zone defined the area where contamination could occur. The contaminant reduction zone provided a transition zone between the exclusion zone and clean area of the site. Personnel entering the exclusion zone were required to have the health and safety training required by 29 CFR 1910.120, the 40-hour health-and-safety course offered by PGDP, and the level of personnel protection specified by the project Health and Safety Plan.

The exclusion zone was provided with a 20 mil cross laminate high density polyethylene secondary containment liner to guard against possible contamination of the site due to spillage. The liner was laid over a set of forms which created a series

of secondary containment cells. In addition, a two-inch trash pump was kept on site so that, in the event of a spill, the spillage could be immediately pumped into an empty tank.

The injection/extraction tanks and surfactant drum were stored in the area identified as the Unloading Bay on Figure 5.3. This bay is designed to contain spills. It is constructed of concrete being sloped from both ends to a central drain. Placing the secondary containment liner down in the bay and adding forms to support the liner at each end provided much more spillage containment volume than required. Plywood sheeting was laid over the liner to protect it from the forklift traffic bringing tanks in and out of the bay.

A consideration in the overall design of the plumbing system was that it should maintain integrity, without leaking or rupturing, if a valve was inadvertently closed during operation or a line became clogged. All materials, including the reinforced Teflon hose, were chosen with this criterion in mind. In addition, a submersible pump was chosen which allowed the pumping rate to be controlled by adjusting the speed of revolution of the pump motor rather than running a pump at a constant speed and constricting flow by means of a valve. This assured that even if there was a break in the discharge line, no more than approximately 3.8 L/min would be released until the personnel on site could shut the system down.

The rate of injection and extraction was closely monitored and controlled. Both the injection and extraction systems were equipped with a one-gallon-per-minute flow control or dose valve, a rotameter, and a totalizing flow meter. These items were mounted on a vertical panel to facilitate proper function and monitoring. Flow rates were checked and adjusted, if required, at intervals not exceeding an hour during all phases of the test (i.e., pre-test, injection, and extraction).

Power and lighting were supplied by PGDP, as were the 1,200-gallon (4,500-liter) polyethylene tanks used to store the surfactant solution and extraction water. All water extracted was picked up and transferred to tanker trucks by PGDP Waste Management. The water was then transported to an incinerator at DOE Oak Ridge, Tennessee.

As it was critical that test operations were not interrupted, spare pumps, hose, fittings, and a generator were in place if needed. The only piece of equipment that failed during the test was a centrifugal pump used to inject the surfactant solution. This pump was immediately replaced and operations resumed.

5.2 The Pre-Test

A pre-test of the system was conducted on August 3 and 4, with water being extracted from well MW-156. The purpose of the pre-test was to establish background concentrations of dissolved TCE, test the system's operation, and allow the field team to function together under actual test conditions.

A test of system integrity was conducted before initiating injection/extraction operations. The valves at the well head and discharge tank were closed and the system was pressurized with nitrogen gas. The initial test revealed several loose connections which were tightened and the system was repressurized. The system was then monitored for half an hour with no loss of pressure.

A total of 3,796 L (1,003 gallons) of water was extracted between 1030 hours on August 3 and 0243 hours on August 4. The water was directed to a storage tank for handling as described in Section 5.1.

5.3 Injection Operations

A total of 19,553 L (5,166 gallons) of surfactant solution was pumped into well MW-156, beginning at 1830 hours on August 5 and ending at 0949 hours on August 9. The surfactant, T-MAZ 80K (PPG Industries, Inc.), was prepared as a 1% solution with drinking quality water obtained at PGDP. A Materials Safety Data Sheet for the surfactant is given in Appendix A. The rate of injection was 3.8 L/min.

The surfactant mixture was prepared in the injection tanks on site. Figure 5.4 is a schematic showing the mixing apparatus. Once the injection tank was filled with drinking-quality water, surfactant was transferred from the storage drum to a metered feed tank. With the recirculating pump in operation, the surfactant was bled into the system for mixing. The recirculating pump was kept in continuous operation during injection until the fluid level in the tank had been drawn down to the point that the mixing action caused the surfactant solution to foam.

During mixing operations, the flow rate of surfactant into the process was closely monitored. Samples of the mixture were collected at a minimum of hourly intervals by raising the diffuser in the tank and filling the sample vial from a diffuser port. These samples were visually monitored for the presence of surfactant globules. The surfactant mixture in each tank was measured prior to allowing the mixture to be injected into the subsurface. In addition, a sample of the surfactant mixture from each

tank was captured at the system sampling connection during injection and analyzed. At no time was anything injected other than thoroughly mixed 1% surfactant solution.

During the course of injection, the rate remained generally steady at one gallon per minute plus or minus a few hundredths of a gallon. Only one significant deviation from this rate occurred during the first day of injection. For a period of less than one hour the average injection rate fell to 2.4 L/min. The average overall flow rate for the 87.32 hours of injection was 3.73 L/min.

Although the rate of injection remained constant, the water level in the well increased steadily over the entire period of injection. This was during the same period that the water level in piezometer 109, completed in the same stratigraphic horizon and monitored as a control point, fell. Piezometer 109 is located approximately 450 m due south of well MW-156. Figure 5.5 shows the injection rate and water levels in well MW-156. The water level in piezometer 109 during this time period is shown in Figure 5.6. The continuous rise in the water level at MW-156 suggests that the hydraulic conductivity of the aquifer/filter pack was progressively degraded. Possible explanations for this degradation are adhesion of the surfactant to the aquifer materials and some of the surfactant coming out of solution in the aquifer. Injection data, including injection rates and water levels, are given in Appendix B.

5.4 Extraction Operations

Injection of the surfactant solution ended at 0949 hours on August 9, 1994. At that time, the system was reconfigured for extraction operations. Fluid extraction was initiated at 1400 hours the same day and continued until 1100 hours on August 25, 1994. During that time, a total of 86,949 liters of fluid was removed from the well. This water was directed to polyethylene tanks for temporary storage at the bay area prior to removal. PGDP Waste Management staff periodically retrieved the tanks for transfer and disposal of the water, as described in Section 5.1.

The rate of extraction was verified and adjusted, if required, at a minimum of once an hour during the extraction phase. Although the rate periodically deviated from 3.8 L per minute, these variations were of short duration. The average extraction rate for the entire test was 3.80 L/min (1.005 gpm).

Water-level changes in the well during the first few days of extraction lend support to the possibility that the hydraulic conductivity of the aquifer/filter pack was degraded by injection operations. Figure 5.7 shows the extraction rate and water level in well MW-156. The water level in control piezometer 109 during this period is shown in

Figure 5.8. Water levels typically respond to the initiation of extraction operations by falling. The level in MW-156 actually rose for the first two days and did not begin to decline steadily until the fifth day. Such behavior would be expected if material in the aquifer/filter pack responsible for a general degradation of hydraulic conductivity were being removed by back production. Water levels at the control point, Piezometer 109, were generally declining during this same period. Extraction phase data, to include extraction rates and water levels, are given in Appendix C.

Upon completion of the test, the extraction system was disassembled and all equipment removed to on-site storage facilities. Equipment which had come into contact with the extracted ground water was first scanned for radiation by personnel from the PGDP Health Physics Department and decontaminated at an on-site decontamination pad before storage.

5.5 Sampling Procedures

Water samples were collected at MW-156 and MW-155 throughout the test. Samples from MW-156 were analyzed for trichloroethene (TCE), surfactant, technetium-99 (Tc-99), temperature, and dichloroethene (DCE). MW-155 samples were analyzed for TCE, surfactant, dissolved oxygen (DO), temperature, and pH. By design, more samples were collected than were analyzed. Water samples were collected from MW-156 and MW-155 as outlined in the Sampling and Analysis Plan. PGDP staff collected the samples from MW-155, and INTERA and PGDP staff collected the samples from MW-156.

The MW-155 samples were collected according to the projected sampling schedule in the Sampling and Analysis Plan, except that two samples per day were collected during the surfactant injection phase also. The number of samples collected from MW-156 also exceeded the number projected in the Sampling and Analysis Plan. This was because of the unanticipated slow recovery of TCE concentrations in MW-156 during the extraction phase. The slow return to background TCE concentrations required an extension of the period during which frequent sampling was needed. Thus, hourly samples were collected during the first 4.5 days of the extraction phase. This period was followed by a 2-day period of bi-hourly sampling before the sampling frequency was lowered to 6 times per day.

INTERA analyzed for TCE and surfactant concentrations in MW-155 and MW-156 samples at the PGDP laboratory trailer (T-17). These samples were collected in 20 mL glass EPA vials with teflon septa. Triplicate samples from MW-156 were collected at least once for every 10 samples collected. All the samples from MW-155 were

triplicates, but only two triplicates per set were given to INTERA for analysis. The remaining triplicates from MW-155 were analyzed by PGDP.

In addition to these samples, 2 to 6 Tc-99 samples were collected daily from MW-156. These samples were collected in 500 mL polyethylene bottles containing nitric acid preservative.

Finally, additional samples for "IR Qual," alpha and beta radiation, and volatile organic compounds (VOCs) were collected in containers provided by PGDP. The VOC samples were analyzed by PGDP for TCE, 1,1,1-trichloroethane, and pyrene.

Sampling from MW-156 began by opening the valve on the sample line to allow about one liter of water to flush through the line into a waste bucket. The flow was then maintained at a rate of approximately 100 mL/min while sample bottles were filled. The temperature of the sample port purge water was frequently measured and recorded in the sample log book. For VOC samples, the amount of headspace in the bottles was always kept below 0.1 mL and almost always below about 0.01 mL.

The small amount of headspace allowed in the sample vials has a negligible impact on the concentrations of TCE measured. A headspace of 0.1 mL can only contain about 0.003 mg TCE as estimated by the following calculations. First, if it is assumed that the water contains TCE at a concentration (C) of 100 mg/L, then according to the Henry's Law constant for TCE ($H_{TCE} = 0.007 \text{ atm}\cdot\text{m}^3/\text{mol}$, Schwille, 1988), the partial pressure of TCE in the headspace (P_{TCE}) would be

$$P_{TCE} = \frac{H_{TCE} * C}{MW_{TCE}} = 0.0053 \text{ atm.}$$

MW_{TCE} is the molecular weight of TCE (131.5 g/mol). The mass of TCE in the headspace (M_{hs}) can be estimated from the following equation

$$M_{hs} = \frac{P_{TCE}}{P_T} * G * V_{hs} * MW_{TCE} = 0.003 \text{ mg}$$

where P_T is the total pressure (1 atm), G is the standard molar volume for an ideal gas (0.0446 mol/L), and V_{hs} is the volume of headspace (0.1 mL). The mass of TCE in the water (M_{aq}) is calculated to be

$$M_{aq} = C * V_{aq} = 2 \text{ mg}$$

where V_{aq} is the volume of water (20 mL). Comparing M_{hs} to M_{aq} reveals that 99.85% of the TCE is in the water. Thus, volatilization of TCE into a very large 0.1 mL headspace could only decrease the aqueous concentration by 0.15%. Of course, the error would be even smaller in water containing surfactant above the critical micelle concentration. Certainly, the potential error in TCE analyses introduced by a large 0.1 mL headspace in a 20 mL vial is negligible compared to the error introduced by the injection of sample to the gas chromatograph (GC), the calibration of the GC, and the detector response. The accuracy and precision of GC analyses is discussed in depth later.

All samples from MW-156 were immediately placed in coolers containing frozen "blue-ice" packs. Within 24 hours they were transferred either to a refrigerator in the field laboratory trailer or to PGDP. Those transferred to PGDP were accompanied by chain-of-custody forms. Samples from MW-155 were transferred to INTERA upon collection and were immediately placed in the field coolers to await delivery to the refrigerator in the field laboratory trailer.

5.6 Field Analytical Procedures

The field analytical procedures were outlined in detail in the Sampling and Analysis Plan. Basically, these procedures refer to the analyses performed by INTERA at the field laboratory trailer, i.e., surfactant, TCE, and some DCE analyses.

5.6.1 TCE and DCE Analysis

All the field TCE analyses for samples from MW-156 were performed on an SRI 8610 gas chromatograph (GC) equipped with an electrolytic conductivity detector (ELCD). At first, this GC was used to analyze samples from MW-155, but because the TCE detection limit for the ELCD is about 1 mg/L, the backup GC, an SRI 8610a with an electron capture detector (ECD), was used for the remaining samples from MW-155. The 8610a with ECD was also used to measure DCE concentrations in a few samples from MW-156.

Injections were performed using a 1 microliter Hamilton 7000 series syringe with Chaney adapter. The syringe was cleaned in methanol (5 pumps) and then in deionized rinse water (5 pumps) before collecting a microliter of sample. To check the effectiveness of this cleaning procedure, a microliter of the deionized rinse water was frequently injected into the GC. No more than a negligible TCE peak ever resulted.

The sample was collected by inserting the needle through the teflon septum of the 20 mL sample vial, pumping five times to remove any air bubbles or residual from the deionized rinse water, and slowly filling the syringe. Within about 5 seconds, the sample was rapidly injected onto the column of the GC.

Before each batch of analyses, the GCs were allowed to warm up and calibration standards were run. Retention times, peak heights, and peak areas were recorded in the laboratory log book. Each calibration standard was run at least twice to ensure reproducible measurements. When the peak area of a repeated injection of a calibration standard differed from the previous measurement by more than 10%, an additional injection was performed for an additional peak area measurement. Drift in GC response was monitored by rerunning standards after about every 10 samples analyzed. When the drift appeared greater than 10%, all of the calibration standards were rerun.

Occasionally, the response of the 8610 with ELCD drifted and/or varied markedly. When this happened, the capillary tubing of the detector was inspected. If the tubing was believed damaged, it was replaced. During the course of the field test, the capillary tubing was replaced three times. The 8610a with ECD proved more reliable than the 8610 with ELCD. Measurements were always reproducible and drifting was never a problem after the initial warm-up period.

5.6.2 Surfactant Analysis

The concentration of surfactant, T-MAZ-80K, was measured using a Hitachi U-2000 UV spectrophotometer and rectangular quartz cuvettes. The spectrophotometer measures the difference in absorbance at a given wavelength between a cuvette containing an aliquot of sample and one containing a blank.

A standard of 0.1% surfactant in deionized water was used to determine the optimum wavelength for concentration measurements. The scan from 200 to 800 nm indicated that 232.4 nm was the optimum wavelength. However, TCE strongly absorbs UV light below 240 nm. As the wavelength increases to 250 nm, the TCE absorbance fades rapidly. Thus, the wavelength for T-MAZ-80K concentration measurements was chosen to be 245 nm. At this wavelength, the absorbance of about 40 mg/L TCE was approximately 0.02 while the absorbance of 0.1% T-MAZ was about 0.64.

Surfactant analysis of a sample was always performed after the TCE concentration was determined so that possible interference in surfactant concentration measurement could be determined. As it turned out, samples containing high concentrations of surfactant

(greater than 0.1%) had low concentrations of TCE (less than 50 mg/L). Also, because all samples with high concentrations of surfactant had to be diluted 9 to 1 with deionized water prior to surfactant analysis, the diluted samples contained less than 5 mg/L TCE. Thus, for these samples, no special procedures were necessary to remove TCE prior to surfactant analysis.

When surfactant concentrations were low and TCE concentrations were high, TCE had to be sparged from the sample prior to surfactant analysis. This was done by bubbling nitrogen into the sample for about 10 minutes. The TCE concentration was measured after the sparging to make sure that it was below 40 mg/L.

The UV spectrophotometer provided highly reliable and reproducible measurements as demonstrated by repeated readings of calibration standards. The practical quantitation limit for the surfactant at 245 nm was around 0.01%.

Surfactant concentrations in MW-156 samples were also measured in the PGDP laboratory. The results, listed in Table 5.3 and plotted in Figure 5.11, closely match the results obtained by INTERA.

5.6.3 Temperature Measurement

Thermometers were used to measure the temperature of water flowing out of the sample port from MW-156, coolers, and refrigerators. Special thermometers with data loggers were used to monitor the temperature of the refrigerators at the field laboratory trailer.

Three field thermometers, each having a slightly different range of temperatures, were used at the site. Prior to use they were tested against each other in ice water at about 2.5°C and tap water at about 20°C. The readings from each thermometer were within 0.5°C at both temperatures. Temperature measurement simply involved immersing the tip of the thermometer in the fluid being analyzed for at least 30 seconds.

5.7 MW-156 Results

MW-156, which is screened in the Upper RGA, was monitored for temperature and concentrations of TCE, surfactant, Tc-99, and DCE. The following sections present the results from each type of analysis.

5.7.1 TCE Concentrations

A summary of the qualified TCE concentrations measured by INTERA appears in Table 5.1. After rigorous calibration calculations and QA/QC screening, some of the data collected by INTERA were eliminated due to excessive drift in GC response, manifested by rapidly increasing or decreasing peak areas for given standards over short periods of time. When more than one qualified concentration measurement was available for a given sample, the measurements were averaged. This table contains the qualified and averaged data resulting from the QA/QC screening. The calibration curves, squares of the correlation coefficients (R Squared), and qualified raw data are included in Appendix D.

The precision of the measurements was determined by calculating 95% confidence intervals for the field triplicates. Confidence intervals were estimated assuming a Student's t distribution with two degrees of freedom. The estimates are presented in Table 5.2 and plotted in Figure 5.9. Measurements from 15 of the 17 triplicates indicate confidence intervals within $\pm 16\%$ of the sample mean. Only the 2 sets of triplicates from the pre-test showed 95% confidence intervals larger than $\pm 16\%$.

The accuracy of the measurements depends on the calibration standards and the calibration curves. A review of the R Squared values (the squares of the correlation coefficients) in Appendix D reveals that 38% of the R Square values were 0.999 or higher, 38% were in the range of 0.995 to 0.999, and 23% were in the range of 0.99 to 0.995. Note that if R Square equals 0.990, then the correlation coefficient (the square root of R Square) is 0.995.

A final check on the accuracy of field TCE concentration measurements is provided by the results of the PGDP TCE measurements listed in Table 5.3. The differences in matched pairs were calculated to determine the mean, sample standard deviation, and whether the differences in field and PGDP lab measurements were significantly different at the 5% significance level. The results are shown in Table 5.4.

The hypothesis test indicated that TCE measurements by the PGDP lab were significantly lower than the field measurements. Table 5.4 indicates that the PGDP measurements were consistently higher than field measurements during the pre-test and consistently lower than the field measurements during last 12 days of the extraction period. While differences are apparent, they are not large considering the differences in analytical equipment and the precision of the measurements; the pairs with the largest differences still agree within a factor of 2. The procedures, equipment, and notes taken during the field and laboratory analyses would need to be closely

examined to determine which measurements are most credible. However, it should be noted that the field-measured TCE data (Figure 5.10) indicates that the final TCE concentrations during the extraction phase are about equal to the pre-test values, which is not the case for the laboratory data (Figure 5.11). Because each set of measurements provides clear and unconflicting results regarding the objectives of the test (i.e., the efficacy of the surfactant), there is no need to determine which measurements are more accurate.

A plot of the field TCE concentration measurements from Table 5.1 is shown in Figure 5.10. The PGDP TCE concentration measurements are plotted in Figure 5.11. The measurements are plotted versus time in days since the extraction phase began. Negative time indicates time before the beginning of the extraction phase. The pre-test, surfactant injection phase, and extraction phase are marked on the figure. The TCE concentration measured during the surfactant injection phase is the TCE concentration of the surfactant solution being injected.

According to the field data, the approximate TCE concentration during the pre-test was around 350 mg/L. The concentration dropped to less than 1 mg/L during the injection phase while clean surfactant solution was injected. Once the extraction phase started, the TCE concentration slowly increased to around 75 mg/L after 4 days, increased more rapidly in the next 4 days to about 250 mg/L, and then more slowly to about 320 mg/L by the end of the extraction phase. The apparent dip in TCE concentrations during the ninth day may or may not be real. While the field data shows a dip at this time, the PGDP laboratory data suggests a temporary leveling off instead.

5.7.2 Surfactant Concentrations

All surfactant data obtained during the test exceeded QA/QC standards and are included in Table 5.1. Unlike the GC, the UV-spectrophotometer was calibrated to calculate concentrations directly, without resorting to calculation of peak areas. The calibration curve was forced through the origin (i.e., $ABS = 0$ at 0.000% surfactant concentration). Calibration was highly consistent throughout the test and the squares of the correlation coefficients always exceeded 0.999. Precision calculations based on triplicates indicate a 95% confidence interval of about $\pm 4\%$ of the mean concentration for high surfactant concentrations. The practical detection limit was about 0.01% due to background interferences and the sensitivity of the detector at 245 nm. The accuracy and precision calculations for the surfactant analyses are included in Appendix E.

The data are plotted in Figure 5.10. The data in this figure are in units of % by volume ($P_{v/v}$) and are calculated from the following equation

$$P_{v/v} = 100\% * \frac{M_{\text{surf}}}{M_T} * \frac{d_T}{d_{\text{surf}}}$$

where M_{surf}/M_T is the weight fraction of surfactant in the solution and d_T/d_{surf} is the ratio of the density of the solution (approximately 1.0 g/mL) to the density of surfactant (1.09 g/mL).

The data show that the surfactant was injected at a concentration of around 1% by volume. However, almost as soon as the extraction phase began, the surfactant concentration in MW-156 started falling. In about 2 days, the surfactant concentration fell to about 0.15% by volume, and after about 5 days of extraction it was below practical detection limits of 0.01%. Comparing areas under the curve for the surfactant injection and extraction phases indicates that about 34% of the surfactant injected was recovered.

5.7.3 Tc-99 Concentrations

The results of the Tc-99 analyses by PGDP are included in Table 5.3 and plotted in Figure 5.11. The Tc-99 concentration at MW-156 during the pre-test was around 107 pCi/L. Although there was some scatter in the Tc-99 data during the extraction phase, it appears that the Tc-99 concentration dropped to a minimum around 20-40 pCi/L in the first two days of extraction and then slowly recovered to near pre-test concentrations after about 7 days of extraction where it leveled off.

5.7.4 Temperature

Temperature measurements of extracted ground water at MW-156 can be found in Table 5.1. The temperature leveled off around 21°C during the latter part of the pre-test. Although the temperature of the surfactant solution was never measured by thermometer, solar heating in the mixing tanks caused it to become quite warm compared to fresh ground water. This is further indicated by the high temperatures measured shortly after the extraction phase began. The temperature of the extracted ground water returned to pre-test values within about 4 to 5 days. A graph of the temperature data is shown in Figure 5.12.

5.7.5 DCE Concentrations

The sharp drop in surfactant concentration in MW-156 during the first two days of extraction was curious. An early suggestion was that the surfactant was being degraded by *in situ* microorganisms. The only indicator variable INTERA was equipped to analyze for was the concentration dichloroethene (DCE), a product of the degradation of TCE. If the microbial activity was stimulated by the surfactant, it could cause increased biodegradation of TCE to DCE.

Samples from the pre-test and the extraction period were analyzed by the 8610a GC with ECD. Calibration was limited to two standards and a blank because time was limited and the actual concentrations in the samples were not as important as the relative concentrations. Measuring relative concentrations does not require calibration because they are directly reflected in the raw response of the GC.

Figure 5.13 is a plot of the DCE measurements showing the DCE concentration around 1 mg/L throughout the test. Although only a few measurements were made, it appears that the DCE concentration was slightly higher during the initial part of the extraction phase, suggesting some increased microbial activity. However, considering the high concentrations of TCE, much higher concentrations of DCE would be expected if the microbial activity increased to the level required to degrade a considerable proportion of the injected surfactant. This finding supports the conclusion that microbial activity was not likely the cause of the loss of the bulk of the surfactant injected. The DCE measurements and calibration data can be found in Appendix D.

5.8 MW-155 Results

MW-155, which is screened in the lower RGA, was monitored for temperature, pH, and concentrations of TCE, surfactant, and dissolved oxygen. The purpose of monitoring this well was to determine if the injection of a micellar-surfactant solution into a suspected DNAPL zone around MW-156 would cause vertical mobilization of the DNAPL, which would appear, together with surfactants, in MW-155. The following sections present the results from each type of analysis.

5.8.1 TCE Concentrations

The measured TCE concentrations at MW-155 are shown in Figure 5.14. They remained around 1.5 mg/L for the entire test. A slight increase in measured TCE concentration was observed over the course of the experiment. However, the increase is so small that it easily could have occurred naturally regardless of the surfactant test.

It is also possible that the extended extraction period drew new ground water of slightly different composition into MW-155 from farther outside the testing zone. The data is summarized in Table 5.5.

The MW-155 samples were first analyzed for TCE using the 8610 GC with ELCD, but because the TCE concentrations were near the detection limits of this GC, a switch was made to the 8610a GC with ECD. The calibration curves and raw data are presented in Appendix F. In all cases the square of the correlation coefficient (R Squared) is greater than 0.995 (which implies that the correlation coefficient is always greater than 0.9975).

The best estimate of the precision of the MW-155 TCE measurements is derived by: (1) taking a linear regression of the data collected during the surfactant injection and extraction periods versus time; (2) calculating the standard deviation from this line; and (3) determining the Student's t statistic for the 95% confidence interval. Although this procedure assumes that the TCE concentration is linearly related to time (as it appears to be), it allows a much larger sample population ($n = 39$) from which to estimate 95% confidence intervals. The sample standard deviation from the fitted line was calculated to be 0.13 mg/L, giving a Student t test statistic, $t_{0.025}$, of about 2.025. This value is used to estimate the 95% confidence interval for each independent TCE concentration measured. The result for this data set is a 95% confidence interval for each measurement of approximately ± 0.26 mg/L (or approximately $\pm 18\%$).

A few of the MW-155 samples were analyzed by PGDP for TCE concentrations. These results are listed in Table 5.6. These measurements closely match the field measurements by INTERA.

The differences in field and PGDP lab measurements were analyzed by calculating the mean and standard deviation of the differences of matched pairs. These statistics are shown in Table 5.7. A hypothesis test was used to indicate whether the differences in the field and PGDP laboratory measurements are significantly different. Assuming the matched-pair differences can be described by the Student's t distribution, it was found that the field and PGDP TCE measurements for MW-155 are not significantly different.

5.8.2 Surfactant Concentrations

Samples analyzed from MW-155 showed no signs of surfactant. Had surfactant reached MW-155, its maximum concentration at MW-155 would have appeared at the end of the surfactant injection period and the beginning of the extraction period. In addition, TCE concentrations would have increased because the contaminated ground water displaced by the injected surfactant solution would have reached MW-155 before

the surfactant. The TCE concentration at MW-155 remained around 1.5 mg/L, which is far below the 350 mg/L TCE concentration in the contaminated ground water in the vicinity of MW-156 prior to the injection of the surfactant solution.

5.8.3 Dissolved Oxygen Concentrations, Temperature, and pH

The dissolved oxygen, temperature, and pH of the MW-155 samples were analyzed by PGDP in the field using a Hydrolab probe with an in-line flow cell. Table 5.6 contains the results. The dissolved oxygen (DO) measurements fluctuated between about 3 and 7 mg/L with no clear trend during the test. The data is plotted in Figure 5.15.

There appeared to be no real trend in temperature either. The temperature of MW-155 samples was nearly always between 18 and 22°C. A plot of the temperature versus time is displayed in Figure 5.16.

The pH was fairly steady during the test except for an increasing trend during days 9 through 12 of the extraction period. Prior to this rise, the pH was around 6, and afterwards it appeared to level off at pH 6.5. The pH data is shown in Figure 5.17. If this pH change is real (i.e., not due to analytical error), it could be due to naturally occurring processes. Whether such changes in pH at MW-155 could result naturally could be determined by examining historical pH data for MW-155. It is also possible that the extended extraction period drew new ground water of slightly different composition into MW-155 from farther outside the testing zone.

The relatively low pH values and the presence of significant amounts of DO in the MW-155 data indicate that the ground waters sampled in MW-155 have not migrated to this part of the RGA by intergranular flow through the Upper Continental Deposits above the RGA (see Figure 3.2). These deposits likely contain substantial amounts of carbonate minerals, in particular calcite and dolomite, as well as considerable amounts of organic matter and other reductants. Intergranular flow through a thick sequence of such common sedimentary materials would result in pH values greater than neutral and the reduction of DO to non-measurable amounts (e.g., Jackson and Patterson, 1982). Rather, the data argue for a mechanism of rapid recharge of ground water to the RGA through an interconnected network of fractures in the Upper Continental Deposits such as has been postulated for DNAPL migration at the C-400 site by Clausen et al. (1992). Fracture flow would expose ground-water recharge to lesser amounts of carbonate minerals and organic matter over shorter residence times, such that recharge to the RGA could produce a ground water similar to that observed in MW-155.

5.9 Simulation of Test

The recovery responses of the TCE, Tc-99, and surfactant from the field were investigated using numerical simulations. The simulations were performed using the SWIFT II flow-and-transport simulator. The model is a 2-dimensional cylindrical grid of the upper RGA centered on the injection/extraction well MW-156. The model consists of 20 radial grid blocks that extend from the wellbore out to 100 feet and 7 vertical layers which make up the 7-foot completed interval of the well. An infinite aquifer boundary condition at the outer edge of the model grid was applied using the Carter-Tracy method. The model parameters are consistent with the parameters used in Section 3.0 and listed in Table 3.3.

The normalized (C/C_o) recovery responses of the TCE and Tc-99 are plotted against the simulated recovery of a conservative tracer in Figure 5.18. The simulation of the conservative tracer response was performed by injecting clean water into formation water which contained the tracer. As in the field test, injection continued for 3.72 days, followed by a static period of 0.17 days, followed by extraction for 16 days. From the extraction-period plot it can be seen that the Tc-99 reacted as a conservative tracer with the exception of very early time. However, the TCE responded non-conservatively.

Figure 5.19 shows the normalized surfactant recovery plotted against the simulated recovery of a conservative tracer. In this simulation, a conservative tracer was injected into clean formation water for 3.72 days, followed by a static period of 0.17 days, followed by extraction for 16 days. The plot shows that the surfactant injected during the field test did not respond conservatively.

The conservative recovery of the Tc-99 and the non-conservative recoveries for the surfactant and TCE suggest that the surfactant may have affected the TCE recovery. The surfactant, had it become immobilized by sorbing onto the RGA soils or precipitating in the pore space, may have increased the available sites for sorption of TCE. This would have caused the responses for both the surfactant and TCE to be non-conservative.

6.0 SUMMARY AND CONCLUSIONS

The specific objectives of this first phase of the project were:

1. to screen surfactants in the laboratory and identify those that will efficiently extract PCE, carbon tetrachloride, and TCE from sand aquifers by micellar solubilization, and then to investigate the physical-chemical properties of the best surfactants; and
2. to test, *in situ*, the efficacy of one of these surfactants to solubilize a TCE DNAPL (with minor amounts of PCE) by injection and then extraction of the surfactant solution through an existing well set within a sand and gravel aquifer at the Paducah Gaseous Diffusion Plant.

A total of 99 surfactants (25 nonionics and 74 anionics) were screened for their ability to solubilize TCE, PCE, and carbon tetrachloride. Ten of the 99 surfactants were capable of solubilizing TCE to concentrations greater than 15,000 mg/L. Four surfactants were identified as good solubilizers of all three DNAPL chemicals: a sorbitan monooleate (T-MAZ-80), an alkylaryl sulfonate isopropylamine, a secondary alcohol ethoxylate (Tergitol 15-S-12), and a polyoxyethylene oleamide.

Tergitol was the first choice because of its excellent solubilizing ability and its low propensity to sorb. However, this secondary alcohol ethoxylate did not meet the Commonwealth of Kentucky's acceptance criteria because of the potential presence of unreacted reagents which are banned for injection into ground waters in Kentucky. Consequently, it was decided to use a surfactant approved for use by the FDA as a food-grade additive, namely, T-MAZ-80K, which is manufactured by PPG Chemicals. As a 1% micellar-surfactant solution, this sorbitan monooleate has a solubilization capacity of 16,000 mg TCE/L, but has a higher propensity to sorb to clays than has the Tergitol.

After a year of intense field work by PGDP, the first site chosen for *in situ* testing was found to be unsuitable for conducting a short-term injection-extraction test. Therefore, a second site at PGDP was chosen, the C-400 site, on account of the fact that a particular well at the site (MW-156) had a sufficiently high hydraulic conductivity and had TCE concentrations > 100 mg/L, which suggested a nearby TCE DNAPL zone in this aquifer.

A field test of the efficacy of sorbitan monooleate in solubilizing TCE DNAPL was conducted in August 1994. The injection phase lasted 96 hours, during which time a 1% surfactant solution was injected at the rate of 3.8 L/min (1 gpm). The extraction

phase lasted 16 days at a rate of 3.8 L/min. Only one third of the injected surfactant was recovered during the extraction period and, consequently, there was no enhancement in the concentrations of TCE recovered from the well. It is believed that the remainder of the surfactant became sorbed to the aquifer materials or underwent precipitation or liquid crystal formation or some combination of the above. TCE behaved nonconservatively during the early stages of extraction, suggesting that some may have been sorbed to the immobilized surfactant. Therefore, the test has demonstrated that sorbitan monooleate is unsuitable for use as a solubilizer in this aquifer.

It is probable that this result could have been identified in the laboratory beforehand and an alternative surfactant could have been chosen and tested. Paradoxically, these same results demonstrate that the single-well test is a useful method for the *in situ* testing of surfactants or cosolvents before proceeding to larger-scale field testing or remediation.

PGDP's original conceptual model of DNAPL migration and distribution at the C-400 site (Figure 3.5), which is based on the work of Kueper (1991) and supported by the numerical simulations of McConnell et al. (1994), has been tested by numerical simulation and found to be inconsistent with the aqueous TCE concentrations beneath the site. A more probable conceptual model of DNAPL within the sand and gravel aquifer is presented in this report. This model assumes that DNAPL migrated through a fracture network system in the Upper Continental Deposits and penetrated the sand and gravel aquifer (RGA) beneath. This new scenario of DNAPL distribution indicates that it is advisable to repeat this test, following laboratory studies of the reaction of surfactants with the aquifer materials, by an interwell surfactant test, rather than a single-well test, to raise the probability that the DNAPL zone will be encountered by the injected surfactant solution.

7.0 RECOMMENDATIONS

While it has been shown that the micellar surfactant solution did not perform as intended, the single-well test demonstrated its utility for testing surfactants prior to full-scale SEAR. It is probable that the loss of surfactant could have been identified in laboratory tests, had it been possible to ship core from PGDP to SUNY Buffalo for testing beforehand. Furthermore, some way must be found to allow Sandia National Laboratories to play its designated role in this research. Had this contract been in place, some of the difficulties experienced in the field with the surfactant might have been avoided.

Therefore, we urge that the restrictions placed on the testing of the surfactants with aquifer materials from the RGA be swiftly resolved so that aquifer materials from the RGA can be shipped to SUNY-Buffalo and Sandia National Laboratories. Failing this, it will be necessary to set up a temporary laboratory at PGDP to conduct the necessary tests. The expense of such a solution strongly recommends the resolution of the restrictions.

The understanding of the distribution of DNAPL in the RGA beneath C-400 at PGDP is limited. This is quite typical of sites with DNAPL contamination, because of the complexity of the problem. The anticipated program of drilling and coring planned (WAG-6 program) for 1995 at C-400 should be devised to help test divergent hypotheses of the geometry of the DNAPL zone which have been explored in this report. The application of NAPL partitioning tracer tests and multiphase, multicomponent simulators permit an integrated approach to the characterization of DNAPL zones.

Recommendation 1: The program of drilling and aquifer coring planned by PGDP for WAG-6 1995 should be complemented with field and computational studies to develop a better understanding of the geometry of the DNAPL zones in the Regional Gravel Aquifer and the nature of DNAPL migration at PGDP.

Because of the limited understanding of the DNAPL zone and the loss of the surfactant *in situ*, it would be advisable to repeat this test as an interwell test rather than a single-well test, so that a larger volume of the RGA can be tested for the presence and composition of the DNAPL. Figure 7.1 is a schematic showing how an interwell DNAPL solubilization test would be undertaken, assuming that the test zone would contain only a limited thickness of residual DNAPL in the upper RGA. A micellar-

surfactant solution would be introduced through the injection well and produced at the extraction well. Because the zone of residual TCE DNAPL is much thinner than the thickness of the upper RGA, which is identified as having a hydraulic conductivity of 3×10^{-3} cm/s, the solubilized TCE will be greatly diluted by uncontaminated ground water. This effect is shown in Figure 7.2, which displays the effluent surfactant and TCE concentrations. The coelution of TCE and surfactant in Figure 7.2 indicates the presence of DNAPL and will permit an *in situ* evaluation of the efficacy of a particular surfactant solution.

Recommendation 2: Following the re-evaluation of appropriate surfactants for use in the RGA at Paducah and the installation of an additional well at the C-400 site, an interwell DNAPL solubilization test should be undertaken over a distance of at least 10 m to test the efficacy of DNAPL solubilization by micellar surfactant solutions.

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TABLES

Table 2.1: HLB Determination for TCE, PCE, and CTET, Using Tergitol Series (Secondary Linear Alcohol Ethoxylates)

Surfactant No.	HLB	TCE ppm	PCE ppm	CTET ppm
133	12.4		1,450	1,376
134	13.3	6,250	22,548*	12,220
135	14.7	13,322*	5,792	17,876*
136	15.6	6,224	2,770	8,173
137	16.4	7,362	2,516	4,451
138	17.5	3,701		1,701
139	18.0	2,606		

* HLB for each compound

Table 2.2: Solubilization Results for TCE, PCE and CTET in Nonionic Surfactants

Surfactant No.	Surfactant Name	HLB	TCE (ppm)	PCE (ppm)	CTET (ppm)
3/4	POE C12-C15 Linear Alcohol	14.8	3,031		6,308
9	Ethoxylated Alcohol	13	3,247	11,624	2,173
9/10	Ethoxylated Alcohol	14.8	2,020		4,571
10	Ethoxylated Alcohol	15.0	2,777		3,692
18	Sorbitan Monooleate POE 20	15.0	16,157	6,023	12,509
24	Tridecyl Alcohol POE 12	14.5	1,602		5,913
25	Linear Alcohol Ethoxylate	14.4	3,367		7,513
37	PEG Monolaurate	13.6	3,785	23,447	21,071
38/39	PEG Monolaurate	14.8	10,620		3,305
38/39	PEG Monolaurate	14.0	1,694		
60	Sorbitan Monooleate POE 20	15.0	16,338	6,734	10,595
121	PEG 25 Soya Sterol	17.0	29,627	7,783	19,748
133	C11-C15 Secondary Alcohol	12.4		1,450	1,376
134	C11-C15 Secondary Alcohol	13.3	6,250	22,548	12,220
135	C11-C15 Secondary Alcohol	14.7	13,322	5,792	17,876
136	C11-C15 Secondary Alcohol	15.6	6,224	2,770	8,173
137	C11-C15 Secondary Alcohol	16.4	7,362	2,516	4,451
138	C11-C15 Secondary Alcohol	17.5	3,701		1,701
139	C11-C15 Secondary Alcohol	18.0	2,606		
144/145	2,6,8 Trimethyl-4 Nonanol	14.8	9,638		6,902
151	Nonylphenyl Ethoxylate	13.5	8,407	19,063	26,018
154	POE 7 Oleamide	14.0	18,118	32,066	36,850
164	Octylphenol/Polyethoxy Ethanol	13.5		9,573	
170/172	PEG-20/40 Lanolin Alcohol	14.9	14,669		4,355
185	Block Copolymer	12-18	4,319		
213	PEG 1100 Castor Oil		38,358	11,396	21,187
234/235	POE 10/20 Cetyl Ether	14.9	6,674		6,750
271	12 POE Nonylphenol	14.1	14,367	5,916	
272	8 POE Nonylphenol	12.4	1,535	534	

Table 2.3: Solubilization Results for TCE, PCE and CTET in Anionic Surfactants

Surfactant No.	Surfactant Name	TCE (ppm)	PCE (ppm)	CTET (ppm)
14	Aliphatic Phosphate Ester	13,579	1,872	7,748
22	Phosphated Alkyl Ethoxy K-salt	6,529	732	2,843
31	Na Dodecylbenzene Sulfonate	4,339	773	2,154
32	C12-C13 Alcohol Ethoxysulfate	3,737	584	2,589
41	Aliphatic Phosphate Ester	8,289	863	4,896
45	POE Fatty Alcohol Phosphate Ester	7,346	1,470	7,204
54	Phosphate Ester		4,472	12,253
57	Sulfate		486	2,750
62	Phosphate Ester	4,816	5,083	23,765
67	Anionic/Nonionic Blend	8,668	9,322 8,429	22,452
72	Sulfonate/ POE Ether Blend	15,801	9,940 9,809	29,716
78	Cyclic Carboxylated Amide	3,261	1,752	5,164
109	Na Dioctyl Sulfosuccinate	3,800	3,911	8,302
110	Alkylaryl Polyoxyl Carboxylate	2,711	19,688	
111	Alkylaryl Polyoxyl Carboxylate	1,815	1,450	3,317
112	Alkyl Phenoxyl Ether Sulfate	2,688		2,732
113	Phosphate Ester	4,526	2,490	6,055
118	Na C14-C16 Olefin Sulfonate	3,337	758	2,176
119	Alkyl Aryl Sulfonate Isopropylamine	19,976	3,704	26,125
128	Aliphatic Phosphate Ester	27,284	16,594 12,089	23,279
177	Alkyl Aryl Sulfonate/ Nonionic Blend	21,515	15,070	25,422
193	Benzene, 1,1-oxybis Tetrapropylene Sulfonate	3,695	1,590	2,029
194	DiNa Dihexa/Hexadecyl Diphenol Disulfonate	3,592	2,180	1,800
195	Linear Alkylbenzene Sulfonate	7,411	2,001	5,745

Table 2.3 (continued): Solubilization Results for TCE, PCE and CTET in Anionic Surfactants

Surfactant No.	Surfactant Name	TCE (ppm)	PCE (ppm)	CTET (ppm)
196	Alpha Olefin Sulfonate	6,189	2,226	7,872
197	Alpha Olefin Sulfonate	2,298	1,197	4,959
198	Alkyl Aryl Sulfonate		284	2,414
199	Amine Alkylbenzene Sulfonate	4,154	11,078 10,598	19,773
200	NH3 Alcohol POE(4) Sulfate	4,469	1,057	3,312
205	Na Alkyl Sulfonate	2,891	617	2,137
206	Na Ethoxylated Alcohol Sulfate	2,451	380	1,216
207	Na Alkyl Aryl Sulfonate	2,848	494	1,900
208	Na Alkyl Diphenyl Oxide	1,770 ⁽¹⁾		2,110
214	Na Alkyl Ether Sulfonate	4,321	939	2,285
215	Na Alkyl Ether Sulfonate	1,712	316	2,444
222	Dodecyl Benzene Sulfonate	3,574	2,040	1,473
223	Dodecyl Benzene Sulfonate	2,358	374	2,656
242	Sulfonated Castor Oil	10,721	6,411	7,652
243	Natural and Synthetic Sulfonate Blend	10,475	2,636	7,217
244	Na POE Nonylphenol Sulfate	3,634	378	3,085
245	Na Sulfonate of Coconut Oil	3,578	413	2,765
246	NH3 POE Alcohol Sulfate	3,464	559	1,636
247	Di-Na Laureth sulfosuccinate		1,293	2,595
248	Sulfated Ester	3,857	624	2,681
249	Na Sulfated Ester	22,996	3,636	11,802
250	Sulfated Castor Oil	14,382	4,243	8,451
251	Sulfated Castor Oil			9,065

Table 2.3 (continued): Solubilization Results for TCE, PCE and CTET in Anionic Surfactants

Surfactant No.	Surfactant Name	TCE (ppm)	PCE (ppm)	CTET (ppm)
252	Sulfated Vegetable Oils			7,592
253	Sulfonated Tall Oil Fatty Acid		3,293	4,963
254	Sulfated Soybean Oil/Ester			15,171
255	Sulfated Glycerol Trioleate			14,895
256	Sulfated Castor Oil	5,390	1,501	6,317
257	Sulfonate/Nonionic Blend			11,921
258	Na Linear Alkylate Sulfonate	4,659	2,914	4,510
260	Alpha Sulfo Methyl Ester	1,443	397	
261	C10 Alpha Olefin Sulfonate	1,854	659	
262	Linear Alkylaryl Na Sulfonate	4,504	1,312	
264	Alkyl Ether Sulfate	2,448	1,051	
266	Cetyl/Steryl Alcohol & Fatty Alcohol Sulfate		744	
267	Sulfonate	1,704	1,720	
268	Sulfated Castor Oil	7,006	7,134	
269	Na C14-C16 Olefin Sulfonate/Na Laureth Sulfate/Lauramide DEA	5,876	2,111	
270	Sodium Lauryl Sulfoacetate/ Di-sodium Laureth	2,757	888	
273	Na 1-Octane Sulfonate	6,293	466	
274	Sulfated Castor Oil	2,961	3,712	
275	Ammonia Neutralized Sulfated Oleic Acid	8,765	6,703	
277	Sodium Tridecyl Sulfosuccinate		908	
278	Sodium Oleoylisopropanolamide Sulfosuccinate	827	906	

Table 2.3 (continued): Solubilization Results for TCE, PCE and CTET in Anionic Surfactants

Surfactant No.	Surfactant Name	TCE (ppm)	PCE (ppm)	CTET (ppm)
279	Sodium Dioctyl Sulfosuccinate	6,088	4,277	
280	Sodium Ethoxylated Alcohol Sulfosuccinate	1,598	418	
281	Sodium Oleoylisopropanolamide Sulfosuccinate	2,655	992	
282	Sodium Octyl Sulfate	1,828	363	
283	Sodium Laureth Sulfate	4,909	1,710	
284	Di-sodium Mono-oleamido PEG-2 sulfosuccinate	1,989	653	
285	Sodium Myreth Sulfate	5,147	1,482	
286	Sodium n-decyl Sulfate	1,616	228	
287	Sodium 2-ethylhexyl Sulfate	2,129	625	
288	Sodium Dioctyl Sulfosuccinate/ propylene Glycol	5,444	5,200 ⁽²⁾	
289	Sodium Dicyclohexyl Sulfosuccinate	1,370	295	
290	Sodium Dihexyl Sulfosuccinate	1,000	300	
291	Sodium Diisobutyl Sulfosuccinate	1,208	486	
292	Octylphenol Ethoxylate Sulfonate	3,114	796	
293	C12-C15 Ethoxylate (EO 15) Sulfonate	2,418	854	
294	C12-C15 Ethoxylate (EO 7) Sulfonate	2,563	927	
295	Ammonium Nonylphenoxypoly (ethyleneoxy) Ethanol Sulfate	4,659		

⁽¹⁾ Surf 208 incorrectly reported as 1,170 previously.

⁽²⁾ Surf 288 5200 ppm is average of duplicate analyses of 5420 ppm and 4980 ppm.

Table 2.4: Percent TCE and PCE Solubilized to Percent TCE and PCE in DNAPL Mixtures

Surfactant No.	TCE:PCE in Mixture	% TCE	% PCE
18 Sorbitan Monooleate	90:10	89.1	10.9
	75:25	78.7	21.3
	50:50	57.8	42.2
	25:75	30.9	69.1
154 POE 7 Oleamide	90:10	90.5	9.5
	75:25	77.2	22.8
	50:50	51.3	48.7
	25:75	26.3	73.7
135 C11-C15 Secondary Alcohol	90:10	91.2	8.8
	75:25	79.0	21.0
	50:50	52.6	47.4
	25:75	27.9	72.1

Table 2.5: Retardation Factors for Selected Surfactants

Surfactant number	Natural soil with 10% smectite ⁽¹⁾	Na smectite - sand mixtures ⁽¹⁾⁽²⁾	Ca smectite - sand mixtures ⁽¹⁾⁽²⁾	3% illite/smectite - sand mixture
18	22.05	1% = 1.51 5% = 13.68 10% = 20.70 20% = 19.98	1% = 1.48 5% = 5.95 10% = 12.09 20% = 20.80	
60				2.22
64	20.71			
135				3.54
154				4.33
161	21.68			

⁽¹⁾ Studies other than DOE.

⁽²⁾ Percentages indicate fraction of clay in mixture.

Table 2.6: Interfacial Tension Measurements Between 1% Surfactant Solutions and PCE, TCE and CTET

Surfactant ⁽¹⁾ No. and Standards	PCE IFT (dynes/cm)	TCE IFT (dynes/cm)	CTET IFT (dynes/cm)
Referenced value with D.I. water	44.40	34.50	45.00
Measured value with D.I. water	44.43	27.49	43.48
18	11.08	11.67	11.10
37	8.86	15.85 ⁽²⁾	11.58
60	10.72	11.26	10.72
121	13.64	14.36	14.82
134	6.08	15.26 ⁽²⁾	10.15
135	5.03	14.96 ⁽²⁾	7.01
151	4.08	18.55 ⁽²⁾	8.12
154	9.54	15.6 ⁽²⁾	13.0
194	10.20	9.40	11.43
199	1.67 ^e	1.64 ⁽²⁾	1.03 ^e
213	16.32	13.16	13.42
222	6.84	7.04	7.23
242	13.06	9.9	13.62
249	7.62	2.46	6.88 ^e

⁽¹⁾ See Tables 2.2 and 2.3 for surfactant names.

⁽²⁾ An emulsion was present at the interface.

Table 2.7: Surfactant Critical Micellar Concentration

Surfactant No.	Surfactant (Volume %)
18	0.012
135	0.011

Table 2.8: Surfactant Solution Viscosities

Solution	Viscosity (kg/m-s)
Distilled water	8.95×10^{-4}
1% Solution No. 18	9.38×10^{-4}
2% Solution No. 18	1.01×10^{-3}
1% Solution No. 135	9.79×10^{-4}
2% Solution No. 135	1.05×10^{-3}
1% Solution No. 154	2.18×10^{-3}
2% Solution No. 154	7.06×10^{-3}

Table 2.9: Surfactant Solubilization Kinetics

Surfactant No.	ml	Pore Volumes	ppm TCE	Average MAC* ppm TCE
18A	40	1	3,526	
18A	57	1.4	12,620	13,136
18B	54	1	3,589	
18B	66	1.2	13,155	13,605
135	56.5	1	806	
135	79.5	1.4	3,923	3,111
154	52	1	2,499	
154	74.5	1.4	9,746	10,796

* The average MAC value as determined once TCE ppm values had reached a plateau.

Table 2.10: Solubilization Data for 1% Sorbitan Monooleate Solutions

Surfactant No.	TCE ppm	PCE ppm	CTET ppm
18	16157	6023	12509
60	16338	6734	10595
64	15407*	5161*	

* From studies other than DOE

Table 2.11: Interfacial Tension (IFT) Measurements Between 1% Sorbitan Monooleate Solutions and TCE, PCE, or CTET

Surfactant No. and Standards	TCE IFT (dynes/cm)	PCE IFT (dynes/cm)	CTET IFT (dynes/cm)
Referenced value with D.I. water	34.50	44.40	45.00
Measured value with D.I. water	27.49	44.43	43.48
18	11.67	11.08	11.10
60	11.26	10.72	10.72

Table 2.12: Viscosity of Sorbitan Monooleates (No. 18)

Solution	Viscosity (kg/m-s)
Distilled Water	8.95×10^{-4}
1% Solution no. 18	9.38×10^{-4}
2% Solution no. 18	1.01×10^{-3}

Table 2.13: Retardation Factors for Sorbitan Monooleates

Surfactant number	Natural soil with 10% smectite ⁽¹⁾	Na smectite - sand mixtures ⁽¹⁾⁽²⁾	Ca smectite - sand mixtures ⁽¹⁾⁽²⁾	3% illite/smectite - sand mixture
18	22.05	1% = 1.51 5% = 13.68 10% = 20.70 20% = 19.98	1% = 1.48 5% = 5.95 10% = 12.09 20% = 20.80	
60				2.22
64	20.71			
161	21.68			

⁽¹⁾ Studies other than DOE.

⁽²⁾ Percentages indicate fraction of clay in mixture.

Table 3.1: Hydrostratigraphic Data for MW-156 from Phillips (1992)

Hydrogeologic Unit	Thickness (feet)	Description
HU1	21	Loess; mainly yellow-brown clay
HU2	16	Gravel unit, fining upward into a sandy clay
HU3	17	Sandy clay
HU4	6.5	Sand, fine- to medium-grained
HU5	32	Regional Gravel Aquifer; sandy gravel fining upward into a gravelly, fine- to medium-grained sand
-	?	McNairy Fm.; sandy clay

Table 3.2: TCE Contamination in mg/L in the WMU-11 Monitor Well Nest

Date (month and year)	MW-155 Screened Interval: 87-92 feet below surface	MW-156 Screened Interval: 63-70 feet below surface	MW-157 Screened Interval: 30-35 feet below surface
3.91	1.8	>300	>900
7.91	2.4	550	640
6.93	--	460	--
7.93	2.3	400	100
8.93	1.8	380	160
9.93	1.9	400	530
10.93	2.2	380	550
11.93	1.9	370	110

Table 3.3: Model Parameters

Model Parameter	Value
Grid Dimensions	750 ft long, 1ft wide, 54 ft thick
Grid Blocks	Scenario A: 25 x 27 Scenario B: 25 x 32
Volume of TCE	Scenario A: 9.45 ft ³ Scenario B: 20.87 ft ³
Porosity	0.35
Hydraulic Conductivity	Lacustrine Units — 2×10^{-5} cm/s 3100 md Upper RGA — 3×10^{-3} cm/s 4132 md Lower RGA — 4×10^{-3} cm/s 1.0 md McNairy Formation — 1×10^{-6} cm/s
K_v/K_h	0.1
Hydraulic Gradient	0.00175 ft/ft
Recharge Rate	4.7 in/yr
Longitudinal Dispersivity	1.0 ft
Transverse Dispersivity	0.2 ft
Residual Saturation of Water	0.35
Residual Saturation of TCE	0.20 in all blocks except for 0.40 for bottom of DNAPL source in Scenario B
Model Dip	0.0 ft/ft

Table 3.4: Comparison of Averaged Concentrations

Well Number	Measured Value (mg/L)	Measured Value* (vol/vol)	Scenario A Value (vol/vol)	Scenario B Value (vol/vol)
155	2.5	1.7×10^{-6}	4.71×10^{-6}	6.7×10^{-4}
156	320	2.2×10^{-4}	3.36×10^{-4}	3.84×10^{-4}
178	110	7.5×10^{-5}	3.62×10^{-5}	4.0×10^{-5}

* Assumes density of TCE = 1,460 kg/m³.

Table 5.1: Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
1	3	11.5	-6.10	353			
4	3	12.5	-6.06	367			22
5	3	13.5	-6.02	350			23
7	3	14.5	-5.98	322			
8	3	15.5	-5.94	308			
10	3	16.5	-5.90	376			
11	3	17.5	-5.85	348			
12	3	18.5	-5.81	312			
13	3	19.5	-5.77	387			
14	3	20.5	-5.73	300			
15	3	21.5	-5.69	382			
16	3	22.5	-5.65	300			21
17	3	23.5	-5.60	356			21
18	4	0.5	-5.56	327			21
19	4	1.5	-5.52	392			
20	4	2.5	-5.48	359			
24	5	18.75	-3.80	< 1	1.14	1.04	
25	6	7.83	-3.26	< 1	1.15	1.06	
30	7	11.17	-2.12	< 1	1.12	1.03	
32	7	15.17	-1.95	< 1	1.12	1.03	
35	8	11.25	-1.11	< 1	1.13	1.04	
37	8	16.5	-0.90		1.09	1.00	
39	9	9.6	-0.18	< 1	1.08	0.99	
40	9	14.25	0.01	< 1	1.09	1.00	
41	9	15	0.04	1	1.04	0.95	
43	9	16	0.08	1	1.05	0.96	
44	9	17	0.13	2	1.04	0.95	
45	9	18	0.17	3			
46	9	19	0.21	4	0.99	0.91	27

Table 5.1 (continued): Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
48	9	20	0.25	4			27
49	9	21	0.29	5	0.96	0.88	26
50	9	22	0.33	6			26
51	9	23	0.38	6			26
52	10	0	0.42	7	0.92	0.84	26
53	10	1	0.46	7			25
54	10	2	0.50	8	0.87	0.80	25
55	10	3	0.54	8			25
56	10	4	0.58	9	0.85	0.78	25
57	10	5	0.63	11			25
58	10	6	0.67	11			24
59	10	7	0.71	9	0.78	0.72	24
61	10	8	0.75	12	0.75	0.69	
62	10	9	0.79	11			
63	10	10	0.83	11			
64	10	11	0.88	11	0.69	0.63	
65	10	12	0.92	12			
66	10	13	0.96	11			
67	10	14	1.00	12	0.61	0.56	
68	10	15	1.04	12			
70	10	16	1.08	12	0.56	0.51	
71	10	17	1.13	15			26
72	10	18	1.17	14			25
73	10	19	1.21	15	0.48	0.44	25
76	10	22	1.33	15	0.39	0.36	24
77	11	0	1.42	15			24
78	11	1	1.46	20			23
79	11	2	1.50	19	0.32	0.29	23
80	11	3	1.54	24			23

Table 5.1 (continued): Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
81	11	4	1.58	24			23
82	11	5	1.63	27			23
83	11	6	1.67	26	0.25	0.23	23
84	11	7	1.71	29			23
86	11	8	1.75	28			23
87	11	9	1.79	28	0.22	0.20	
88	11	10	1.83	29			
89	11	11	1.88	28			
90	11	12	1.92	28			
91	11	13	1.96	31	0.17	0.16	
92	11	14	2.00	32			
93	11	15	2.04	34			
95	11	16	2.08	36	0.15	0.14	
96	11	17	2.13	43			24
98	11	19	2.21	44			24
100	11	21	2.29	41	0.11	0.10	23
102	11	23	2.38	43			23
105	12	2	2.50		0.09	0.08	22
107	12	4	2.58	50			22
109	12	6	2.67	53	0.06	0.06	22
110	12	7	2.71	57	0.099	0.09	22
112	12	8	2.75	55			22
114	12	10	2.83	54			
115	12	11	2.88		0.061	0.06	
116	12	12	2.92	60			
118	12	14	3.00	63			
120	12	16	3.08	65	0.049	0.04	24
122	12	17	3.13	71			24
124	12	19	3.21	51			23

Table 5.1 (continued): Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
125	12	20	3.25		0.048	0.04	22.5
127	12	22	3.33	60			23
129	12	24	3.42	62			22
130	13	1	3.46		0.053	0.05	22
131	13	2	3.50	65			21
133	13	4	3.58	65			21
135	13	6	3.67	67	0.045	0.04	21
138	13	8	3.75	75			22
140	13	10	3.83	73	0.039	0.04	23
142	13	12	3.92	69			
143	13	13	3.96	51			25
144	13	14	4.00	80			
145	13	15	4.04	64	0.028	0.03	24
147	13	16	4.08	66			24
149	13	18	4.17	71			
150	13	19	4.21	81	0.03	0.03	22
153	13	22	4.33	85			22
154	14	3.33	4.56	103			21
155	14	4.33	4.60		0.015	0.014	21
158	14	8	4.75	104			22
159	14	10	4.83		0.012	0.011	22
160	14	12	4.92	101			22
163	14	16	5.08	160			22
164	14	18	5.17	158	0.01	0.009	22
166	14	22	5.33	154			20
167	15	7.5	5.73	207			
169	15	9.15	5.80	209	< 0.01	< 0.009	
171	15	13	5.96	196			22
172	15	15	6.04		< 0.01	< 0.009	

Table 5.1 (continued): Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
174	15	17	6.13	218			21
176	15	21	6.29	214			20
178	16	7	6.71	230			
180	16	11	6.88	246			
182	16	15	7.04	225			
184	16	19	7.21	250			21
185	16	23	7.38	250			20
187	17	7.5	7.73	250			
188	17	11	7.88	262			
190	17	15	8.04	236			
192	17	19	8.21	281			21
193	17	23	8.38	240			
195	18	7.5	8.73	218			
196	18	11.25	8.89	209			
198	18	15	9.04	227			
200	18	19	9.21				21
201	18	23	9.38				20
204	19	11	9.88	249			23
208	19	19	10.21				21
209	19	23	10.38				20
211	20	7.75	10.74	265			
212	20	11	10.88	260			20.5
214	20	15	11.04	256			
216	20	19	11.21				20
217	20	23	11.38				19
219	21	7.5	11.73	275			
220	21	11	11.88	289			
222	21	15	12.04	303			
224	21	19	12.21	315			20

Table 5.1 (continued): Results of Field Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Avg. TCE Conc. Data (mg/L)	Surfactant Conc. Data (% by wt)	Surfactant Conc. Data (% by vol)	Temp. (°C)
225	21	23	12.38	275			19
227	22	7.5	12.73	277			
230	22	15	13.04	329			
233	22	23	13.38	313			20
236	23	11	13.88	293			
238	23	15	14.04	325			
240	23	19	14.21	299			20
244	24	11	14.88	312			
248	24	19	15.21				
253	25	10.83	15.87	312			20.5

Table 5.2: Precision Estimates for MW-156 Field TCE Analyses

Sample Number	Area 1	Area 2	Area 3	Area 1 Conc. (mg/L)	Area 2 Conc. (mg/L)	Area 3 Conc. (mg/L)	Sample Stand. Dev. (mg/L)	Sample Mean Conc. (mg/L)	Student t 95% Conf. Interval	
									+/- (mg/L)	+/- (% of mean)
11	22002	18706	19028	413	311	321	56.2	348.2	139.6	40.1%
17	21428	19156	19887	395	325	347	35.9	355.8	89.1	25.0%
44	198.8	221.5	240	1.9	2.0	2.1	0.1	2.0	0.3	16.0%
59	1271	1406	1323	8.6	9.4	8.9	0.4	9.0	1.1	11.8%
70	2215	2315	2167	14	14	13	0.5	13.8	1.2	8.5%
88	3142	3222	3168	29	30	29	0.7	29.2	1.7	5.9%
107	4790	4772	4539	52	52	48	2.4	50.4	6.1	12.1%
118	5151	5080	5215	63	62	64	1.2	63.1	2.9	4.6%
127	5945	5778	5985	61	58	61	1.5	60.1	3.8	6.3%
153	5066	5227	5242	82	87	87	3.1	85.4	7.8	9.1%
180	14355	14561	14964	240	245	254	6.9	246.0	17.1	7.0%
196	11574	11701	11729	207	210	211	2.0	209.0	5.0	2.4%
220	12902	13428	12420	239	252	227	12.2	239.3	30.4	12.7%
228	14563	15772	14592	246	273	247	15.2	255.6	37.7	14.7%
236	13684	13627	12714	227	226	206	12.0	219.7	29.7	13.5%
244	39772	43585	40651	297	334	306	19.5	312.4	48.5	15.5%
253	39456	41907	42505	294	318	324	15.8	311.9	39.2	12.6%

Table 5.3: Results of PGDP Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	PGDP TCE Conc. Data (mg/L)	PGDP Tc-99 Conc. Data (pCi/L)	PGDP Surfactant Conc. Data (%)
1	3	11.5	-6.10	370	120	0
6	3	14	-6.00		107	
8	3	15.5	-5.94	390		0
10	3	16.5	-5.90		106	
13	3	19.5	-5.77		109	
14	3	20.5	-5.73	400		0
16	3	22.5	-5.65		104	
20	4	2.5	-5.48	400	109	0
41	9	15	0.04	1.3	55	1.1
47	9	19.58	0.23	5.5	79	0.99
49	9	21	0.29		72	
53	10	1	0.46	11	117	0.92
57	10	5	0.63		39	
59	10	7	0.71	15		0.86
62	10	9	0.79		26	
66	10	13	0.96	19	33	0.58
71	10	17	1.13		52	
73	10	19	1.21	24		0.53
75	10	21	1.29		32	
78	11	1	1.46	30	33	0.35
82	11	5	1.63		30	
84	11	7	1.71	35		0.23
87	11	9	1.79		35	
91	11	13	1.96	38	21	0.23
96	11	17	2.13		47	
98	11	19	2.21	44		0.17
100	11	21	2.29		49	
112	12	8	2.75	52	65	0.09
115	12	11	2.88		53	

Table 5.3 (continued): Results of PGDP Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	PGDP TCE Conc. Data (mg/L)	PGDP Tc-99 Conc. Data (pCi/L)	PGDP Surfactant Conc. Data (%)
118	12	14	3.00		67	
122	12	17	3.13		54	
123	12	18	3.17	59		0.05
138	13	8	3.75	85	80	0.04
141	13	11	3.88		84	
144	13	14	4.00		89	
148	13	17	4.13	80	72	0.02
158	14	8	4.75	100	104	0.018
161	14	14	5.00		86	
164	14	18	5.17	110	97	0.015
166	14	22	5.33		93	
167	15	7.5	5.73	130	92	0
171	15	13	5.96		95	
175	15	19	6.21	120	101	0
177	15	23	6.38		115	
178	16	7	6.71	150	94	0
181	16	13	6.96		93	
184	16	19	7.21	150	105	0
185	16	23	7.38		88	
187	17	7.5	7.73	210	93	0
189	17	13	7.96		100	
192	17	19	8.21	170	113	0
193	17	23	8.38		103	
195	18	7.5	8.73	200	90	0
197	18	13	8.96		107	
200	18	19	9.21	210	106	0
201	18	23	9.38		112	
203	19	7.5	9.73	210	107	0
205	19	13	9.96		112	

Table 5.3 (continued): Results of PGDP Analyses for MW-156

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	PGDP TCE Conc. Data (mg/L)	PGDP Tc-99 Conc. Data (pCi/L)	PGDP Surfactant Conc. Data (%)
208	19	19	10.21	210	100	0
209	19	23	10.38		94	
211	20	7.75	10.74	190	117	0
213	20	13	10.96		108	
216	20	19	11.21	200	95	0
217	20	23	11.38		115	
219	21	7.5	11.73	200	98	0
221	21	13	11.96		111	
224	21	19	12.21	230	102	0
225	21	23	12.38		100	
227	22	7.5	12.73	220	107	0
232	22	19	13.21	210	105	0
233	22	23	13.38		98	
235	23	7.33	13.72	220	97	0
237	23	13	13.96		104	
240	23	19	14.21	240	111	0
242	23	23	14.38		96	
243	24	7.5	14.73	230	95	0
245	24	13	14.96		105	
248	24	19	15.21	220	113	0
249	24	23	15.38		109	
251	25	7.42	15.73	210	121	0
253	25	10.83	15.87	220	105	0

Table 5.4: Matched-Pairs Analysis of Differences in Field and PGDP Results for MW-156

Sample Number	PGDP TCE Conc. Data (ppm)	Field TCE Conc. Data (mg/L)	Difference (mg/L)		
1	370	353	17		
8	390	308	82		
14	400	300	100		
20	400	359	41		
41	1.3	1	0		
53	11	7	4		
59	15	9	6		
66	19	11	8	Student t	
73	24	15	9		
78	30	20	10		
84	35	29	6	Sample Mean Difference	-22
91	38	31	7	Sample Standard Deviation	53
98	44	44	0		
112	52	55	-3	Number of Matched Pairs	29
138	85	75	10	Degrees of Freedom	28
158	100	104	-4		
164	110	158	-48	Critical Value of Test Statistic	
167	130	207	-77	5% significance level	-1.70
178	150	230	-80		
184	150	250	-100	Actual Value of Test Statistic	-2.19
187	210	250	-40		
192	170	281	-111		
195	200	218	-18	Conclusion	
211	190	265	-75		
219	200	275	-75	The PGDP TCE measurements are significantly lower than the field measurements.	
224	230	315	-85		
227	220	277	-57		
240	240	299	-59	There is a probability of less than 5% that this conclusion is incorrect.	
253	220	312	-92		

Table 5.5: Results of Field Analyses for MW-155

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Average TCE Concentration Measurement (mg/L)	Surfactant Concentration Measurement (% by wt)	Surfactant Concentration Measurement (% by vol)
2	3	11.5	-6.10	1.4	< 0.01	< 0.01
9	3	15.5	-5.94	< 1	< 0.01	< 0.01
26	6	7.0	-3.29	< 1	< 0.01	< 0.01
28	6	15.5	-2.94	1.4	< 0.01	< 0.01
29	7	6.9	-2.30	1.4	< 0.01	< 0.01
33	7	15.8	-1.92	1.5	< 0.01	< 0.01
34	8	7.0	-1.29	1.4	< 0.01	< 0.01
36	8	16.0	-0.92	1.1	< 0.01	< 0.01
38	9	7.0	-0.29	1.3	< 0.01	< 0.01
42	9	15.5	0.06	1.2	< 0.01	< 0.01
60	10	7.0	0.71	1.4	< 0.01	< 0.01
69	10	16.0	1.08	1.4	< 0.01	< 0.01
85	11	7.0	1.71	1.2	< 0.01	< 0.01
94	11	16.0	2.08	1.3	< 0.01	< 0.01
111	12	7.0	2.71	1.4		
121	12	16.0	3.08	1.2		
137	13	7.0	3.71	1.3		
146	13	16.0	4.08	1.5		
157	14	7.0	4.71	1.4		
162	14	16.0	5.08	1.5		
168	15	7.0	5.71	1.4		
173	15	16.0	6.08	1.4		
179	16	7.0	6.71	1.5		
183	16	16.0	7.08	1.5		
186	17	7.0	7.71	1.5		
191	17	16.0	8.08	1.3		
194	18	7.0	8.71	1.7		
199	18	16.0	9.08	1.6		
202	19	7.0	9.71	1.7		

Table 5.5 (continued): Results of Field Analyses for MW-155

Sample Number	Day of Month	Hour of Day	Time Since Extraction Began (days)	Average TCE Concentration Measurement (mg/L)	Surfactant Concentration Measurement (% by wt)	Surfactant Concentration Measurement (% by vol)
207	19	16.0	10.08	1.5		
210	20	7.0	10.71	1.6		
215	20	16.0	11.08	1.6		
218	21	7.0	11.71	1.7		
223	21	16.0	12.08	1.5		
226	22	7.0	12.71	1.8		
231	22	16.0	13.08	1.6		
234	23	7.0	13.71	1.6		
239	23	16.0	14.08	1.7		
241	24	7.0	14.71	1.8		
247	24	16.0	15.08	1.6		
250	25	7.0	15.71	1.7		
252	25	11.0	15.88	2.2		

Table 5.6: Results of PGDP Analyses for MW-155

Sample Numbe	Day of Month	Hour of Day	Time Since Extraction Began (days)	Dissolved Oxygen (mg/L)	Temp. (°F)	Temp. (°C)	pH	TCE (ppm)
2	3	11.5	-6.10	3.78	67	19.4	5.7	2.0
9	3	15.5	-5.94		77	25.0	6.4	
26	6	7.0	-3.29	5.3	65	18.3	5.2	
28	6	15.5	-2.94	3.94	67	19.4	5.3	
29	7	6.9	-2.30	4	65	18.3	6.1	
33	7	15.8	-1.92	3.94	68	20.0	5.8	
34	8	7.0	-1.29	4.54	65	18.3	6.1	
36	8	16.0	-0.92	3.74	67	19.4	5.8	
38	9	7.0	-0.29	5.56	65	18.3	5.9	1.6
42	9	15.5	0.06	5.62	68	20.0	6	
60	10	7.0	0.71	5.11	66	18.9	5.9	
69	10	16.0	1.08	5.45	73	22.8	6.2	
85	11	7.0	1.71	6.06	72	22.2	5.9	
94	11	16.0	2.08	5.22	72	22.2	6.2	
111	12	7.0	2.71	2.45	66	18.9	5.9	
121	12	16.0	3.08	3.87	68	20.0	6	
137	13	7.0	3.71	3.5	66	18.9	6	1.5
146	13	16.0	4.08	3.72	68	20.0	6.1	
157	14	7.0	4.71	3.88	66	18.9	6.1	
162	14	16.0	5.08	4.06	66	18.9	6	
168	15	7.0	5.71	4.65	66	18.9	6.1	
173	15	16.0	6.08	6.03	72	22.2	6.1	
179	16	7.0	6.71	6.48	65	18.3	5.7	
183	16	16.0	7.08	5.08	68	20.0	5.9	
186	17	7.0	7.71	5.84	67	19.4	5.7	1.5
191	17	16.0	8.08	4.99	70	21.1	6	
194	18	7.0	8.71	6.62	67	19.4	5.8	
199	18	16.0	9.08	4.88	69	20.6	6.1	
202	19	7.0	9.71	6.27	67	19.4	6.2	

Table 5.6 (continued): Results of PGDP Analyses for MW-155

Sample Numbe	Day of Month	Hour of Day	Time Since Extraction Began (days)	Dissolved Oxygen (mg/L)	Temp. (°F)	Temp. (°C)	pH	TCE (ppm)
207	19	16.0	10.08	6.12	72	22.2	6.5	
210	20	7.0	10.71	6.73	69	20.6	6.4	
215	20	16.0	11.08	6.33	69	20.6	6.3	
218	21	7.0	11.71	5.78	65	18.3	6.3	
223	21	16.0	12.08	6.13	70	21.1	6.4	
226	22	7.0	12.71	6.37	66	18.9	6.5	
231	22	16.0	13.08	4.82	67	19.4	6.5	
234	23	7.0	13.71	5.61	66	18.9	6.5	
239	23	16.0	14.08					
241	24	7.0	14.71	6.12	67	19.4	6.5	
247	24	16.0	15.08	5.26	71	21.7	6.6	
250	25	7.0	15.71	6.2	71	21.7	6.5	1.6
252	25	11.0	15.88	4.97	76	24.4	6.5	1.6

Table 5.7: Matched-Pairs Analysis of Differences in Field and PGDP Results for MW-155

Sample Number	PGDP TCE Conc.	Field TCE Conc.	Difference (mg/L)	Student t	
	Data (ppm)	Data (mg/L)		Number of Matched Pairs	Degrees of Freedom
2	2	1.4	0.6	6	
42	1.6	1.2	0.4	5	
168	1.5	1.4	0.1		
202	1.5	1.7	-0.2		
250	1.6	1.7	-0.1		
252	1.6	2.2	-0.6		
Conclusion					
Sample Mean			0.2	The PGDP TCE measurements are not significantly different from the field measurements for MW-155.	
Sample Standard Deviation			0.3		

FIGURES

Figure 1.1: Schematic showing the migration of DNAPL in a granular aquifer system and the development of both a DNAPL zone , comprising several vertical fingers and horizontal lenses, and two dissolved-phase plumes.

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Paducah Gaseous Diffusion Plant
Paducah, Kentucky

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REF: 1125-004

Figure 1.2: Schematic mechanism for initial solubilization. Mixed micelle desorption and diffusion [steps (4) to (5)] are assumed to control DNAPL solubilization (Modified after Chan, et al., 1976).

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

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Figure 2.1: Solubility vs HLB for TCE, PCE and CTET.

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Figure 3.2: Hydrostratigraphic Section for MW-155 Showing Screened Interval for MW-156.

Figure 3.3: Locations of soil borings near C-400 and the cross section F-G (after Phillips, 1992).

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Paducah, Kentucky

Figure 3.4: Hydrostratigraphy along east side of building C-400 (after Phillips, 1992).

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Figure 3.5: Conceptual model of DNAPL distribution in the subsurface beneath the C-400 building at PGDP (from Clausen et al., 1992).

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Figure 3.6: Two scenarios simulated to investigate aqueous TCE concentrations in the RGA.

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Figure 3.7: Stratigraphy and Location of Wells

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Figure 3.8: Cross Sectional Simulation Grid for Scenario A

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Figure 3.9: Cross Sectional Simulation Grid for Scenario B

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TCE Concentration
(mg/L)

Figure 3.10: Scenario A: Log of TCE Concentrations

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TCE Concentration
(mg/L)

Figure 3.11: Scenario B: Log of TCE Concentrations

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Figure 4.1: PCE desaturation curves following the injection of water and surfactant solutions into soil columns containing different size fractions of Ottawa sand. (after Abriola et al., 1993).

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NOTE: NOT TO SCALE

Figure 5.1: Injection Configuration

DATE: 10/10/94
REF: INJECTIO.DWG

Figure 5.2: Extraction Configuration

DATE: 10/10/94
REV: EXTRACT.DWG

• Water Level □ Injection Rate

Figure 5.5: Injection Phase - MW-156, August 5 - 9, 1994

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Paducah, Kentucky

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Figure 5.6: Water Levels in Piezometer 109 During the Injection Phase, August 5 - 9, 1994

Figure 5.7: Extraction Phase - MW-156, August 9 - 25, 1994

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Paducah, Kentucky

DATE: 10/26/94

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DATE: 10/26/94

REF: 1125-004

Figure 5.8: Water Level in Piezometer 109 During the Extraction Phase, August 9 - 25, 1994

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Figure 5.9: Plot of Precision Measurements for MW-156 Field TCE Analyses versus Mean TCE Concentrations

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Paducah, Kentucky

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Figure 5.10: Plot of Results of Field Analyses for MW-156 versus Time

DATE: 10/26/94

REF: 1125-004

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Figure 5.11: Plot of Results of PGDP Analyses for MW-156 versus Time

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

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DATE: 10/26/94

REF: 1125-004

Figure 5.12: Plot of Sample Temperature for MW-156 versus Time

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Figure 5.13: Plot of Approximate DCE Concentration in Several MW-156 Samples versus Time

DATE: 10/26/94

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Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Figure 5.14: Plot of Results of Field Analyses for MW-155 versus Time

DATE: 10/26/94

REF: 1125-004

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Paducah, Kentucky

Figure 5.15: Plot of Dissolved Oxygen Concentration for MW-155 versus Time

DATE: 10/26/94

REF: 1125-004

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Figure 5.16: Plot of Sample Temperature for MW-155 versus Time

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

DATE: 10/26/94

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Figure 5.17: Plot of pH for MW-155 versus Time

DATE: 10/26/94

REF: 1125-004

Paducah Gaseous Diffusion Plant
Paducah, Kentucky

DATE: 10/26/94

REF: 1125-004

Figure 5.18: ^{99}Tc and TCE Response During Extraction Phase in MW-156

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Paducah, Kentucky

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REF: 1125-004

Figure 5.19: Surfactant recovery during extraction phase compared with that of a conservative tracer.

Paducah Gaseous Diffusion Plant
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Figure 7.1: Schematic of Interwell NAPL Solubilization Test

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Paducah, Kentucky

DATE: 10/26/94

REF: 1125-004

Figure 7.2: TCE and Surfactant Concentrations at the Extraction Well

Paducah Gas Diffusion Plant
Paducah, Kentucky

DATE: 10/26/94

REF: 1125-004

Appendix A

T-MAZ 80K Material Safety Data Sheet

T-MAZ® 80K POLYSORBATE 80 K

PPG INDUSTRIES, INC.
SPECIALTY CHEMICALS, CHEMICALS GROUP
3938 PORETT DRIVE
GURNEE, ILLINOIS 60031
TEL: (708) 244-3410 TELEX: 25-3310
FAX: (708) 244-9633
CABLE: MAZCHEM GURNEEILL

GENERAL STATEMENT:

T-MAZ 80K is a sorbitan monooleate which has been ethoxylated with approximately 20 moles of ethylene oxide to give a water soluble, oil and water emulsifier. This product is one of a group of ethoxylated sorbitan fatty acid esters which are often referred to as Polysorbates. These surfactants are mixtures of partial esters of sorbitol and its anhydrides made from fatty acids, such as, tall oil, lauric, palmitic, stearic and oleic, which are then reacted with ethylene oxide, to make them hydrophilic in nature. Some T-MAZ products are designated with an "FG" in the product name, which means they are food grade. This product is marked "K" which means it is food grade with Kosher U Certification.

APPLICATIONS:

T-MAZ 80K can be used as a solubilizer and emulsifier of essential oils and fragrances, as a wetting agent, viscosity modifier, anti-stat, stabilizer and dispersing agent. Typical applications are found in baby shampoos because of very low eye irritation, cosmetics and toiletries and ointments. T-MAZ surfactants can also be used in the food, pharmaceutical, textile, and metalworking industries.

SOLUBILITIES:

T-MAZ surfactants are generally soluble or dispersible in water, and, soluble in varying degrees in organic liquids. They are used for oil-in-water emulsions, dispersions or solubilizing oils and to make anhydrous ointments water soluble or washable. Frequently, the T-MAZ surfactants are combined with similarly numbered S-MAZ surfactants to promote emulsion stability.

$$CMC = 0.0013g/dL = 13mg/L$$

SALES SPECIFICATIONS

ACID VALUE	2 MAX
SAPONIFICATION VALUE	45-55
HYDROXYL VALUE	65-80
WATER, %	3 MAX
RESIDUE ON IGNITION, %	0.25 MAX
POE, %	65-69.5
APPEARANCE @ 25 C	CLEAR YELLOW LIQUID
ppm, 1,4 DIOXANE	1 MAX
ARSENIC, ppm	1 MAX
HEAVY METALS, %	0.001 MAX

This product is available in bulk, drum, and 5 gallon pail quantities

last revised 01 DEC 1993 DBM/RGL Technical Service Dept.

Statements, methods, and data presented herein are based upon the best available information and practices known to PPG Industries, Inc. at present; but are not representations or warranties concerning fitness or suitability of use or of performance or results, nor do they imply any recommendations to infringe any patent or an offer of license under any patent.

The products mentioned herein can be hazardous if not used properly. Any health hazard and safety information contained herein should be passed on to your customers or employees, as the case may be. PPG Industries, Inc. also recommends that, before use, anyone using or handling this product thoroughly read and understand the information and precautions on the label as well as in other product safety publications, such as the Material Safety Data Sheet.

For all potentially hazardous materials, this product must be kept out of the reach of children.

PPG® INDUSTRIES, INC.
Specialty Chemicals
3938 Porett Drive Gurnee, IL 60031
Informational phone number: (800) 552-1912
24 hour emergency phone number: (304) 843-1300

MATERIAL SAFETY DATA SHEET

PRODUCT INFORMATION

Trade Name: T-MAZ® 80K

Name and/or Family or Description: POLYSORBATE 80 K

DOT Hazard Classification: NON-HAZARDOUS

DOT:

NFPA: HEALTH HAZARD-0-NORMAL MATERIAL; FLAMMABILITY-1-ABOVE 200 DEG F; REACTIVITY-0-STABLE

CAS NUMBER:

9005-65-6

RCRA HAZARD CLASS: (IF DISCARDED)

NON-HAZARDOUS

EPA PRIORITY POLLUTANTS

NONE

SARA TITLE III (Sec. 313) HAZARDOUS MATERIAL

NONE

HAZARDOUS INGREDIENTS

(This material contains no ingredients which are known by PPG Industries to be hazardous unless listed below).

MATERIAL OR COMPONENT

TLV (UNITS)

APPROX %

NONE KNOWN

As established by the American Conference of Governmental Industrial Hygienists and/or standards promulgated by the Occupational Safety and Health Administration.

PHYSICAL DATA

BOILING POINT, °F	>300
SOLUBILITY IN WATER @ 25°C	SOLUBLE
SPECIFIC GRAVITY @ 25°C	1.09
VAPOR PRESSURE, mm Hg @ 25°C	<1
VAPOR DENSITY, (AIR=1)	>1
VOLATILES, %, BY VOLUME	<4
APPEARANCE @ 25°C	CLEAR YELLOW LIQUID
ODOR	BLAND
FLASH POINT, PMCC, °F	>300

FIRE AND EXPLOSION HAZARD DATA

Flash Point: (See PHYSICAL DATA section)

Flammable Limits in Air, % by Volume: Unknown LOWER: Undetermined UPPER: Undetermined

Extinguishing Media: Use Carbon Dioxide or Dry Chemical on small fires. Use foam (alcohol, polymer or ordinary) and water spray for large fires.

Special Fire Fighting Procedures: Self-contained breathing apparatus and protective clothing should be worn in fighting fires involving chemicals.

Unusual Fire & Explosion Hazards: None Known to PPG Industries.

HEALTH HAZARD DATA

Threshold Limit Value: Not listed by OSHA or ACGIH.

Effects of Overexposure: Contact with skin or eyes not expected to cause irritation.

Effects of a Single Overexposure:

Swallowing: No evidence of adverse effects from available information.

Skin Absorption: No evidence of adverse effects from available information.

Skin Contact: No evidence of adverse effects from available information.

Eye Contact: No evidence of adverse effects from available information.

Inhalation: No evidence of adverse effects from available information.

Effects of Repeated Overexposure: No evidence of adverse effects from available information.

Emergency and First Aid Procedures: Flush eyes with copious amounts of water for a minimum of 15 minutes. Wash contacted skin areas with soap and water. If irritation develops, consult a physician. Soaked clothing should be changed immediately! Remove to fresh air.

Medical Conditions Aggravated by Overexposure: A knowledge of available toxicology information and of the physical and chemical properties of the material suggests that overexposure is unlikely to aggravate existing medical conditions.

Significant Laboratory Data with Possible Relevance to Human Health Hazard Evaluation:

None currently known unless listed below.

Oral, LD50, rat	>30ml/kg (MILD)
Oral, LD50, mouse	25g/kg (RTECS)
Ocular irritation, rabbit	2.0 (VERY MILD)
Dermal irritation, rabbit	PII = 1.3 (MILD)
Dermal, human patch test	0/50 NON-IRRITATING
Intraperitoneal, LD50, rat	6804mg/kg (RTECS)
Intraperitoneal, LD50, mouse	7600mg/kg (RTECS)
Intravenous, LD50, rat	1790mg/kg (RTECS)
Comedogenicity	0/5 NON-COMEDOGENIC

REACTIVITY DATA

Stability: Stable ☒ Unstable ☐

Incompatibilities: (Materials to Avoid) Strong oxidizing material can cause a reaction.

Hazardous Decomposition Products: Thermal decomposition may produce carbon mono/dioxides.

Hazardous Polymerization: May Occur ☐ Will not occur ☒

Conditions to Avoid: See above statements.

SPILL, LEAK AND DISPOSAL PROCEDURES

Action to take for spills: (Use appropriate Safety Equipment) Use absorbent material to collect and contain for disposal. Contain large spills and pump into a suitable tank. Wash area with suitable detergent and thoroughly rinse.

Disposal Method: All Local, State and Federal Regulations concerning health and pollution should be reviewed to determine approved disposal procedures.

SPECIAL HANDLING INFORMATION

Ventilation:

1. Local Exhaust: None should be needed
2. Mechanical (general): Recommended
3. Respiratory Protection (type): None should be needed (for emergency, use a canister for organic vapors such as GMA from Mine Safety Appliance Co.)

Protective Clothing: Clean, body-covering clothing. In addition, rubber gloves, boots, and apron, depending upon the exposure likely, or as required by your company.

Eye Protection: Chemical Workers Goggles recommended.

Other Protective Equipment: Eye Fountain and Safety Shower in work area.

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORAGE

Store in well ventilated areas at temperatures below 120°F.

last revised 20 OCT 1993 MJC/TBH Compliance Department

Appendix B

Injection Data (Rates and Heads)

Paducah Gaseous Diffusion Plant						
Paducah, Kentucky						
DNAPL Solubilization Test - Well MW-156, SE Corner of Building C-400						
Injection Phase Data - August 5-9, 1994						
Time	Minutes	Solinst	Hours	Ground Water	Totalizer	Average
	Between Readings	TOC DTW	into Test	Elevation	Total Gallons	Injection Rate
		(feet)		(feet msl)	Pumped	(gallons/minute)
06:30 PM		50.91	0.00	331.15	1174	1.00
09:07 PM	157	50.95	2.62	331.11	1336	1.03
11:17 PM	130	50.95	4.78	331.11	1463.5	0.98
12:17 AM	60	50.92	5.78	331.14	1529	1.09
01:00 AM	43	50.89	6.50	331.17	1556.4	0.64
01:22 PM	742	50.6	18.87	331.46	2299	1.00
03:07 PM	105	50.5	20.62	331.56	2402.62	0.99
06:00 PM	173	50.39	23.50	331.67	2573	0.98
06:30 PM	30	50.39	24.00	331.67	2602.5	0.98
08:30 PM	120	50.34	26.00	331.72	2720.2	0.98
10:30 PM	120	50.32	28.00	331.74	2837.8	0.98
01:30 AM	180	50.21	31.00	331.85	3014.2	0.98
02:30 AM	60	50.18	32.00	331.88	3072.8	0.98
03:30 AM	60	50.16	33.00	331.9	3131.3	0.97
04:30 AM	60	50.13	34.00	331.93	3189.2	0.96
05:30 AM	60	50.1	35.00	331.96	3246.9	0.96
06:30 AM	60	50.16	36.00	331.9	3309	1.03
07:30 AM	60	50.08	37.00	331.98	3367.6	0.98
08:30 AM	60	50.03	38.00	332.03	3425.7	0.97
09:30 AM	60	49.98	39.00	332.08	3483.4	0.96
12:00 PM	150	49.9	41.50	332.16	3630.3	0.98
05:00 PM	300	49.55	46.50	332.51	3926.8	0.99
06:00 PM	60	49.5	47.50	332.56	3985.7	0.98
07:00 PM	60	49.43	48.50	332.63	4043.4	0.96
08:00 PM	60	49.4	49.50	332.66	4103.7	1.00
09:00 PM	60	49.37	50.50	332.69	4160.9	0.95
10:00 PM	60	49.35	51.50	332.71	4219.6	0.98
11:00 PM	60	49.35	52.50	332.71	4279.3	0.99
12:00 AM	60	49.32	53.50	332.74	4338.8	0.99
01:00 AM	60	49.29	54.50	332.77	4398.3	0.99
02:00 AM	60	49.24	55.50	332.82	4458.1	1.00
03:00 AM	60	49.22	56.50	332.84	4517.6	0.99
04:00 AM	60	49.18	57.50	332.88	4577.2	0.99
05:00 AM	60	49.16	58.50	332.9	4636.6	0.99
06:00 AM	60	49.14	59.50	332.92	4695.9	0.99
07:00 AM	60	49.13	60.50	332.93	4755.2	0.99
08:00 AM	60	49.11	61.50	332.95	4814.5	0.99
09:00 AM	60	49.1	62.50	332.96	4873.8	0.99
10:00 AM	60	49.06	63.50	333	4933.1	0.99
11:03 AM	63	49.02	64.55	333.04	4995.2	0.99
12:00 PM	57	48.95	65.50	333.11	5051.5	0.99
01:30 PM	90	48.8	67.00	333.26	5139.5	0.98
02:30 PM	60	48.7	68.00	333.36	5199	0.99
04:00 PM	90	48.52	69.50	333.54	5290.2	1.01
05:20 PM	80	48.33	70.83	333.73	5373.1	1.04
06:00 PM	40	48.26	71.50	333.8	5414.4	1.03

Paducah Gaseous Diffusion Plant						
Paducah, Kentucky						
DNAPL Solubilization Test - Well MW-156, SE Corner of Building C-400						
Injection Phase Data - August 5-9, 1994						
Time	Minutes	Solinst	Hours	Ground Water	Totalizer	Average
	Between Readings	TOC DTW	into Test	Elevation	Total Gallons	Injection Rate
		(feet)		(feet msl)	Pumped	(gallons/minute)
07:00 PM	60	48.16	72.50	333.9	5476.2	1.03
08:00 PM	60	48.13	73.50	333.93	5535.3	0.99
09:00 PM	60	48.06	74.50	334	5594.6	0.99
11:00 PM	120	47.96	76.50	334.1	5712.9	0.99
12:00 AM	60	47.91	77.50	334.15	5772.1	0.99
01:00 AM	60	47.88	78.50	334.18	5832.2	1.00
02:00 AM	60	47.86	79.50	334.2	5891.2	0.98
03:00 AM	60	47.8	80.50	334.26	5949.5	0.97
04:00 AM	60	47.8	81.50	334.26	6007.3	0.96
05:00 AM	60	47.66	82.50	334.4	6064.9	0.96
06:00 AM	60	47.6	83.50	334.46	6121.9	0.95
07:00 AM	60	47.58	84.50	334.48	6179.2	0.96
08:00 AM	60	47.54	85.50	334.52	6236.8	0.96
09:00 AM	60	47.53	86.50	334.53	6293.6	0.95
* TOC DTW - Top of Casing Depth to Water						

Paducah Gaseous Diffusion Plant
DNAPL Solubilization Test

Water Level in Control Piezometer 109
During the Injection Phase
August 5 - 9, 1994

Date	Time	Ground Water Elevation (feet, msl)
05-Aug-94	12:00 AM	331.974
05-Aug-94	01:00 AM	331.974
05-Aug-94	02:00 AM	331.968
05-Aug-94	03:00 AM	331.945
05-Aug-94	04:00 AM	331.928
05-Aug-94	05:00 AM	331.889
05-Aug-94	06:00 AM	331.861
05-Aug-94	07:00 AM	331.833
05-Aug-94	08:00 AM	331.816
05-Aug-94	09:00 AM	331.799
05-Aug-94	10:00 AM	331.793
05-Aug-94	11:00 AM	331.788
05-Aug-94	12:00 PM	331.793
05-Aug-94	01:00 PM	331.799
05-Aug-94	02:00 PM	331.805
05-Aug-94	03:00 PM	331.816
05-Aug-94	04:00 PM	331.827
05-Aug-94	05:00 PM	331.827
05-Aug-94	06:00 PM	331.816
05-Aug-94	07:00 PM	331.799
05-Aug-94	08:00 PM	331.776
05-Aug-94	09:00 PM	331.765
05-Aug-94	10:00 PM	331.76
05-Aug-94	11:00 PM	331.748
06-Aug-94	12:00 PM	331.76
06-Aug-94	01:00 AM	331.782
06-Aug-94	02:00 AM	331.765
06-Aug-94	03:00 AM	331.76
06-Aug-94	04:00 AM	331.76
06-Aug-94	05:00 AM	331.76
06-Aug-94	06:00 AM	331.76
06-Aug-94	07:00 AM	331.743
06-Aug-94	08:00 AM	331.714
06-Aug-94	09:00 AM	331.737
06-Aug-94	10:00 AM	331.748
06-Aug-94	11:00 AM	331.754
06-Aug-94	12:00 PM	331.765
06-Aug-94	01:00 PM	331.805
06-Aug-94	02:00 PM	331.816
06-Aug-94	03:00 PM	331.827
06-Aug-94	04:00 PM	331.838
06-Aug-94	05:00 PM	331.85
06-Aug-94	06:00 PM	331.844

Date	Time	Ground Water Elevation (feet, msl)
06-Aug-94	02:00 PM	331.816
06-Aug-94	03:00 PM	331.827
06-Aug-94	04:00 PM	331.838
06-Aug-94	05:00 PM	331.85
06-Aug-94	06:00 PM	331.844
06-Aug-94	07:00 PM	331.833
06-Aug-94	08:00 PM	331.816
06-Aug-94	09:00 PM	331.793
06-Aug-94	10:00 PM	331.799
06-Aug-94	11:00 PM	331.799
07-Aug-94	12:00 AM	331.788
07-Aug-94	01:00 AM	331.793
07-Aug-94	02:00 AM	331.799
07-Aug-94	03:00 AM	331.799
07-Aug-94	04:00 AM	331.805
07-Aug-94	05:00 AM	331.788
07-Aug-94	06:00 AM	331.771
07-Aug-94	07:00 AM	331.748
07-Aug-94	08:00 AM	331.76
07-Aug-94	09:00 AM	331.748
07-Aug-94	10:00 AM	331.754
07-Aug-94	11:00 AM	331.754
07-Aug-94	12:00 PM	331.788
07-Aug-94	01:00 PM	331.788
07-Aug-94	02:00 PM	331.816
07-Aug-94	03:00 PM	331.821
07-Aug-94	04:00 PM	331.816
07-Aug-94	05:00 PM	331.833
07-Aug-94	06:00 PM	331.821
07-Aug-94	07:00 PM	331.81
07-Aug-94	08:00 PM	331.793
07-Aug-94	09:00 PM	331.765
07-Aug-94	10:00 PM	331.76
07-Aug-94	11:00 PM	331.76
08-Aug-94	12:00 PM	331.754
08-Aug-94	01:00 AM	331.743
08-Aug-94	02:00 AM	331.743
08-Aug-94	03:00 AM	331.748
08-Aug-94	04:00 AM	331.726
08-Aug-94	05:00 AM	331.692
08-Aug-94	06:00 AM	331.692
08-Aug-94	07:00 AM	331.681
08-Aug-94	08:00 AM	331.658
08-Aug-94	09:00 AM	331.647
08-Aug-94	10:00 AM	331.63
08-Aug-94	11:00 AM	331.647
08-Aug-94	12:00 PM	331.664
08-Aug-94	01:00 PM	331.675
08-Aug-94	02:00 PM	331.692
08-Aug-94	03:00 PM	331.692
08-Aug-94	04:00 PM	331.709

Date	Time	Ground Water Elevation (feet, msl)
08-Aug-94	05:00 PM	331.72
08-Aug-94	06:00 PM	331.692
08-Aug-94	07:00 PM	331.669
08-Aug-94	08:00 PM	331.647
08-Aug-94	09:00 PM	331.63
08-Aug-94	10:00 PM	331.63
08-Aug-94	11:00 PM	331.624
09-Aug-94	12:00 PM	331.607
09-Aug-94	01:00 AM	331.529
09-Aug-94	02:00 AM	331.591
09-Aug-94	03:00 AM	331.591
09-Aug-94	04:00 AM	331.619
09-Aug-94	05:00 AM	331.591
09-Aug-94	06:00 AM	331.591
09-Aug-94	07:00 AM	331.551
09-Aug-94	08:00 AM	331.529
09-Aug-94	09:00 AM	331.512
09-Aug-94	10:00 AM	331.5
09-Aug-94	11:00 AM	331.495
09-Aug-94	12:00 PM	331.5
09-Aug-94	01:00 PM	331.529
09-Aug-94	02:00 PM	331.54
09-Aug-94	03:00 PM	331.54
09-Aug-94	04:00 PM	331.557
09-Aug-94	05:00 PM	331.557
09-Aug-94	06:00 PM	331.545
09-Aug-94	07:00 PM	331.523
09-Aug-94	08:00 PM	331.495
09-Aug-94	09:00 PM	331.489
09-Aug-94	10:00 PM	331.489
09-Aug-94	11:00 PM	331.489

Appendix C

Extraction Data (Rates and Heads)

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
2	DNAPL Solubilization Test											
3	Extraction Phase - Well MW-156											
4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
11	0.0	8/9/94 14:00	0	NA	6340.4		1	NA	54	54	JL	
12	3.2	8/9/94 17:14	194	<250	6538.1	1.019	0.95	NA	53.93	53.9	JL	328.16
13	4.4	8/9/94 18:23	263	300	6606.3	0.988	0.8	NA	53.88	53.87	AHB	328.19
14	5.1	8/9/94 19:03	303	350	6645	0.967	0.8	NA	53.86	53.86	AHB	328.2
15	6.0	8/9/94 20:02	362	400	6701.7	0.961	0.8	NA	53.8	53.81	AHB	328.25
16	7.1	8/9/94 21:04	424	460	6759.5	0.932	0.8	NA	53.74	53.76	AHB	328.3
17	8.2	8/9/94 22:10	490	550	6819.2	0.905	0.7	NA	53.67	53.7	AHB	328.36
18	9.1	8/9/94 23:05	545	600	6866.2	0.855	1	NA	53.94	53.96	AHB	328.1
19	9.8	8/9/94 23:45	585	640	6915.4	1.230	0.9	172	53.9	53.93	AHB	328.13
20	10.1	8/10/94 0:04	604	650	6934.4	1.000	0.95	172	53.86	53.9	AHB	328.16
21	11.0	8/10/94 1:01	661	740	6990.9	0.991	0.95	172	53.78	53.82	CJM	328.24
22	12.0	8/10/94 2:00	720	800	7048.4	0.975	0.95	172	53.79	53.83	CJM	328.23
23	13.0	8/10/94 3:00	780	860	7105.7	0.955	0.95	172	53.71	53.76	CJM	328.3
24	14.0	8/10/94 4:00	840	920	7162.2	0.942	0.95	172	53.65	53.7	CJM	328.36
25	15.0	8/10/94 5:00	900	980	7217.6	0.923	0.9	172	53.62	53.63	CJM	328.43
26	16.0	8/10/94 6:00	960	1040	7278	1.007	1	175/176	53.93	54	CJM	328.06
27	17.0	8/10/94 7:00	1020	1110	7339.5	1.025	0.95	175/176	53.86	53.9	CJM	328.16
28	18.5	8/10/94 8:28	1108	60	7425.6	0.978	0.95	175/176	53.84	54.14	JTL	327.92
29	19.3	8/10/94 9:18	1158	115	7476.5	1.018	0.95	169/170	53.8	53.82	JTL	328.24
30	20.4	8/10/94 10:25	1225	180	7541.8	0.975	0.9	169/170	55.7	53.73	JTL	328.33
31	21.0	8/10/94 11:00	1260	?	7575.5	0.963	0.9	169/170	53.6	53.64	KRD	328.42
32	22.1	8/10/94 12:03	1323	?	7637	0.976	0.9	171	53.72	53.75	JTL	328.31
33	23.0	8/10/94 13:00	1380	330	7691.3	0.953	0.9	171	53.62	53.64	JTL & KRD	328.42
34	24.1	8/10/94 14:08	1448	395	7758	0.981	0.95	172/173	55.69	53.72	JTL	328.34
35	25.2	8/10/94 15:09	1509	460	7817.6	0.977	0.95	172/173	53.62	53.67	JTL	328.39
36	26.2	8/10/94 16:14	1574	550	7880	0.960	0.95	172/173	53.55	53.61	JTL	328.45
37	27.1	8/10/94 17:03	1623	600	7928.7	0.994	0.9	173/174	53.57	53.66	AHB	328.4
38	28.2	8/10/94 18:13	1693	660	7997	0.976	0.85	173/174	53.55	53.64	AHB	328.42
39	29.0	8/10/94 19:00	1740	750	8046.1	1.045	1	175/176	53.76	53.88	AHB	328.18

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
2	DNAPL Solubilization Test											
3	Extraction Phase - Well MW-156											
4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
40	30.2	8/10/94 20:11	1811	810	8121.7	1.065	1	175/176	53.71	53.82	AHB	328.24
41	31.2	8/10/94 21:11	1871	870	8184.5	1.047	1	175/176	53.66	53.8	AHB	328.26
42	32.0	8/10/94 22:00	1920	950	8234.8	1.027	0.9	175/176	53.63	53.74	AHB	328.32
43	33.0	8/10/94 23:00	1980	1010	8295.1	1.005	0.9	175/176	53.62	53.71	AHB	328.35
44	34.1	8/11/94 0:03	2043	1090	8360	1.030	1	176/177	53.66	53.79	AHB	328.27
45	35.0	8/11/94 1:00	2100	1150	8418.6	1.028	0.95	176/177	53.56	53.68	CJM	328.38
46	36.0	8/11/94 2:00	2160	60	8471	0.873	0.5	171	53.51	53.64	CJM	328.42
47	37.0	8/11/94 3:00	2220	120	8540.5	1.158	1.3	176/177	53.69	53.84	CJM	328.22
48	38.0	8/11/94 4:00	2280	180	8602.8	1.038	1	171/172	53.57	53.71	CJM	328.35
49	39.0	8/11/94 5:00	2340	240	8663.1	1.005	0.95	171/172	53.52	53.66	CJM	328.4
50	40.0	8/11/94 6:00	2400	300	8721.9	0.980	0.95	171/172	53.49	53.64	CJM	328.42
51	41.0	8/11/94 7:00	2460	360	8779	0.952	0.8	171/172	53.4	53.57	CJM	328.49
52	42.0	8/11/94 8:00	2520	420	8829.6	0.843	0.8	171/172	53.39	53.55	CJM	328.51
53	43.0	8/11/94 9:00	2580	505	8890	1.007	0.9	172	53.45	53.59	JTL	328.47
54	44.2	8/11/94 10:11	2651	570	8960.8	0.997	0.95	174	53.58	53.74	JTL	328.32
55	45.0	8/11/94 11:00	2700	650	9009.3	0.990	0.95	174	53.52	53.66	JTL	328.4
56	46.2	8/11/94 12:10	2770	710	9076.4	0.959	0.9	174	53.47	53.61	JTL	328.45
57	47.2	8/11/94 13:11	2831	770	9138.1	1.011	0.98	175/176	53.55	53.7	JTL	328.36
58	48.1	8/11/94 14:08	2888	850	9195.9	1.014	0.98	175/176	53.55	53.7	JTL	328.36
59	49.1	8/11/94 15:08	2948	920	9255.8	0.998	0.95	175/176	53.47	53.63	JTL	328.43
60	50.0	8/11/94 16:00	3000	965	9306.1	0.967	0.95	175/176	53.38	53.55	JTL	328.51
61	51.0	8/11/94 17:00	3060	1020	9367.6	1.025	0.98	176/177	53.56	53.74	AHB	328.32
62	52.0	8/11/94 18:00	3120	1110	9429	1.023	0.98	176/177	53.5	53.7	AHB	328.36
63	53.0	8/11/94 19:00	3180	1160	9489.2	1.003	0.9	176/177	53.42	53.6	AHB	328.46
64	54.0	8/11/94 20:00	3240	70	9548.7	0.992	1.2	176/177	53.7	53.89	AHB	328.17
65	55.0	8/11/94 21:00	3300	150	9613.6	1.082	1	173/174	53.62	53.83	AHB	328.23
66	56.0	8/11/94 22:00	3360	200	9675.5	1.032	1	173	53.62	53.83	AHB	328.23
67	57.0	8/11/94 23:00	3420	250	9737.4	1.032	1	173/174	53.57	53.78	AHB	328.28
68	58.0	8/12/94 0:00	3480	310	9799.3	1.032	1.03	173/174	53.52	53.72	AHB	328.34

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
2	DNAPL Solubilization Test											
3	Extraction Phase - Well MW-156											
4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
69	59.0	8/12/94 1:00	3540	380	9858	0.978	0.95	173/174	53.48	53.68	CJM	328.38
70	60.0	8/12/94 2:00	3600	440	9915.4	0.957	0.9	173	53.38	53.58	CJM	328.48
71	61.0	8/12/94 3:00	3660	500	9971.6	0.937	0.9	173	53.37	53.57	CJM	328.49
72	62.0	8/12/94 4:00	3720	560	10030.3	0.978	0.95	174/175	53.5	53.7	CJM	328.36
73	63.0	8/12/94 5:00	3780	620	10089.2	0.982	0.95	174/175	53.47	53.67	CJM	328.39
74	64.0	8/12/94 6:00	3840	720	10147.1	0.965	0.95	174/175	53.45	53.66	CJM	328.4
75	65.0	8/12/94 7:00	3900	785	10204	0.948	0.9	174/175	53.37	53.6	CJM	328.46
76	66.0	8/12/94 8:00	3960	850	10260.2	0.937	0.9	174/175	53.39	53.59	CJM	328.47
77	67.2	8/12/94 9:10	4030	920	10322.3	0.887	0.9	174/175	53.3	53.5	JTL	328.56
78	68.2	8/12/94 10:11	4091	990	10383.6	1.005	1	176/177	53.56	53.25	JTL	328.81
79	69.2	8/12/94 11:11	4151	1050	10442.5	0.982	0.98	176/177	53.5	53.68	JTL	328.38
80	70.0	8/12/94 12:00	4200	1100	10490	0.969	0.95	176/177	53.43	53.64	JTL	328.42
81	71.0	8/12/94 13:00	4260	1150	10546.7	0.945	0.95	176/177	53.48	53.66	JTL	328.4
82	72.0	8/12/94 14:00	4320	<100	10604.4	0.962	1.25	176/177	53.9	54.2	JTL	327.86
83	73.0	8/12/94 15:00	4380	100	10661	0.943	0.75	169/170	53.1	53.37	AHB	328.69
84	74.0	8/12/94 16:00	4440	>100	10713.2	0.870	0.75	170	53.14	53.39	AHB	328.67
85	75.0	8/12/94 17:00	4500	>100	10764.3	0.852	0.75	169/170	53.09	53.32	AHB	328.74
86	76.0	8/12/94 18:01	4561	300	10813.6	0.808	0.7	169/170	52.97	53.2	AHB	328.86
87	77.0	8/12/94 19:00	4620	360	10879.3	1.114	1.1	175/176	53.67	53.95	AHB	328.11
88	78.0	8/12/94 20:00	4680	440	10946.1	1.113	1.1	176	53.63	53.9	AHB	328.16
89	79.0	8/12/94 21:00	4740	530	11011.5	1.090	1.1	176	53.58	53.86	AHB	328.2
90	80.0	8/12/94 22:00	4800	600	11075.3	1.063	1.1	176	53.55	53.83	AHB	328.23
91	81.0	8/12/94 23:00	4860	>600	11136.9	1.027	1	175/176	53.55	53.84	AHB	328.22
92	82.0	8/13/94 0:00	4920	720	11198.2	1.022	1	175/176	53.42	53.71	KRD	328.35
93	83.0	8/13/94 1:00	4980	800	11258	0.997	1	175/176	53.42	53.69	KRD	328.37
94	84.0	8/13/94 2:00	5040	850	11317.2	0.987	1	175/176	53.37	53.66	KRD	328.4
95	85.0	8/13/94 3:00	5100	915	11375.1	0.965	0.95	175/176	53.27	53.55	KRD	328.51
96	86.0	8/13/94 4:00	5160	990	11431.2	0.935	0.95	175/176	53.23	53.49	KRD	328.57
97	87.0	8/13/94 5:00	5220	1030	11488.8	0.960	1	177/178	53.36	53.64	KRD	328.42

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
2	DNAPL Solubilization Test											
3	Extraction Phase - Well MW-156											
4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
98	88.0	8/13/94 6:00	5280	1105	11546.8	0.967	0.98	177	53.33	53.6	KRD	328.46
99	89.2	8/13/94 7:11	5351	60	11614.1	0.948	1.15	177	53.75	54.06	KRD	328
100	90.4	8/13/94 8:25	5425	130	NA		0.95	NA	53.26	53.56	KRD	328.5
101	91.2	8/13/94 9:11	5471	180	11728.1		0.9	NA	53.24	53.52	KRD	328.54
102	92.1	8/13/94 10:07	5527	NA	11783.1	0.982	1.05	NA	53.56	53.84	PEM	328.22
103	93.2	8/13/94 11:12	5592	300	11849.3	1.018	1	NA	53.39	53.7	PEM	328.36
104	94.1	8/13/94 12:07	5647	350	11902.9	0.975	1	NA	53.32	53.62	PEM	328.44
105	95.1	8/13/94 13:03	5703	410	11956.9	0.964	0.95	173/174	53.24	53.55	PEM	328.51
106	96.0	8/13/94 14:00	5760	470	12010.6	0.942	0.95	173/174	53.21	53.53	AHB	328.53
107	97.0	8/13/94 15:00	5820	540	12066	0.923	0.95	173/174	53.14	53.46	AHB	328.6
108	98.0	8/13/94 16:00	5880	610	12123.5	0.958	1	175/176	53.34	53.66	AHB	328.4
109	99.0	8/13/94 17:00	5940	670	12183.2	0.995	1	175/176	53.3	53.61	AHB	328.45
110	100.0	8/13/94 18:02	6002	740	12248	1.045	1.15	178/179	53.52	53.88	AHB	328.18
111	101.0	8/13/94 19:01	6061	820	12313.1	1.103	1.15	178/179	53.48	53.81	AHB	328.25
112	102.1	8/13/94 20:08	6128	920	12386.1	1.090	1.15	178/179	53.4	53.75	AHB	328.31
113	103.0	8/13/94 21:02	6182	960	12442.8	1.050	1.15	178/179	53.36	53.7	AHB	328.36
114	104.0	8/13/94 22:00	6240	1020	12502.5	1.029	1.15	178/179	53.32	53.66	AHB	328.4
115	105.0	8/13/94 23:00	6300	1095	12563.8	1.022	1.05	178/179	53.33	53.64	KRD	328.42
116	106.0	8/14/94 0:00	6360	1145	12618.2	0.907	0.9	176/177	52.98	53.29	KRD	328.77
117	107.0	8/14/94 1:00	6420	75	12677.2	0.983	1.4	180/181	53.88	53.23	KRD	328.83
118	108.0	8/14/94 2:00	6480	140	12737.8	1.010	0.92	172	53.06	53.39	KRD	328.67
119	109.0	8/14/94 3:00	6540	225	12798.1	1.005	1	174/175	53.26	53.6	KRD	328.46
120	110.2	8/14/94 4:10	6610	280	12867.8	0.996	1	174/175	53.24	53.58	KRD	328.48
121	111.0	8/14/94 5:00	6660	320	12917.8	1.000	1	174/175	53.23	53.55	KRD	328.51
122	112.0	8/14/94 6:00	6720	380	12975.6	0.963	0.95	174/175	53.14	53.48	KRD	328.58
123	113.0	8/14/94 7:00	6780	450	13035.9	1.005	1.05	176/177	53.32	53.64	KRD	328.42
124	114.0	8/14/94 8:00	6840	535	13096.2	1.005	1	176/177	53.27	53.6	KRD	328.46
125	115.0	8/14/94 9:00	6900	NA	13155.9	0.995	1	176/177	53.28	53.6	PEM	328.46
126	116.0	8/14/94 10:00	6960	660	13215.7	0.997	1	176/177	53.25	53.58	PEM	328.48

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
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4	August 9 - 25, 1994											
5												
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7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
127	117.0	8/14/94 11:00	7020	730	13276	1.005	1	176/177	53.28	53.62	AHB	328.44
128	118.0	8/14/94 12:00	7080	800	13334.3	0.972	1	176/177	53.2	53.55	AHB	328.51
129	119.0	8/14/94 13:01	7141	870	13398.1	1.046	1.15	178/179	53.48	53.84	AHB	328.22
130	120.0	8/14/94 14:01	7201	945	13463.4	1.088	1.15	178/179	53.43	53.79	AHB	328.27
131	121.1	8/14/94 15:03	7263	1020	13529.2	1.061	1.15	178/179	53.34	53.7	AHB	328.36
132	122.1	8/14/94 16:03	7323	1080	13591.3	1.035	1.1	178/179	53.28	53.63	AHB	328.43
133	123.2	8/14/94 17:11	7391	1150	13660.1	1.012	1.1	178/179	53.23	53.6	AHB	328.46
134	124.1	8/14/94 18:03	7443	75	13714.4	1.044	1.25	178/179	53.76	54.16	AHB	327.9
135	125.1	8/14/94 19:05	7505	155	13790.7	1.231	1.12	178/179	53.67	54.06	AHB	328
136	126.0	8/14/94 20:01	7561		13857.6	1.195	1.12	178/179	53.63	54.01	AHB	328.05
137	127.1	8/14/94 21:06	7626	300	13926.2	1.055	0.9	173.174	53.1	53.44	AHB	328.62
138	128.1	8/14/94 22:05	7685	360	13978.4	0.885	0.8	173.174	53.24	53.66	AHB	328.4
139	129.1	8/14/94 23:03	7743	420	14035.1	0.978	1	173.174	53.17	53.56	JED	328.5
140	130.1	8/15/94 0:03	7803	480	14088.7	0.893	0.9	173.174	53.08	53.48	JED	328.58
141	131.0	8/15/94 1:00	7860	550	14137	0.847	1	174/175	53.1	53.52	JED	328.54
142	132.0	8/15/94 2:00	7920	610	14190.7	0.895	1	174/175	53.14	53.5	JED	328.56
143	133.0	8/15/94 3:01	7981	670	14245	0.890	0.9	174/175	53.08	53.46	JED	328.6
144	134.0	8/15/94 3:57	8037	730	14296.5	0.920	0.85	177/178	53.24	53.64	JED	328.42
145	135.0	8/15/94 4:59	8099	790	14359.5	1.016	1.15	177/178	53.44	53.88	JED	328.18
146	136.0	8/15/94 6:00	8160	860	14422.4	1.031	1	178	53.39	53.78	JED	328.28
147	137.0	8/15/94 6:59	8219	935	14483.3	1.032	1	178	53.4	53.78	JED	328.28
148	138.2	8/15/94 8:14	8294	1030	14556.9	0.981	1	178	53.34	53.74	"PE,M"	328.32
149	139.0	8/15/94 9:00	8340	1060	14602.2	0.985	0.9	178	53.22	53.62	"PE,M"	328.44
150	140.0	8/15/94 10:00	8400	50	14657	0.913	0.95	177	53.32	53.68	"PE,M"	328.38
151	142.0	8/15/94 12:00	8520	155	14744.4	0.728	0.95	172/173	53.27	53.64	KRD	328.42
152	143.0	8/15/94 13:00	8580	220	14834.3	1.498	0.95	172/173	53.25	53.63	AHB	328.43
153	144.1	8/15/94 14:05	8645	NA	14894	0.918	0.95	172/173	53.13	53.5	KRD	328.56
154	145.0	8/15/94 15:00	8700	335	14946.6	0.956	1	173/174	53.23	53.61	KRD	328.45
155	146.0	8/15/94 16:00	8760	390	15004.8	0.970	0.97	173/174	53.14	53.53	AHB	328.53

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
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5												
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7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
156	147.0	8/15/94 17:00	8820	450	15061.8	0.950	0.98	173/174	53.14	53.52	AHB	328.54
157	148.0	8/15/94 18:00	8880	530	15121.6	0.997	1.01	176/177	53.36	53.75	AHB	328.31
158	149.0	8/15/94 19:01	8941	600	15185	1.039	1	176/177	53.33	53.75	AHB	328.31
159	150.1	8/15/94 20:05	9005	700	15250.7	1.027	1	176/177	53.29	53.69	AHB	328.37
160	151.0	8/15/94 21:01	9061	750	15306.5	0.996	1	176/177	53.26	53.66	AHB	328.4
161	152.0	8/15/94 22:00	9120	800	15364.4	0.981	1	176/177	53.27	53.68	AHB	328.38
162	153.0	8/15/94 23:00	9180	880	15422.6	0.970	1	175/176	53.22	53.64	JED & KRD	328.42
163	154.2	8/16/94 0:10	9250	940	15489.3	0.953	1	175/176	53.16	53.55	JED & KRD	328.51
164	155.0	8/16/94 1:02	9302	1000	15534.5	0.869	0.95	175/176	53.12	53.54	JED & RDS	328.52
165	156.1	8/16/94 2:08	9368	1070	15595.3	0.921	1	177/178	53.22	53.65	JED & RDS	328.41
166	157.0	8/16/94 3:00	9420	1130	15648.2	1.017	1	177/178	53.26	53.68	JED & RDS	328.38
167	158.0	8/16/94 4:01	9481	55	15708.4	0.987	1	177/178	53.23	53.66	JED & RDS	328.4
168	159.0	8/16/94 4:59	9539	130	15776.7	1.178	1.5	171/172	53.26	53.69	JED & RDS	328.37
169	160.0	8/16/94 5:59	9599	200	15835.1	0.973	1	171/172	53.2	53.63	JED & RDS	328.43
170	161.0	8/16/94 7:00	9660	250	15893.5	0.957	1	172/173	53.22	53.64	JED & RDS	328.42
171	162.3	8/16/94 8:20	9740	350	15972.9	0.992	0.95	172/173	53.18	53.61	KRD	328.45
172	163.0	8/16/94 9:00	9780	390	16013.4	1.013	1	174/175	53.3	53.7	JTL	328.36
173	164.0	8/16/94 10:00	9840	450	16073.5	1.002	1	174/175	53.25	53.67	JTL	328.39
174	165.3	8/16/94 11:15	9915	550	16147.6	0.988	1	174/175	53.24	53.64	JTL	328.42
175	166.0	8/16/94 12:00	9960	600	16191.5	0.976	1	175	53.22	53.63	KRD	328.43
176	167.2	8/16/94 13:10	10030	700	16259.2	0.967	0.95	175	53.1	53.54	JTL	328.52
177	168.0	8/16/94 14:00	10080	730	16319.2	1.200	1	176	53.24	53.65	JTL	328.41
178	169.0	8/16/94 15:00	10140	790	16369	0.830	1	176	53.22	53.63	JTL	328.43
179	170.1	8/16/94 16:05	10205	855	16433.1	0.986	0.95	176	53.12	53.55	AHB	328.51
180	171.3	8/16/94 17:20	10280	950	16509.5	1.019	1	177/178	53.25	53.7	AHB	328.36
181	172.0	8/16/94 18:00	10320	1000	16550.4	1.023	1	177/178	53.22	53.66	AHB	328.4
182	173.0	8/16/94 19:00	10380	1060	16609.8	0.990	0.98	177/178	53.1	53.54	AHB	328.52
183	174.2	8/16/94 20:14	10454	NA	16686	1.030	1.05	178/179	53.31	53.76	AHB	328.3
184	175.0	8/16/94 21:00	10500	1150	16735.9	1.085	1.1	179	53.38	53.84	AHB	328.22

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5												
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7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
185	176.1	8/16/94 22:06	10566	150	16818.9	1.258	1.2	179	53.74	54.2	AHB	327.86
186	177.0	8/16/94 23:00	10620	220	16871.6	0.976	0.95	171/172	52.98	53.44	AHB	328.62
187	178.0	8/17/94 0:00	10680	280	16929.9	0.972	1	174/175	53.34	53.82	JED/RDS	328.24
188	179.0	8/17/94 0:59	10739	340	16993.3	1.075	1	174/175	53.3	53.76	JED/RDS	328.3
189	180.0	8/17/94 2:00	10800	390	17058	1.061	1	174/175	53.28	53.79	JED/RDS	328.27
190	181.0	8/17/94 3:00	10860	455	17118.4	1.007	1	174/175	53.25	53.72	JED/RDS	328.34
191	182.0	8/17/94 4:00	10920	530	17182	1.060	1	174/175	53.28	53.76	JED/RDS	328.3
192	183.0	8/17/94 5:00	10980	595	17243.8	1.030	1	174/175	53.19	53.64	JED/RDS	328.42
193	184.0	8/17/94 6:00	11040	650	17304.3	1.008	1	174/175	53.17	53.66	JED/RDS	328.4
194	185.0	8/17/94 7:00	11100	740	17363.5	0.987	1	174/175	53.18	53.69	JED/RDS	328.37
195	186.0	8/17/94 8:00	11160	810	17423.2	0.995	0.95	174/175	53.11	53.56	KRD	328.5
196	187.1	8/17/94 9:03	11223	880	17489.5	1.052	1	177	53.34	53.82	JTL	328.24
197	188.0	8/17/94 10:02	11282	950	17550.2	1.029	1	177	53.3	53.76	JTL	328.3
198	189.0	8/17/94 11:00	11340	1010	17619.4	1.193	1	177	53.28	53.76	KRD	328.3
199	190.0	8/17/94 12:00	11400	1070	17668.9	0.825	1	177	53.22	53.65	KRD/JTL	328.41
200	191.0	8/17/94 13:00	11460	1130	17726.6	0.962	1	177/178	53.11	53.58	KRD	328.48
201	192.0	8/17/94 14:00	11520	50	17788.6	1.033	0.95	177/178	53.13	53.57	JTL	328.49
202	193.0	8/17/94 15:00	11580	140	17845.2	0.943	1.25	177	53.59	54.07	JTL	327.99
203	194.2	8/17/94 16:12	11652	210	17919.5	1.032	0.99	172/173	53.13	53.6	AHB	328.46
204	195.0	8/17/94 17:00	11700	NA	17969.4	1.040	1	174/175	53.3	53.76	AHB	328.3
205	196.0	8/17/94 18:00	11760	330	18031.1	1.028	1	174/175	53.23	53.72	AHB	328.34
206	197.0	8/17/94 19:00	11820	400	18093.8	1.045	1	175/176	53.28	53.74	AHB	328.32
207	198.0	8/17/94 20:00	11880	470	18155.5	1.028	1	175/176	53.29	53.77	AHB	328.29
208	200.0	8/17/94 22:02	12002	600	18282.8	1.043	1.05	176/177	53.37	53.86	AHB	328.2
209	201.0	8/17/94 23:00	12060	675	18343.6	1.048	1.2	176/177	53.38	53.86	AHB	328.2
210	202.0	8/18/94 0:00	12120	760	18402.5	0.982	1	176/177	53.31	53.8	RDS & RWP	328.26
211	203.0	8/18/94 1:00	12180	825	18463.3	1.013	1	176/177	53.27	53.76	RDS & RWP	328.3
212	204.0	8/18/94 2:00	12240	890	18523.4	1.002	1	176/177	53.31	53.78	RDS & RWP	328.28
213	205.0	8/18/94 3:00	12300	960	18583.1	0.995	1	176/177	53.23	53.72	RDS & RWP	328.34

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8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
214	206.0	8/18/94 4:00	12360	1020	18642.9	0.997	1	176/177	53.26	53.75	RDS & RWP	328.31
215	207.0	8/18/94 5:00	12420	1080	18702	0.985	1	176/177	53.2	53.7	RDS & RWP	328.36
216	208.0	8/18/94 6:00	12480	1140	18759.4	0.957	0.99	177/178	53.29	53.79	RDS & RWP	328.27
217	209.0	8/18/94 7:00	12540	70	18821.9	1.042	1	177/178	53.34	53.82	RDS & RWP	328.24
218	210.0	8/18/94 8:00	12600	150	18892.4	1.175	1	172	53.31	53.78	JTL	328.28
219	211.2	8/18/94 9:09	12669	210	18957	0.936	0.9	172	53.12	53.6	JTL & KRD	328.46
220	212.0	8/18/94 10:00	12720	300	19008.8	1.016	1	174/175	53.36	53.85	JTL & KRD	328.21
221	213.1	8/18/94 11:06	12786	340	19074.8	1.000	1	174/175	53.32	53.81	KRD	328.25
222	214.0	8/18/94 12:00	12840	390	19127.8	0.981	0.95	174/175	53.23	53.72	JTL	328.34
223	215.0	8/18/94 13:00	12900	445	19185.4	0.960	0.95	174	53.2	53.69	JTL	328.37
224	216.0	8/18/94 14:00	12960	540	19247.1	1.028	1	176/177	53.37	53.86	JTL	328.2
225	217.0	8/18/94 15:00	13020	650	19309.1	1.033	1	176/177	53.32	53.81	JTL	328.25
226	218.3	8/18/94 16:15	13095	675	19386.1	1.027	1	176/177	53.26	53.76	AHB	328.3
227	219.0	8/18/94 17:00	13140	740	19431.6	1.011	0.99	176/177	53.18	53.66	AHB	328.4
228	220.0	8/18/94 18:00	13200	800	19491.2	0.993	0.98	176/177	53.18	53.68	AHB	328.38
229	221.0	8/18/94 19:00	13260	880	19555.2	1.067	1.05	178	53.38	53.89	AHB	328.17
230	222.1	8/18/94 20:05	13325	950	19623.9	1.057	1	178	53.29	53.8	AHB	328.26
231	223.0	8/18/94 21:00	13380	1010	19680.5	1.029	1	178/179	53.33	53.86	AHB	328.2
232	224.0	8/18/94 22:00	13440	1080	19741.3	1.013	1	178	53.26	53.76	AHB	328.3
233	225.0	8/18/94 23:00	13500	1150	19800.2	0.982	0.98	178	53.27	53.79	AHB	328.27
234	226.0	8/19/94 0:00	13560	80	19863.2	1.050	1.25	177/178	53.23	53.74	RDS & RWP	328.32
235	227.0	8/19/94 1:00	13620	140	19913	0.830	0.75	174/175	53.29	53.88	RDS & RWP	328.18
236	228.0	8/19/94 2:00	13680	200	19979.8	1.113	1	174	53.37	53.92	RDS & RWP	328.14
237	229.0	8/19/94 3:00	13740	260	20042.2	1.040	1	173/174	53.35	53.89	RDS & RWP	328.17
238	230.0	8/19/94 4:00	13800	330	20104.9	1.045	1	174	53.33	53.86	RDS & RWP	328.2
239	231.0	8/19/94 5:00	13860	400	20165.5	1.010	1	174	53.26	53.8	RDS & RWP	328.26
240	232.0	8/19/94 6:00	13920	460	20226.4	1.015	1	174	53.29	53.82	RDS & RWP	328.24
241	233.0	8/19/94 7:00	13980	550	20285.5	0.985	1	174	53.23	53.78	RDS & RWP	328.28
242	234.0	8/19/94 8:00	14040	650	20343.5	0.967	0.9	173/174	53.09	53.61	JTL	328.45

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
2	DNAPL Solubilization Test											
3	Extraction Phase - Well MW-156											
4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
243	235.0	8/19/94 9:00	14100	670	20402.6	0.985	0.98	175	53.26	53.77	JTL	328.29
244	236.0	8/19/94 10:00	14160	745	20462.2	0.993	0.98	176/177	53.28	53.82	KRD	328.24
245	237.0	8/19/94 11:00	14220	805	20520.8	0.977	1	176/177	53.26	53.8	KRD	328.26
246	238.0	8/19/94 12:00	14280	880	20581.1	1.005	1	177/178	53.38	53.92	JTL	328.14
247	239.0	8/19/94 13:00	14340	950	20643.5	1.040	1	177/178	53.32	53.86	JTL	328.2
248	240.0	8/19/94 14:00	14400	1010	20705	1.025	1	178	53.27	53.91	JTL	328.15
249	241.0	8/19/94 15:00	14460	NA	20766.6	1.027	1.25	178	53.7	54.26	JTL	327.8
250	242.0	8/19/94 16:00	14520	175	20832.6	1.100	0.98	173	53.7	53.15	AHB	328.91
251	243.1	8/19/94 17:03	14583	NA	20894.2	0.978	0.95	172/173	53.06	53.6	AHB	328.46
252	244.5	8/19/94 18:31	14671	NA	20991.2	1.102	1.01	175/176	53.31	53.86	AHB	328.2
253	245.0	8/19/94 19:00	14700	350	21019.8	0.986	1.01	175/176	53.28	53.84	AHB	328.22
254	246.2	8/19/94 20:10	14770	430	21093.3	1.050	1	175/176	53.23	53.8	AHB	328.26
255	247.0	8/19/94 21:00	14820	500	21144.8	1.030	1	175/176	53.23	53.8	AHB	328.26
256	248.0	8/19/94 22:00	14880	570	21205.2	1.007	1	175/176	53.16	53.73	AHB	328.33
257	249.0	8/19/94 23:00	14940	NA	21265.2	1.000	1	175/176	53.14	53.7	AHB	328.36
258	250.0	8/20/94 0:00	15000	700	21323.5	0.972	1	177/178	53.28	53.9	JWD	328.16
259	251.0	8/20/94 1:00	15060	752	21389	1.092	1.01	177/178	53.3	53.95	EFJ	328.11
260	252.0	8/20/94 2:00	15120	840	21453.6	1.077	1	178	53.3	53.91	EFJ	328.15
261	253.0	8/20/94 3:00	15180	915	21517.5	1.065	1	176/178	53.3	53.92	EFJ & JWD	328.14
262	254.0	8/20/94 4:00	15240	970	21574.8	0.955	0.98	176	53.02	53.93	EFJ & JWD	328.13
263	255.0	8/20/94 5:00	15300	1030	21635.5	1.012	1	177/178	53.13	53.77	EFJ & JWD	328.29
264	256.0	8/20/94 6:00	15360	1110	21694.2	0.978	0.98	177	53.09	53.74	EFJ & JWD	328.32
265	257.0	8/20/94 7:00	15420	70	21757	1.047	1	179	53.27	53.86	EFJ & JWD	328.2
266	258.0	8/20/94 8:00	15480	145	21821.2	1.070	0.98	173/174	53.2	53.8	KRD & JTL	328.26
267	259.0	8/20/94 9:00	15540	220	21880.3	0.985	0.98	173/174	53.21	53.82	JTL	328.24
268	260.0	8/20/94 10:00	15600	300	21940.3	1.000	1	173/174	53.2	53.78	JTL	328.28
269	261.0	8/20/94 11:00	15660	330	22000.3	1.000	1	174/175	53.22	53.78	KRD	328.28
270	262.0	8/20/94 12:00	15720	400	22059.6	0.988	1	174/175	53.16	53.8	JTL	328.26
271	263.0	8/20/94 13:00	15780	460	22120.1	1.008	0.99	175/176	53.25	53.8	JTL	328.26

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
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4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
272	264.0	8/20/94 14:00	15840	545	22179.7	0.993	1	175/176	53.22	53.84	JTL	328.22
273	265.0	8/20/94 15:00	15900	620	22242.6	1.048	1	176/177	53.22	53.79	JTL	328.27
274	266.0	8/20/94 15:59	15959	690	22304.4	1.047	1	176/177	53.21	53.78	AHB	328.28
275	266.8	8/20/94 16:50	16010	750	22356.2	1.016	1	176/177	53.16	53.74	AHB	328.32
276	268.0	8/20/94 18:02	16082	820	22427.5	0.990	1	176/177	53.21	53.76	AHB	328.3
277	269.0	8/20/94 19:00	16140	880	22486	1.009	0.9	176/177	53.13	53.67	AHB	328.39
278	270.0	8/20/94 19:57	16197	945	22541.5	0.974	0.9	176/177	53.14	53.68	AHB	328.38
279	271.0	8/20/94 21:02	16262	1010	22606.5	1.000	1	178/179	53.21	53.78	AHB	328.28
280	272.0	8/20/94 22:00	16320	1070	22664.8	1.005	0.9	178	53.18	53.75	AHB	328.31
281	273.0	8/20/94 23:00	16380	1140	22724.2	0.990	1	178	53.21	53.8	AHB	328.26
282	274.0	8/21/94 0:00	16440	60	22785	1.013	1	178	53.26	53.82	RDS & EFJ	328.24
283	275.0	8/21/94 1:00	16500	150	22858.6	1.227	1.25	178	53.69	53.4	RDS & EFJ	328.66
284	276.0	8/21/94 2:00	16560	220	22916.4	0.963	1	173/174	53.21	53.78	RDS & EFJ	328.28
285	277.0	8/21/94 3:00	16620	300	22976.5	1.002	1	174/175	53.19	53.84	RDS & EFJ	328.22
286	278.0	8/21/94 4:00	16680	340	23038.2	1.028	1	174/175	53.27	53.88	RDS & EFJ	328.18
287	279.0	8/21/94 5:00	16740	400	23099.2	1.017	1	174/175	53.27	53.86	RDS & EFJ	328.2
288	280.0	8/21/94 6:00	16800	470	23156.8	0.960	1	174/175	53.35	53.94	RDS & EFJ	328.12
289	281.0	8/21/94 7:00	16860	550	23218.1	1.022	0.9	174/175	53.29	53.88	RDS & EFJ	328.18
290	282.0	8/21/94 8:00	16920	650	23277.1	0.983	0.98	174/175	53.24	53.86	JTL	328.2
291	283.0	8/21/94 9:00	16980	680	23334.8	0.962	0.98	175	53.21	53.8	JTL	328.26
292	284.0	8/21/94 10:00	17040	750	23395.7	1.015	1	177	53.36	53.97	JTL	328.09
293	285.0	8/21/94 11:00	17100	815	23455.7	1.000	1	176/177	53.34	53.96	KRD	328.1
294	286.0	8/21/94 12:00	17160	890	23514.8	0.985	0.98	176/177	53.25	53.86	KRD & JTL	328.2
295	287.0	8/21/94 13:00	17220	950	23571.9	0.952	0.98	176/177	53.23	53.82	JTL & WMS	328.24
296	288.0	8/21/94 14:00	17280	1010	23633.9	1.033	1	178/179	53.37	54	JTL & WMS	328.06
297	289.0	8/21/94 15:00	17340	1070	23695.2	1.022	1	178/179	53.34	53.96	JTL	328.1
298	290.0	8/21/94 16:00	17400	1140	23757.2	1.033	0.95	178/179	53.3	53.92	AHB	328.14
299	291.0	8/21/94 17:00	17460	100	23822.6	1.090	1.25	178/179	53.79	54.46	AHB	327.6
300	292.0	8/21/94 18:00	17520	165	23885.8	1.053	1	173/174	53.3	53.96	AHB	328.1

A	A	B	C	D	E	F	G	H	I	J	K	L
1	Paducah Gaseous Diffusion Plant - Paducah, Kentucky											
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4	August 9 - 25, 1994											
5												
6												
7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
301	293.3	8/21/94 19:17	17597	220	23962.3	0.994	0.9	173/174	53.28	53.92	AHB	328.14
302	294.2	8/21/94 20:12	17652	300	24016.8	0.991	0.9	173/174	53.26	53.9	AHB	328.16
303	295.0	8/21/94 21:00	17700	350	24070.3	1.115	1.15	177	53.56	54.24	AHB	327.82
304	296.0	8/21/94 22:02	17762	430	24139.3	1.113	1.12	177	53.54	54.23	AHB	327.83
305	297.0	8/21/94 23:00	17820	510	24201.6	1.074	1.12	177	53.48	54.18	AHB	327.88
306	298.0	8/22/94 0:00	17880	600	24276.4	1.247	1.11	177	53.47	54.2	SJK	327.86
307	299.1	8/22/94 1:03	17943	NA	24330.8	0.863	1.1	177	53.46	54.1	SJK	327.96
308	300.0	8/22/94 2:02	18002	725	24393	1.054	1	177	53.41	54.12	SJK	327.94
309	301.0	8/22/94 3:01	18061	800	24453.1	1.019	0.98	177	53.34	54.05	SJK	328.01
310	302.0	8/22/94 4:00	18120	870	24516.7	1.078	1.15	178	53.52	54.2	SJK	327.86
311	303.0	8/22/94 5:00	18180	950	24580.1	1.057	1	178	53.48	54.2	SJK	327.86
312	304.0	8/22/94 6:00	18240	1020	24642.6	1.042	1	178	53.46	54.15	SJK	327.91
313	305.0	8/22/94 7:01	18301	1075	24704.8	1.020	0.98	178	53.41	54.2	SJK	327.86
314	306.0	8/22/94 8:00	18360	1145	24769.9	1.103	1	178/179	53.45	54.15	JTL	327.91
315	307.0	8/22/94 9:02	18422	90	24832.7	1.013	1	173/174	53.55	54.21	JTL	327.85
316	308.0	8/22/94 10:00	18480	150	24889.8	0.984	0.95	173/174	53.37	54.04	JTL & WMS	328.02
317	309.0	8/22/94 11:00	18540	210	24951.9	1.035	1	174/175	53.5	54.17	KRD	327.89
318	310.0	8/22/94 12:01	18601	300	25013.3	1.007	1	175	53.43	54.13	JTL	327.93
319	311.0	8/22/94 13:00	18660	340	25072.5	1.003	0.99	175	53.4	54.11	JTL	327.95
320	312.0	8/22/94 14:00	18720	400	25136.8	1.072	1.01	176/177	53.55	54.25	JTL	327.81
321	313.0	8/22/94 15:00	18780	475	25200.5	1.062	1.01	176/177	53.49	54.23	JTL & WMS	327.83
322	314.0	8/22/94 16:00	18840	560	25261.8	1.022	1	176/177	53.45	54.12	AHB	327.94
323	315.0	8/22/94 17:00	18900	620	25321.6	0.997	0.98	176/177	53.35	54.1	AHB	327.96
324	316.0	8/22/94 18:00	18960	690	25380.8	0.987	0.95	176/177	53.33	54.06	AHB	328
325	317.1	8/22/94 19:04	19024	760	25443.3	0.977	1.01	178/179	53.58	54.28	AHB	327.78
326	318.0	8/22/94 20:00	19080	825	25503.5	1.075	1.01	178/179	53.54	54.26	AHB	327.8
327	319.0	8/22/94 21:00	19140	900	25567	1.058	1	178/179	53.52	54.25	AHB	327.81
328	320.0	8/22/94 22:02	19202	975	25631.3	1.037	1	178/179	53.54	54.28	AHB	327.78
329	321.0	8/22/94 23:00	19260	1030	25690.2	1.016	1	178/179	53.51	54.25	AHB	327.81

A	A	B	C	D	E	F	G	H	I	J	K	L
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4	August 9 - 25, 1994											
5												
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7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
330	322.0	8/23/94 0:00	19320	1110	25750.3	1.002	1	178/179	53.49	54.2	PDN	327.86
331	323.0	8/23/94 1:00	19380	1150	25809.8	0.992	1	178/179	53.45	54.17	PDN	327.89
332	324.0	8/23/94 2:00	19440	110	25873.3	1.058	1.05	174/175	53.61	54.32	PDN	327.74
333	325.0	8/23/94 3:00	19500	180	25934.9	1.027	1	174/175	53.45	54.19	PDN	327.87
334	326.0	8/23/94 4:00	19560	250	25992.5	0.960	0.99	176/177	53.57	54.34	PDN	327.72
335	327.0	8/23/94 5:00	19620	300	26057.3	1.080	1	176/177	53.66	54.41	PDN	327.65
336	328.0	8/23/94 6:00	19680	370	26121.8	1.075	1	176/177	53.63	54.37	PDN	327.69
337	329.0	8/23/94 7:00	19740	440	26184.5	1.045	1	176/177	53.61	54.33	PDN	327.73
338	330.0	8/23/94 8:00	19800	500	26247.5	1.050	1	176/177	53.61	54.25	JTL	327.81
339	331.0	8/23/94 9:00	19860	570	26304.3	0.947	0.95	175/176	53.43	54.17	MS & JTL	327.89
340	332.0	8/23/94 10:00	19920	630	26362.1	0.963	0.9	177	53.63	54.2	MS & JTL	327.86
341	333.0	8/23/94 11:00	19980	715	26427.6	1.092	1.1	179	53.77	54.51	KRD	327.55
342	334.0	8/23/94 12:00	20040	775	26487.7	1.002	0.95	177	53.47	54.19	MS & JTL	327.87
343	335.0	8/23/94 13:00	20100	850	26551.8	1.068	1.01	179/180	53.71	54.47	MS & JTL	327.59
344	336.0	8/23/94 14:00	20160	925	26615.2	1.057	1.01	179	53.63	54.4	MS & JTL	327.66
345	337.0	8/23/94 15:00	20220	10	26673.3	0.968	0.9	177/178	53.39	54.12	KRD	327.94
346	338.0	8/23/94 16:01	20281	100	26739.5	1.085	1.25	179	53.94	54.74	AHB	327.32
347	339.0	8/23/94 17:00	20340	175	26798.9	1.007	0.9	174/175	53.53	54.38	AHB	327.68
348	340.0	8/23/94 18:00	20400	260	26864.5	1.093	1.15	177	53.71	54.48	AHB	327.58
349	341.1	8/23/94 19:03	20463	300	26932.2	1.075	1	177	53.63	54.43	AHB	327.63
350	342.1	8/23/94 20:08	20528	375	27001.1	1.060	1	177	53.6	54.38	AHB	327.68
351	343.0	8/23/94 21:00	20580	450	27054.1	1.019	1	177	53.57	54.37	AHB	327.69
352	344.0	8/23/94 22:00	20640	530	27114.2	1.002	1	177	53.58	54.36	AHB	327.7
353	345.0	8/23/94 23:00	20700	620	27179.3	1.085	1.15	178/179	53.71	54.5	AHB	327.56
354	346.0	8/24/94 0:00	20760	675	27243.3	1.067	1.05	177/178	53.67	54.41	PDH	327.65
355	347.0	8/24/94 1:00	20820	740	27304.1	1.013	1	177/178	53.51	54.3	PDH	327.76
356	348.0	8/24/94 2:00	20880	800	27361.2	0.952	0.9	179/180	53.55	54.47	PDH	327.59
357	349.0	8/24/94 3:00	20940	875	27425.6	1.073	1	179/180	53.73	54.56	PDH	327.5
358	350.0	8/24/94 4:00	21000	940	27490.4	1.080	1	179/180	53.76	54.59	PDH	327.47

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7	Time	Date & Time	Time Since	Volume In	Totalizer	Totalizer Average	Rotometer Rate	Pump	Hermit	Solinst	Measured	Water Level
8	(hours)		Pumping Started	Discharge Tank	Total Flow	Extraction Rate	(gal/min)	Hertz	TOC DTW *	TOC DTW	By	Elevation
9			(min)	(gal)	(gal)	(gal/min)			(ft)	(ft)		(feet msl)
10												
359	351.0	8/24/94 5:00	21060	1025	27554	1.060	1	179/180	53.67	54.5	PDH	327.56
360	352.0	8/24/94 6:00	21120	1090	27614.9	1.015	1	179/180	53.61	54.46	PDH	327.6
361	353.0	8/24/94 7:00	21180	1140	27673.8	0.982	1	179/180	53.61	54.4	PDH	327.66
362	355.0	8/24/94 9:00	21300	110	27803.1	1.077	1.25	179/180	54.14	54.98	JTL	327.08
363	356.1	8/24/94 10:06	21366	180	27868.8	0.995	0.99	174/175	53.63	54.47	MS & JTL	327.59
364	357.0	8/24/94 11:00	21420	250	27923.2	1.007	1	175/176	53.66	54.48	MS & JTL	327.58
365	358.0	8/24/94 12:00	21480	300	27986.2	1.050	0.98	175/176	53.64	54.46	KRD & JTL	327.6
366	359.0	8/24/94 13:00	21540	365	28045.1	0.982	1	175/176	53.62	54.45	KRD	327.61
367	360.0	8/24/94 14:00	21600	430	28102.8	0.962	0.98	175/176	53.52	54.36	MS & JTL	327.7
368	361.0	8/24/94 15:00	21660	495	28162.8	1.000	0.98	176/177	53.59	54.41	KRD	327.65
369	362.1	8/24/94 16:04	21724	560	28225.2	0.975	0.95	176/177	53.5	54.48	AHB	327.58
370	363.0	8/24/94 17:01	21781	650	28285.1	1.051	1	178/179	53.7	54.56	AHB	327.5
371	364.0	8/24/94 18:00	21840	720	28346.2	1.036	1	178/179	53.65	54.5	AHB	327.56
372	365.0	8/24/94 19:00	21900	770	28409	1.047	0.99	178/179	53.58	53.45	AHB	328.61
373	366.0	8/24/94 20:00	21960	850	28469.4	1.007	0.98	178/179	53.53	54.4	AHB	327.66
374	367.0	8/24/94 21:00	22020	910	28532.4	1.050	1	179/180	53.67	54.55	AHB	327.51
375	368.0	8/24/94 22:00	22080	1000	28594.6	1.037	1		53.64	54.53	AHB	327.53
376	369.0	8/24/94 23:00	22140	1060	28655.2	1.010	0.99		53.55	54.45	AHB	327.61
377	370.0	8/25/94 0:00	22200	1125	28714.3	0.985	0.99		53.49	54.36	RS & RP	327.7
378	371.0	8/25/94 1:00	22260	60	28772.8	0.975	0.99		53.51	54.38	RS & RP	327.68
379	372.0	8/25/94 2:00	22320	100	28837.3	1.075	1.25		53.73	54.6	RS & RP	327.46
380	373.0	8/25/94 3:00	22380	175	28893.5	0.937	0.99		53.54	54.42	RS & RP	327.64
381	374.0	8/25/94 4:00	22440	245	28951.2	0.962	0.9		53.62	54.54	RS & RP	327.52
382	375.0	8/25/94 5:00	22500	300	29015.2	1.067	1		53.71	54.62	RS & RP	327.44
383	376.0	8/25/94 6:00	22560	370	29075.2	1.000	1		53.7	54.6	RS & RP	327.46
384	377.0	8/25/94 7:00	22620	440	29136.7	1.025	1		53.67	54.6	RS & RP	327.46
385	378.0	8/25/94 8:00	22680	510	29198.4	1.028	1		53.69	54.59	KRD & JTL	327.47
386	379.0	8/25/94 9:00	22740	650	29258.7	1.005	0.99		53.66	54.56	KRD & JTL	327.5
387	380.0	8/25/94 10:00	22800	650	29292.4	0.562	0.3		52.04	52.97	KRD & JTL	329.09

[illegible]

Paducah Gaseous Diffusion Plant
DNAPL Solubilization Test

Water Level in Control Piezometer 109
During the Extraction Phase
August 9 - 25, 1994

Date	Time	Ground Water Elevation (feet, msl)
09-Aug-94	12:00 AM	331.607
09-Aug-94	01:00 AM	331.529
09-Aug-94	02:00 AM	331.591
09-Aug-94	03:00 AM	331.591
09-Aug-94	04:00 AM	331.619
09-Aug-94	05:00 AM	331.591
09-Aug-94	06:00 AM	331.591
09-Aug-94	07:00 AM	331.551
09-Aug-94	08:00 AM	331.529
09-Aug-94	09:00 AM	331.512
09-Aug-94	10:00 AM	331.5
09-Aug-94	11:00 AM	331.495
09-Aug-94	12:00 PM	331.5
09-Aug-94	01:00 PM	331.529
09-Aug-94	02:00 PM	331.54
09-Aug-94	03:00 PM	331.54
09-Aug-94	04:00 PM	331.557
09-Aug-94	05:00 PM	331.557
09-Aug-94	06:00 PM	331.545
09-Aug-94	07:00 PM	331.523
09-Aug-94	08:00 PM	331.495
09-Aug-94	09:00 PM	331.489
09-Aug-94	10:00 PM	331.489
09-Aug-94	11:00 PM	331.489
10-Aug-94	12:00 PM	331.495
10-Aug-94	01:00 AM	331.484
10-Aug-94	02:00 AM	331.489
10-Aug-94	03:00 AM	331.484
10-Aug-94	04:00 AM	331.478
10-Aug-94	05:00 AM	331.45
10-Aug-94	06:00 AM	331.444
10-Aug-94	07:00 AM	331.433
10-Aug-94	08:00 AM	331.433
10-Aug-94	09:00 AM	331.433
10-Aug-94	10:00 AM	331.444
10-Aug-94	11:00 AM	331.45
10-Aug-94	12:00 PM	331.455
10-Aug-94	01:00 PM	331.467
10-Aug-94	02:00 PM	331.489
10-Aug-94	03:00 PM	331.5
10-Aug-94	04:00 PM	331.512
10-Aug-94	05:00 PM	331.523
10-Aug-94	06:00 PM	331.529

Date	Time	Ground Water Elevation (feet, msl)
10-Aug-94	02:00 PM	331.489
10-Aug-94	03:00 PM	331.5
10-Aug-94	04:00 PM	331.512
10-Aug-94	05:00 PM	331.523
10-Aug-94	06:00 PM	331.529
10-Aug-94	07:00 PM	331.517
10-Aug-94	08:00 PM	331.495
10-Aug-94	09:00 PM	331.489
10-Aug-94	10:00 PM	331.489
10-Aug-94	11:00 PM	331.472
11-Aug-94	12:00 AM	331.472
11-Aug-94	01:00 AM	331.472
11-Aug-94	02:00 AM	331.472
11-Aug-94	03:00 AM	331.472
11-Aug-94	04:00 AM	331.472
11-Aug-94	05:00 AM	331.455
11-Aug-94	06:00 AM	331.444
11-Aug-94	07:00 AM	331.433
11-Aug-94	08:00 AM	331.433
11-Aug-94	09:00 AM	331.427
11-Aug-94	10:00 AM	331.422
11-Aug-94	11:00 AM	331.45
11-Aug-94	12:00 PM	331.455
11-Aug-94	01:00 PM	331.472
11-Aug-94	02:00 PM	331.39
11-Aug-94	03:00 PM	331.407
11-Aug-94	04:00 PM	331.407
11-Aug-94	05:00 PM	331.413
11-Aug-94	06:00 PM	331.413
11-Aug-94	07:00 PM	331.407
11-Aug-94	08:00 PM	331.39
11-Aug-94	09:00 PM	331.362
11-Aug-94	10:00 PM	331.356
11-Aug-94	11:00 PM	331.356
12-Aug-94	12:00 PM	331.351
12-Aug-94	01:00 AM	331.351
12-Aug-94	02:00 AM	331.351
12-Aug-94	03:00 AM	331.345
12-Aug-94	04:00 AM	331.339
12-Aug-94	05:00 AM	331.323
12-Aug-94	06:00 AM	331.317
12-Aug-94	07:00 AM	331.317
12-Aug-94	08:00 AM	331.323
12-Aug-94	09:00 AM	331.311
12-Aug-94	10:00 AM	331.306
12-Aug-94	11:00 AM	331.3
12-Aug-94	12:00 PM	331.311
12-Aug-94	01:00 PM	331.317
12-Aug-94	02:00 PM	331.345
12-Aug-94	03:00 PM	331.351
12-Aug-94	04:00 PM	331.356

Date	Time	Ground Water Elevation (feet, msl)
12-Aug-94	05:00 PM	331.356
12-Aug-94	06:00 PM	331.356
12-Aug-94	07:00 PM	331.345
12-Aug-94	08:00 PM	331.328
12-Aug-94	09:00 PM	331.306
12-Aug-94	10:00 PM	331.311
12-Aug-94	11:00 PM	331.306
13-Aug-94	12:00 PM	331.311
13-Aug-94	01:00 AM	331.311
13-Aug-94	02:00 AM	331.323
13-Aug-94	03:00 AM	331.328
13-Aug-94	04:00 AM	331.3
13-Aug-94	05:00 AM	331.294
13-Aug-94	06:00 AM	331.283
13-Aug-94	07:00 AM	331.272
13-Aug-94	08:00 AM	331.272
13-Aug-94	09:00 AM	331.294
13-Aug-94	10:00 AM	331.294
13-Aug-94	11:00 AM	331.311
13-Aug-94	12:00 PM	331.323
13-Aug-94	01:00 PM	331.334
13-Aug-94	02:00 PM	331.351
13-Aug-94	03:00 PM	331.373
13-Aug-94	04:00 PM	331.39
13-Aug-94	05:00 PM	331.39
13-Aug-94	06:00 PM	331.396
13-Aug-94	07:00 PM	331.396
13-Aug-94	08:00 PM	331.368
13-Aug-94	09:00 PM	331.356
13-Aug-94	10:00 PM	331.373
13-Aug-94	11:00 PM	331.385
14-Aug-94	12:00 AM	331.379
14-Aug-94	01:00 AM	331.385
14-Aug-94	02:00 AM	331.385
14-Aug-94	03:00 AM	331.379
14-Aug-94	04:00 AM	331.379
14-Aug-94	05:00 AM	331.368
14-Aug-94	06:00 AM	331.362
14-Aug-94	07:00 AM	331.339
14-Aug-94	08:00 AM	331.339
14-Aug-94	09:00 AM	331.328
14-Aug-94	10:00 AM	331.323
14-Aug-94	11:00 AM	331.323
14-Aug-94	12:00 PM	331.323
14-Aug-94	01:00 PM	331.328
14-Aug-94	02:00 PM	331.339
14-Aug-94	03:00 PM	331.373
14-Aug-94	04:00 PM	331.368
14-Aug-94	05:00 PM	331.345
14-Aug-94	06:00 PM	331.323
14-Aug-94	07:00 PM	331.311

Date	Time	Ground Water Elevation (feet, msl)
14-Aug-94	08:00 PM	331.283
14-Aug-94	09:00 PM	331.249
14-Aug-94	10:00 PM	331.232
14-Aug-94	11:00 PM	331.221
15-Aug-94	12:00 AM	331.221
15-Aug-94	01:00 AM	331.227
15-Aug-94	02:00 AM	331.227
15-Aug-94	03:00 AM	331.221
15-Aug-94	04:00 AM	331.21
15-Aug-94	05:00 AM	331.199
15-Aug-94	06:00 AM	331.182
15-Aug-94	07:00 AM	331.165
15-Aug-94	08:00 AM	331.17
15-Aug-94	09:00 AM	331.159
15-Aug-94	10:00 AM	331.159
15-Aug-94	11:00 AM	331.17
15-Aug-94	12:00 PM	331.187
15-Aug-94	01:00 PM	331.21
15-Aug-94	02:00 PM	331.232
15-Aug-94	03:00 PM	331.261
15-Aug-94	04:00 PM	331.261
15-Aug-94	05:00 PM	331.255
15-Aug-94	06:00 PM	331.249
15-Aug-94	07:00 PM	331.238
15-Aug-94	08:00 PM	331.227
15-Aug-94	09:00 PM	331.221
15-Aug-94	10:00 PM	331.216
15-Aug-94	11:00 PM	331.216
16-Aug-94	12:00 AM	331.227
16-Aug-94	01:00 AM	331.227
16-Aug-94	02:00 AM	331.232
16-Aug-94	03:00 AM	331.232
16-Aug-94	04:00 AM	331.227
16-Aug-94	05:00 AM	331.21
16-Aug-94	06:00 AM	331.199
16-Aug-94	07:00 AM	331.187
16-Aug-94	08:00 AM	331.193
16-Aug-94	09:00 AM	331.193
16-Aug-94	10:00 AM	331.193
16-Aug-94	11:00 AM	331.204
16-Aug-94	12:00 PM	331.221
16-Aug-94	01:00 PM	331.244
16-Aug-94	02:00 PM	331.255
16-Aug-94	03:00 PM	331.272
16-Aug-94	04:00 PM	331.272
16-Aug-94	05:00 PM	331.278
16-Aug-94	06:00 PM	331.278
16-Aug-94	07:00 PM	331.266
16-Aug-94	08:00 PM	331.255
16-Aug-94	09:00 PM	331.244
16-Aug-94	10:00 PM	331.244

Date	Time	Ground Water Elevation (feet, msl)
16-Aug-94	11:00 PM	331.238
17-Aug-94	12:00 AM	331.244
17-Aug-94	01:00 AM	331.249
17-Aug-94	02:00 AM	331.244
17-Aug-94	03:00 AM	331.238
17-Aug-94	04:00 AM	331.238
17-Aug-94	05:00 AM	331.216
17-Aug-94	06:00 AM	331.187
17-Aug-94	07:00 AM	331.159
17-Aug-94	08:00 AM	331.142
17-Aug-94	09:00 AM	331.159
17-Aug-94	10:00 AM	331.154
17-Aug-94	11:00 AM	331.159
17-Aug-94	12:00 PM	331.176
17-Aug-94	01:00 PM	331.182
17-Aug-94	02:00 PM	331.199
17-Aug-94	03:00 PM	331.199
17-Aug-94	04:00 PM	331.204
17-Aug-94	05:00 PM	331.21
17-Aug-94	06:00 PM	331.187
17-Aug-94	07:00 PM	331.165
17-Aug-94	08:00 PM	331.148
17-Aug-94	09:00 PM	331.137
17-Aug-94	10:00 PM	331.125
17-Aug-94	11:00 PM	331.125
18-Aug-94	12:00 AM	331.12
18-Aug-94	01:00 AM	331.137
18-Aug-94	02:00 AM	331.131
18-Aug-94	03:00 AM	331.125
18-Aug-94	04:00 AM	331.114
18-Aug-94	05:00 AM	331.08
18-Aug-94	06:00 AM	331.063
18-Aug-94	07:00 AM	331.047
18-Aug-94	08:00 AM	331.052
18-Aug-94	09:00 AM	331.047
18-Aug-94	10:00 AM	331.058
18-Aug-94	11:00 AM	331.069
18-Aug-94	12:00 PM	331.086
18-Aug-94	01:00 PM	331.086
18-Aug-94	02:00 PM	331.114
18-Aug-94	03:00 PM	331.131
18-Aug-94	04:00 PM	331.142
18-Aug-94	05:00 PM	331.148
18-Aug-94	06:00 PM	331.142
18-Aug-94	07:00 PM	331.131
18-Aug-94	08:00 PM	331.114
18-Aug-94	09:00 PM	331.103
18-Aug-94	10:00 PM	331.097
18-Aug-94	11:00 PM	331.097
19-Aug-94	12:00 PM	331.092
19-Aug-94	01:00 AM	331.097

Date	Time	Ground Water Elevation (feet, msl)
19-Aug-94	02:00 AM	331.097
19-Aug-94	03:00 AM	331.097
19-Aug-94	04:00 AM	331.086
19-Aug-94	05:00 AM	331.075
19-Aug-94	06:00 AM	331.058
19-Aug-94	07:00 AM	331.047
19-Aug-94	08:00 AM	331.063
19-Aug-94	09:00 AM	331.063
19-Aug-94	10:00 AM	331.069
19-Aug-94	11:00 AM	331.086
19-Aug-94	12:00 PM	331.097
19-Aug-94	01:00 PM	331.097
19-Aug-94	02:00 PM	331.12
19-Aug-94	03:00 PM	331.159
19-Aug-94	04:00 PM	331.193
19-Aug-94	05:00 PM	331.182
19-Aug-94	06:00 PM	331.159
19-Aug-94	07:00 PM	331.154
19-Aug-94	08:00 PM	331.148
19-Aug-94	09:00 PM	331.148
19-Aug-94	10:00 PM	331.148
19-Aug-94	11:00 PM	331.154
20-Aug-94	12:00 PM	331.148
20-Aug-94	01:00 AM	331.159
20-Aug-94	02:00 AM	331.17
20-Aug-94	03:00 AM	331.17
20-Aug-94	04:00 AM	331.17
20-Aug-94	05:00 AM	331.159
20-Aug-94	06:00 AM	331.142
20-Aug-94	07:00 AM	331.114
20-Aug-94	08:00 AM	331.12
20-Aug-94	09:00 AM	331.103
20-Aug-94	10:00 AM	331.125
20-Aug-94	11:00 AM	331.131
20-Aug-94	12:00 PM	331.131
20-Aug-94	01:00 PM	331.17
20-Aug-94	02:00 PM	331.154
20-Aug-94	03:00 PM	331.17
20-Aug-94	04:00 PM	331.165
20-Aug-94	05:00 PM	331.17
20-Aug-94	06:00 PM	331.17
20-Aug-94	07:00 PM	331.165
20-Aug-94	08:00 PM	331.142
20-Aug-94	09:00 PM	331.125
20-Aug-94	10:00 PM	331.12
20-Aug-94	11:00 PM	331.109
21-Aug-94	12:00 PM	331.097
21-Aug-94	01:00 AM	331.103
21-Aug-94	02:00 AM	331.165
21-Aug-94	03:00 AM	331.159
21-Aug-94	04:00 AM	331.125

Date	Time	Ground Water Elevation (feet, msl)
21-Aug-94	05:00 AM	331.086
21-Aug-94	06:00 AM	331.047
21-Aug-94	07:00 AM	331.013
21-Aug-94	08:00 AM	331.002
21-Aug-94	09:00 AM	330.945
21-Aug-94	10:00 AM	330.894
21-Aug-94	11:00 AM	330.911
21-Aug-94	12:00 PM	330.934
21-Aug-94	01:00 PM	330.956
21-Aug-94	02:00 PM	330.985
21-Aug-94	03:00 PM	331.002
21-Aug-94	04:00 PM	331.002
21-Aug-94	05:00 PM	331.007
21-Aug-94	06:00 PM	331.002
21-Aug-94	07:00 PM	330.985
21-Aug-94	08:00 PM	330.968
21-Aug-94	09:00 PM	330.951
21-Aug-94	10:00 PM	330.945
21-Aug-94	11:00 PM	330.94
22-Aug-94	12:00 PM	330.94
22-Aug-94	01:00 AM	330.934
22-Aug-94	02:00 AM	330.923
22-Aug-94	03:00 AM	330.917
22-Aug-94	04:00 AM	330.894
22-Aug-94	05:00 AM	330.872
22-Aug-94	06:00 AM	330.838
22-Aug-94	07:00 AM	330.827
22-Aug-94	08:00 AM	330.821
22-Aug-94	09:00 AM	330.821
22-Aug-94	10:00 AM	330.816
22-Aug-94	11:00 AM	330.821
22-Aug-94	12:00 PM	330.844
22-Aug-94	01:00 PM	330.849
22-Aug-94	02:00 PM	330.855
22-Aug-94	03:00 PM	330.861
22-Aug-94	04:00 PM	330.855
22-Aug-94	05:00 PM	330.855
22-Aug-94	06:00 PM	330.861
22-Aug-94	07:00 PM	330.849
22-Aug-94	08:00 PM	330.821
22-Aug-94	09:00 PM	330.799
22-Aug-94	10:00 PM	330.787
22-Aug-94	11:00 PM	330.782
23-Aug-94	12:00 PM	330.771
23-Aug-94	01:00 AM	330.782
23-Aug-94	02:00 AM	330.771
23-Aug-94	03:00 AM	330.771
23-Aug-94	04:00 AM	330.754
23-Aug-94	05:00 AM	330.737
23-Aug-94	06:00 AM	330.709
23-Aug-94	07:00 AM	330.68

Date	Time	Ground Water Elevation (feet, msl)
23-Aug-94	08:00 AM	330.664
23-Aug-94	09:00 AM	330.664
23-Aug-94	10:00 AM	330.652
23-Aug-94	11:00 AM	330.664
23-Aug-94	12:00 PM	330.675
23-Aug-94	01:00 PM	330.669
23-Aug-94	02:00 PM	330.692
23-Aug-94	03:00 PM	330.697
23-Aug-94	04:00 PM	330.697
23-Aug-94	05:00 PM	330.692
23-Aug-94	06:00 PM	330.686
23-Aug-94	07:00 PM	330.68
23-Aug-94	08:00 PM	330.664
23-Aug-94	09:00 PM	330.652
23-Aug-94	10:00 PM	330.647
23-Aug-94	11:00 PM	330.647
24-Aug-94	12:00 PM	330.641
24-Aug-94	01:00 AM	330.635
24-Aug-94	02:00 AM	330.618
24-Aug-94	03:00 AM	330.607
24-Aug-94	04:00 AM	330.602
24-Aug-94	05:00 AM	330.59
24-Aug-94	06:00 AM	330.562
24-Aug-94	07:00 AM	330.545
24-Aug-94	08:00 AM	330.528
24-Aug-94	09:00 AM	330.517
24-Aug-94	10:00 AM	330.528
24-Aug-94	11:00 AM	330.551
24-Aug-94	12:00 PM	330.551
24-Aug-94	01:00 PM	330.585
24-Aug-94	02:00 PM	330.613
24-Aug-94	03:00 PM	330.664
24-Aug-94	04:00 PM	330.647
24-Aug-94	05:00 PM	330.635
24-Aug-94	06:00 PM	330.63
24-Aug-94	07:00 PM	330.618
24-Aug-94	08:00 PM	330.602
24-Aug-94	09:00 PM	330.579
24-Aug-94	10:00 PM	330.568
24-Aug-94	11:00 PM	330.568
25-Aug-94	12:00 PM	330.551
25-Aug-94	01:00 AM	330.54
25-Aug-94	02:00 AM	330.54
25-Aug-94	03:00 AM	330.54
25-Aug-94	04:00 AM	330.534
25-Aug-94	05:00 AM	330.511
25-Aug-94	06:00 AM	330.495
25-Aug-94	07:00 AM	330.483
25-Aug-94	08:00 AM	330.478
25-Aug-94	09:00 AM	330.489
25-Aug-94	10:00 AM	330.5

Date	Time	Ground Water Elevation (feet, msl)
25-Aug-94	11:00 AM	330.511
25-Aug-94	12:00 PM	330.523
25-Aug-94	01:00 PM	330.528
25-Aug-94	02:00 PM	330.557
25-Aug-94	03:00 PM	330.562
25-Aug-94	04:00 PM	330.579
25-Aug-94	05:00 PM	330.585
25-Aug-94	06:00 PM	330.585
25-Aug-94	07:00 PM	330.585
25-Aug-94	08:00 PM	330.573
25-Aug-94	09:00 PM	330.562
25-Aug-94	10:00 PM	330.562

Appendix D

MW-156 Gas Chromatograph Data

8-4-94

MW156

Stand				Avg.	Fit	Regression Output:	
Conc					Conc	Constant	
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	
0						R Squared	0.999
150	13350	13568		13459	149	No. of Observations	4
371	21339	21110		21225	389	Degrees of Freedom	2
1315	46096	52493	50981	49857	1274	X Coefficient(s)	32.33
1947	70198	74570		72384	1971	Std Err of Coef.	0.796

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
1	19971	20164		20068	353
4	22198	19141	20183	20507	367
5	19982			19982	350
7	17900	22200	17107	19069	322
8	19090	18158		18624	308
10	20799			20799	376
11	22002	18706	19028	19912	348
12	18733			18733	312
13	21175			21175	387
14	18338			18338	300
15	20997			20997	382
16	18356			18356	300
17	21428	19156	19887	20157	356
18	19232			19232	327
19	22646	20008		21327	392
20	18105	22421		20263	359

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MW156

Stand				Avg.	Fit	Regression Output:	
Conc					Conc		
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Constant	-101.12
0						Std Err of Y Est	12.0214
0.9	49.1	45.5		47	1	R Squared	0.99995
3.3	402.9	432.6		418	3	No. of Observations	3
15.0	2301.7	2299.6		2301	15	Degrees of Freedom	1
						X Coefficient(s)	160
						Std Err of Coef.	1.126

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
40	too small			0	< 1
41	42.2			42	1
43	114			114	1
44	198.8	221.5	240	220	2
45	382			382	3
46	460.7			461	4
48	561			561	4
49	729			729	5
50	826			826	6
51	902			902	6
52	1002			1002	7
53	1076			1076	7
54	1185			1185	8
55	1192			1192	8
56	1344			1344	9
57	1628			1628	11
58	1706			1706	11
59	1271	1406	1323	1333	9
61	1780			1780	12
62	1655			1655	11
63	1623			1623	11
64	1659.8			1660	11
65	1782			1782	12
66	1689			1689	11
67	1874			1874	12
68	1763			1763	12
70	1664			1664	11

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MW156

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	23.3665
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	35.4041
0						R Squared	0.99957
0.9	141	141.8		141	1	No. of Observations	3
3.3	579.3	574.7		577	3	Degrees of Freedom	1
15.0	2435	2389.8		2412	15	X Coefficient(s)	159.6
						Std Err of Coef.	3.315

Sample					Avg.	Conc.
Number	Area 1	Area 2	Area 3	Area		(mg/L)
70	2215	2315	2167	2232		14
71	2410			2410		15
72	2329			2329		14
73	2398			2398		15
76	2438			2438		15
77	2470			2470		15

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MW156

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	0.99136
						No. of Observations	3
						Degrees of Freedom	1
15.0	2050	2066		2058	10		
59.2	5370	5362		5366	66	X Coefficient(s)	58.69
150.0	10135	10121		10128	148	Std Err of Coef.	5.477

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
78	2632			2632	20
79	2552			2552	19
80	2878			2878	24
81	2888			2888	24
82	3069			3069	27
83	2972			2972	26
84	3169			3169	29
86	3091			3091	28
87	3118			3118	28
88	3142	3222	3168	3177	29
89	3082			3082	28
90	3133			3133	28
91	3297			3297	31
92	3334			3334	32
93	3156			3156	29
95	3407			3407	33

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MW156

Stand				Avg.	Fit	Regression Output:	
Conc					Conc	Constant	
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	
0.0						R Squared	1821
15.0	2311	2411		2361	9	No. of Observations	589.8
59.2	5622	5732		5677	67	Degrees of Freedom	0.989
150.0	10423	10056		10240	147	X Coefficient(s)	3
						Std Err of Coef.	1
							57.15
							6.059

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
93	4078			4078	39
95	4020			4020	38
96	4261			4261	43
98	4323			4323	44
100	4185			4185	41
102	4300			4300	43
107	4790	4772	4539	4700	50
109	4858			4858	53
110	5072			5072	57

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MW156

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	0.997
						No. of Observations	3
						Degrees of Freedom	1
15.0	2312	2165		2239	12		
59.2	5160	5149.7		5155	63	X Coefficient(s)	57.33
150.0	10329	9785		10057	149	Std Err of Coef.	2.933

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
112	4675			4675	55
114	4614			4614	54
116	4998			4998	60
118	5151	5080	5215	5149	63
120	5280			5280	65
122	5727	5490		5609	71

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MW156

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	1600
15.0	2426	2463		2445	12	No. of Observations	425.5
59.2	6279.5	6078		6179	64	Degrees of Freedom	0.996
150.0	12294	12160		12227	148	X Coefficient(s)	3
						Std Err of Coef.	1
							71.59
							4.372

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
124	5262			5262	51
127	5945	5778	5985	5903	60
129	6017			6017	62
131	6232			6232	65
133	6288			6288	65
135	6420			6420	67
138	6944			6944	75
140	6819			6819	73
142	6568			6568	69

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MW-156

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	51.4455
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	48.709
0.0						R Squared	0.99918
0.88	149	168	166	161	0.7	No. of Observations	3
3.3	621	609		615	3.5	Degrees of Freedom	1
15.0	2424	2426	2463	2438	15.0	X Coefficient(s)	159.5
						Std Err of Coef.	4.561

Sample					Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area		(mg/L)
24	48			48		< 1
25	no TCE peak			0		< 1
30	no TCE peak			0		< 1
32	no TCE peak			0		< 1
35	no TCE peak			0		< 1
39	no TCE peak			0		< 1

8-14-94

MW156

Stand Conc (mg/L)	Area 1	Area 2	Area 3	Area 4	Area 5	Avg. Area	Fit Conc (mg/L)
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0.0							
59.2	4181	3823	3847	4095	4441	4077	50
150.0	7751	7432				7592	163
371.0	14024	13935				13980	367

Sample Numbe	Area 1	Area 2	Area 3	Avg. Area	Conc. (mg/L)	Regression Output:	
143	4115			4115	51	Constant	2510
144	5009			5009	80	Std Err of Y Est	500.5
145	4520			4520	64	R Squared	0.995
147	4580			4580	66	No. of Observations	3
149	4738			4738	71	Degrees of Freedom	1
150	5053			5053	81	X Coefficient(s)	31.23
153	5066	5227	5242	5178	85	Std Err of Coef.	2.207
154	5724			5724	103		
158	5749			5749	104		
160	5653			5653	101		

8-20-94

MW156

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	3560
(mg/L)					(mg/L)	Std Err of Y Est	930.3
0.0						R Squared	0.998
72.2	6224	6163		6194	59	No. of Observations	3
135.0	10566	10050	10364	10327	150	Degrees of Freedom	1
617.0	30920	31548		31234	615	X Coefficient(s)	44.98
						Std Err of Coef.	2.207

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
163	10788	10719		10754	160
164	10670			10670	158
166	10507			10507	154
167	12871			12871	207
169	12948			12948	209
171	12376			12376	196
174	13359			13359	218
176	13203			13203	214
178	13905			13905	230
180	14355	14561	14964	14627	246
182	13660			13660	225
184	14801			14801	250
185	14800			14800	250
187	17256			17256	304
188	15353			15353	262
190	16077			16077	278
192	16213			16213	281
193	15488			15488	265

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MW156

Stand

Conc

(mg/L)

Area 1

Area 2

Area 3

Avg.

Area

Fit

Conc

(mg/L)

Regression Output:

Constant

3047.1

Std Err of Y Est

899.74

R Squared

0.9959

No. of Observations

3

Degrees of Freedom

1

0.0

135.0

8337

8094

8288

8240

126

371.0

18581

19583

19082

389

X Coefficient(s)

41.24

617.0

28459

27807

28133

608

Std Err of Coef.

2.64

Sample

Numbe

Area 1

Area 2

Area 3

Avg.

Area

Conc.

(mg/L)

187

11138

11138

196

190

11354

10705

11030

194

193

11922

11922

215

195

12013

12072

12043

218

196

11574

11701

11729

11668

209

198

12405

12405

227

204

13301

13301

249

211

13989

13989

265

212

13785

13785

260

214

13604

13604

256

219

14381

14381

275

220

12902

13428

12420

12917

239

222

13828

13828

261

225

14404

14404

275

227

13493

13493

253

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MW156

Stand	Conc	Area 1	Area 2	Area 3	Avg.	Fit	Conc	Regression Output:	
(mg/L)					Area	(mg/L)			
0.0								Constant	7285
135.0	19164	20595	20189	19983	119			Std Err of Y Est	4057
371.0	47887	51320	51211	50139	402			R Squared	0.988
617.0	72325	70523		71424	602			No. of Observations	3
								Degrees of Freedom	1
								X Coefficient(s)	106.6
								Std Err of Coef.	11.9

Sample	Area 1	Area 2	Area 3	Avg.	Conc.
Numbe				Area	(mg/L)
243	42081	41287		41684	323
246	36623	37410		37017	279
248	37962	34295	39028	37095	280
249	35859	38887		37373	282
251	40717	43506		42112	327

8-25-94

MW156

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	0.999
72.2	15125	15244		15185	57	No. of Observations	4
135.0	23292	24188		23740	140	Degrees of Freedom	2
617.0	74796	74744		74770	639	X Coefficient(s)	102.3
1102.0	121521	120233		120877	1090	Std Err of Coef.	2.621

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
220	44341	43655		43998	338
222	44617			44617	344
224	41651			41651	315
227	40239			40239	302
230	43768	42253		43011	329
233	41354			41354	313
236	39361			39361	293
238	42625			42625	325
240	39537	40389		39963	299
244	39772	43585	40651	41336	312
253	39456	41907	42505	41289	312

8-15-94

MW156

DCE Concentration Measurements

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	
0.00				0	-0.09	R Squared	46.5505
0.46	277	379	368.5	342	0.55	No. of Observations	66.3439
30.40	16263	16566		16415	30.40	Degrees of Freedom	0.99997
						X Coefficient(s)	3
						Std Err of Coef.	1
							538.4
							2.693

Sample					Avg.	Approx.
Numbe	Area 1	Area 2	Area 3	Area	Conc.	(mg/L)
17	103	302		203	0.3	
50	845	765	556	722	1.3	
81	284			284	0.4	
117	175			175	0.2	
148	356	176		266	0.4	
165	390			390	0.6	
170	323	411	412	382	0.6	

Sample			Time	Approximate
Numbe	Day of	Hour	Since	DCE
	Month	of Day	Extraction	Concentration
			Begun	Measurement
			(days)	(mg/L)
17	3	23.5	-5.60	0.3
50	9	22	0.33	1.3
81	11	4	1.58	0.4
117	12	13	2.96	0.2
148	13	17	4.13	0.4
165	14	20	5.25	0.6
170	15	11	5.88	0.6

Appendix E

Calibration, Precision, and Regression Statistics for Field Surfactant Analyses

Surfactant Concentration Calibration Curves

8-12-94

Stand Conc (% by wt)	ABS	Fit Conc (% by wt)
0.000%	-0.008	-0.000%
0.015%	0.079	0.013%
0.038%	0.249	0.040%
0.112%	0.698	0.111%

Regression Output:

Constant	-0.0062
Std Err of Y Est	0.01174
R Squared	0.99907
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	631.935
Std Err of Coef.	13.6351

8-13-94

Stand Conc (% by wt)	ABS	Fit Conc (% by wt)
0.000%	-0.006	-0.000%
0.015%	0.085	0.014%
0.038%	0.254	0.040%
0.112%	0.708	0.111%

Regression Output:

Constant	-0.0029
Std Err of Y Est	0.01094
R Squared	0.99921
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	638.017
Std Err of Coef.	12.7042

8-14-94

Stand Conc (% by wt)	ABS	Fit Conc (% by wt)
0.000%	-0.009	-0.001%
0.015%	0.084	0.014%
0.038%	0.257	0.040%
0.112%	0.720	0.111%

Regression Output:

Constant	-0.0057
Std Err of Y Est	0.01147
R Squared	0.99916
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	651.367
Std Err of Coef.	13.3182

8-21-94

Stand Conc (% by wt)	ABS	Fit Conc (% by wt)
0.000%	-0.004	-0.000%
0.009%	0.052	0.008%
0.015%	0.087	0.014%
0.038%	0.260	0.041%
0.112%	0.718	0.111%

Regression Output:

Constant	-0.0022
Std Err of Y Est	0.00999
R Squared	0.99913
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	646.676
Std Err of Coef.	10.9979

Precision Calculations

Field Surfactant Triplicates

Sample Number	Conc. (% by wt)	Conc. (% by wt)	Conc. (% by wt)	Sample Standard Deviation (% by wt)	Sample Mean Conc. (% by wt)	Student t 95% Confidence Interval	
						+/- (% by wt)	+/- (% of mean)
44	1.050%	1.020%	1.050%	0.017%	1.040%	0.043%	4.1%
70	0.550%	0.570%	0.560%	0.010%	0.560%	0.025%	4.4%
172	0.005%	0.006%	0.007%	0.001%	0.006%	0.002%	41.4%

Appendix F

MW-155 Gas Chromatograph Data

8-6-94

MW-155

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	
0.0						R Squared	0.9997
0.88	156.4	159.4		158	0.8	No. of Observations	3
3.3	582.8	573.7		578	3.4	Degrees of Freedom	1
15.0	2338	2442		2390	15.0	X Coefficient(s)	157.1
						Std Err of Coef.	2.702

Sample					Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area		(mg/L)
2	259			259		1.4
9	78			78		< 1
26	59	82	74.3	72		< 1

8-7-94

MW-155

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	-92.95
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	48.214
						R Squared	0.9988
						No. of Observations	3
0.0						Degrees of Freedom	1
0.88	53.3	55.8		55	1.1		
3.3	309			309	3.0	X Coefficient(s)	133
15.0	1907.7			1908	15.0	Std Err of Coef.	4.515

Sample					Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area		(mg/L)
28	90.2			90		1.4
29	16.4			16		< 1

8-8-94

MW-155

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	10.706
0.88	53.6	66	64.3	61	0.8	No. of Observations	13.815
3.3	245.5	242		244	3.5	Degrees of Freedom	0.9996
15.0	1024	1016.5		1020	15.0	X Coefficient(s)	3
						Std Err of Coef.	1

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
33	45			45	< 1
34	46			46	< 1

8-9-94

MW-155

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	-25.62
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	12.763
						R Squared	0.9999
						No. of Observations	3
0.0						Degrees of Freedom	1
0.88	52.5	56.8		55	0.8		
3.3	308	322.8		315	3.4	X Coefficient(s)	100.4
15.0	1492	1465		1479	15.0	Std Err of Coef.	1.195

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
36	46.7			47	< 1
38	too low for integration				< 1

8-10-94

MW-155

Stand					Fit	Regression Output:	
Conc				Avg.	Conc	Constant	
(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	
0						R Squared	0.99995
0.9	49.1	45.5		47	1	No. of Observations	3
3.3	402.9	432.6		418	3	Degrees of Freedom	1
15.0	2301.7	2299.6		2301	15	X Coefficient(s)	160
						Std Err of Coef.	1.126

Sample					Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area		(mg/L)
42	92.6			93		1.2
60	127			127		1.4
69	125			125		1.4

8-11-94

MW-155

Stand						Fit	
Conc						Conc	
(mg/L)	Area 1	Area 2	Area 3	Area 4	Area 5	Avg.	(mg/L)
0.0							
0.88	124	106				115	0.8
3.3	442	499	499	454		474	3.4
15.0	1987	2050	2066			2034	15.0

Sample					Avg.	Conc.	Regression Output:	
Numbe	Area 1	Area 2	Area 3	Area		(mg/L)	Constant	
85	154			154		1.1	Std Err of Y Est	22.5574
94	171			171		1.2	R Squared	0.99976
							No. of Observations	3
							Degrees of Freedom	1
							X Coefficient(s)	135.1
							Std Err of Coef.	2.112

8-12-94

MW-155

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	0.99996
0.88	52	61	61.3	58	0.8	No. of Observations	3
3.3	370.5	382		376	3.4	Degrees of Freedom	1
15.0	1871	1829		1850	15.0	X Coefficient(s)	126.6
						Std Err of Coef.	0.789

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
111	115			115	1.3

8-13-94

MW-155

Stand				Avg.	Fit	Regression Output:	
Conc	Area 1	Area 2	Area 3	Area	Conc	Constant	
(mg/L)					(mg/L)	Std Err of Y Est	
0.0						R Squared	0.99918
0.88	149	168	166	161	0.7	No. of Observations	3
3.3	621	609		615	3.5	Degrees of Freedom	1
15.0	2424	2426	2463	2438	15.0	X Coefficient(s)	159.5
						Std Err of Coef.	4.561

Sample				Avg.	Conc.
Numbe	Area 1	Area 2	Area 3	Area	(mg/L)
121	169			169	< 1
137	148			148	< 1
146	164			164	< 1

8-20-94

MW-155

Logarithmic Regression

Stand	Log Stand Conc	Area 1	Area 2	Area 3	Log Avg. Area	Fit Conc (mg/L)	Regression Output:	
(mg/L)	(mg/L)						Constant	4.406
0.0							Std Err of Y Est	0.012
0.92	-0.036	23264	24629		4.38	0.9	R Squared	0.996
1.9	0.279	35506	35593		4.55	2.0	No. of Observations	5
4.9	0.690	53364	53393		4.73	4.6	Degrees of Freedom	3
0.88	-0.056	24191	23754		4.38	0.9	X Coefficient(s)	0.484
3.3	0.519	46485	46341		4.67	3.5	Std Err of Coef.	0.018

Sample	Area 1	Area 2	Area 3	Log Avg. Area	Conc. (mg/L)
Numbe					
34	30171			4.48	1.4
36	26185			4.42	1.1
38	28510			4.45	1.3
42	28678			4.46	1.3
60	29514			4.47	1.4
69	29643			4.47	1.4
85	29550			4.47	1.4
94	30200			4.48	1.4
111	30410			4.48	1.4
121	27538			4.44	1.2
137	28833			4.46	1.3
146	30540			4.48	1.5
157	30458			4.48	1.4
162	30547			4.48	1.5
168	29869			4.48	1.4
173	30126			4.48	1.4
179	30717			4.49	1.5
183	30932			4.49	1.5
186	30857			4.49	1.5
191	29087			4.46	1.3
194	32621			4.51	1.7
199	32242			4.51	1.6
202	32579			4.51	1.7

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MW-155

Logarithmic Regression

Stand	Log Stand Conc	Area 1	Area 2	Area 3	Log Avg. Area	Fit Conc (mg/L)	Regression Output:	
(mg/L)	(mg/L)						Constant	4.362
0.0							Std Err of Y Est	0.007
0.92	-0.036	21833	22059		4.34	0.9	R Squared	0.999
1.9	0.279	32145	31460		4.50	2.0	No. of Observations	3
4.9	0.690	50167	48629	48866	4.69	4.8	Degrees of Freedom	1
							X Coefficient(s)	0.482
							Std Err of Coef.	0.014

Sample	Area 1	Area 2	Area 3	Log Avg. Area	Conc. (mg/L)
Numbe					
28	27588			4.44	1.5
29	27198			4.43	1.4
33	27744			4.44	1.5
34	27623			4.44	1.5
207	28101			4.45	1.5
210	28847			4.46	1.6
215	28723			4.46	1.6
218	29968			4.48	1.7

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MW-155

Logarithmic Regression

Stand	Stand				Log	Fit	Regression Output:	
Conc	Conc				Avg.	Conc	Constant	4.399
(mg/L)	(mg/L)	Area 1	Area 2	Area 3	Area	(mg/L)	Std Err of Y Est	0.006
0.0							R Squared	0.999
0.92	-0.036	25412	22760	23769	4.38	0.9	No. of Observations	3
1.9	0.279	32802	34873	34356	4.53	1.9	Degrees of Freedom	1
4.9	0.690	51823	51451		4.71	4.8	X Coefficient(s)	0.458
							Std Err of Coef.	0.012

Sample				Log	
Numbe	Area 1	Area 2	Area 3	Avg.	Conc.
				Area	(mg/L)
223	30569			4.49	1.5
226	32761			4.52	1.8
231	30967			4.49	1.6
234	31332			4.50	1.6
239	31774			4.50	1.7
241	32505			4.51	1.8
247	31206			4.49	1.6
250	32102			4.51	1.7
252	36159	34144	37297	4.55	2.2