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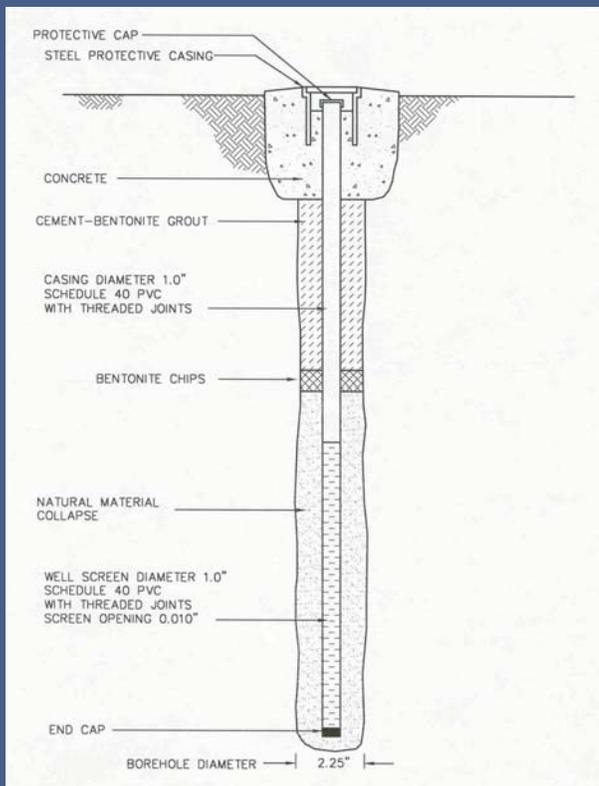
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14. ABSTRACT This study evaluates whether monitoring wells installed using direct-push techniques (DPT) provide ground water chemical data of comparable quality to conventionally-installed wells for evaluation and performance monitoring of monitored natural attenuation (MNA) of dissolved volatile organic compounds (VOCs). Data evaluation methods included statistical and qualitative analyses performed on existing data sets from multiple United States Air Force facilities. Study results provide strong evidence that DPT and conventional wells can be used interchangeably for monitoring MNA of chloroethenes and evaluating local redox conditions. Results are inconclusive on the interchangeable use of DPT and conventional wells for MNA monitoring of dissolved petroleum hydrocarbons, as petroleum hydrocarbon concentrations in DPT wells generally were observed to be higher than concentrations measured in conventional wells. The findings of this study are relevant to monitoring activities at Department of Defense facilities because DPT techniques may allow faster and less expensive well installation, relative to conventional techniques, at shallow (<50-foot) and, in some lithologies, intermediate (50- to 100-foot) depths.					
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FINAL

Technical Basis for Incorporating Ground Water Quality Data Collected from Direct-Push Wells into Evaluation and Monitoring Programs for Natural Attenuation Remedies



Prepared for

Air Force Center for Environmental Excellence

and

Defense Logistics Agency

**Contract No. F41624-00-D8024
Task Order No. 0024**



U.S. AIR FORCE

September 2004

**TECHNICAL BASIS FOR INCORPORATING GROUND
WATER QUALITY DATA COLLECTED FROM DIRECT-PUSH
WELLS INTO EVALUATION AND MONITORING
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TABLE OF CONTENTS

	Page
LIST OF ACRONYMS AND ABBREVIATIONS	iii
SECTION 1 INTRODUCTION	1-1
1.1 Project Scope and Objectives.....	1-1
1.2 Background.....	1-1
1.3 Report Organization.....	1-2
SECTION 2 PRELIMINARY EVALUATION OF AVAILABLE DATA	2-1
2.1 Review of Selected USAF Facilities with MNA Data.....	2-1
2.2 Previous Comparison Studies of Data Collected using DPT and Conventional Well Installations	2-3
2.2.1 ESTCP Study (Farrington <i>et al.</i> , 2003).....	2-3
2.2.2 BP Corporation/USEPA Regions 4 & 5 Study (2002)	2-7
2.2.3 Naval Facility Engineering Command Study (2001).....	2-8
SECTION 3 METHODS	3-1
3.1 Analysis of Colocated Well Data.....	3-1
3.1.1 Hypothesis Testing.....	3-2
3.1.2 Scatter Plot Analysis.....	3-4
3.1.3 Redox Condition Assessment	3-5
3.2 Analysis along a Contaminant Flow Path.....	3-7
SECTION 4 RESULTS	4-1
4.1 Results from Analysis of Colocated Data.....	4-1
4.1.1 Hypothesis Testing.....	4-1
4.1.2 Scatter Plot Analysis.....	4-3
4.1.3 Redox Condition Assessment	4-11
4.2 Results from Analysis along Contaminant Flow Path	4-17
SECTION 5 DISCUSSION AND CONCLUSIONS	5-1
SECTION 6 REFERENCES.....	6-1

LIST OF APPENDICES

A	ASSESSMENT OF FARRINGTON <i>et al.</i> (2003) DATA
B	SELECTED DATA FROM MNA ASSESSMENT AT SITE 56, MACDILL AFB, FLORIDA

TABLE OF CONTENTS (Concluded)

LIST OF TABLES

No.	Title	Page
2.1	Summary of Sites Considered for DPT versus Conventional Well Data Comparison.....	2-1
2.2	Summary of Statistical Results from Farrington <i>et al.</i> (2003).....	2-5
4.1	Statistical Testing Results of Combined Farrington <i>et al.</i> (2003) Data Sets	4-2
4.2	Comparison of VOC Concentrations within Well Pairs.....	4-10
4.3	Summary of Below Detection VOC Measurements by Well Type.....	4-10
4.4	Summary of Results from Redox Indicator Data Assessment.....	4-17
4.5	Redox Indicator Data and Inferred TEAP Conditions for DPT and Conventional Wells.....	4-18
4.6	Well Screen Interval and Redox Indicator Data for Selected Wells at Site 56, MacDill AFB	4-25

LIST OF FIGURES

No.	Title	Page
3.1	Flow Chart for Statistical Analysis of Data.....	3-3
3.2	Flow Chart for Identifying Redox Condition.....	3-5
3.3	Locations of Conventional and DPT Wells at Site 56, MacDill AFB	3-8
4.1	Comparison of Temperature Data Collected from DPT and Conventional Wells... ..	4-4
4.2	Comparison of Potassium Data Collected from DPT and Conventional Wells.....	4-5
4.3	Comparison of Sodium Data Collected from DPT and Conventional Wells.....	4-6
4.4	Comparison of pH Data Collected from DPT and Conventional Wells	4-7
4.5	Comparison of BTEX Data Collected from DPT and Conventional Wells.....	4-8
4.6	Comparison of Chloroethene Data Collected from DPT and Conventional Wells..	4-9
4.7	Comparison of Dissolved Oxygen (DO) Data Collected from DPT and Conventional Wells	4-12
4.8	Comparison of Nitrate Data Collected from DPT and Conventional Wells	4-13
4.9	Comparison of Ferrous Iron Data Collected from DPT and Conventional Wells .	4-14
4.10	Comparison of Manganese(II) Data Collected from DPT and Conventional Wells.....	4-15
4.11	Comparison of Oxidation-reduction Potential (ORP) Data Collected from DPT and Conventional Wells	4-16
4.12	BTEX Concentrations along a Flow Path at Site 56, MacDill AFB (May 1995) ..	4-19
4.13	Petroleum Hydrocarbon Concentrations in Selected Wells at Site 56, MacDill AFB (May 1995)	4-20
4.14	Dissolved Oxygen (DO) Concentrations along a Flow Path at Site 56, MacDill AFB (May 1995)	4-21
4.15	Oxidation-reduction Potential (ORP) Values along a Flow Path at Site 56, MacDill AFB (May 1995).....	4-22
4.16	Sulfate, Sulfide, and Methane Concentrations along a Flow Path at Site 56, MacDill AFB (May 1995).....	4-23

LIST OF ACRONYMS AND ABBREVIATIONS

α	level of significance; probability of type I (false positive) error
β	probability of type II (false negative) error
μ_{DPT}	mean of DPT well values
μ_{CW}	mean of conventional well values
$\mu\text{g/L}$	microgram per liter
AFB	Air Force Base
AFCEE	Air Force Center of Environmental Excellence
AFCEE/ERS	Air Force Center of Environmental Excellence, Science and Engineering Division
ANGB	Air National Guard Base
ARB	Air Reserve Base
AS	Air Station
ASTM	American Society for Testing and Materials
BP Corporation	British Petroleum Corporation
BTEX	benzene, toluene, ethylbenzene, and xylene isomers
CAH	chlorinated aliphatic hydrocarbon
CW	conventional well
DCE	dichloroethene
DLA	Defense Logistics Agency
DO	dissolved oxygen
DoD	Department of Defense
DPT	direct push technology or direct push technique
ESTCP	Environmental Security Technology Certification Program
FPTA	Fire Protection Training Area
H_0	null hypothesis
H_a	alternate hypothesis
HSA	hollow stem auger
LTM	long term monitoring
LNAPL	light non-aqueous phase liquid
mg/L	milligram per liter
MNA	monitored natural attenuation
MtBE	methyl tert-butyl ether
mV	millivolts
N	degrees of freedom
NA	natural attenuation
NFESC	Naval Facilities Engineering Service Center
NTU	nephelometric turbidity unit
ORP	oxidation-reduction
PCE	tetrachloroethene
POL	petroleum, oils, and lubricants
RCRA	Resource Conservation and Recovery Act
redox	oxidation-reduction
TCE	trichloroethene
TDS	total dissolved solids

LIST OF ACRONYMS AND ABBREVIATIONS (Concluded)

TEAP	terminal electron acceptor process
TMB	trimethylbenzene
TSS	total suspended solids
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOC	volatile organic compound

SECTION 1

INTRODUCTION

1.1 PROJECT SCOPE AND OBJECTIVES

This technical report summarizes the results of a study that was designed to evaluate whether monitoring wells installed using direct-push techniques (DPT) provide ground water chemical data that is of comparable data quality to conventionally-installed wells at sites where natural attenuation (NA) of dissolved petroleum hydrocarbons and/or chlorinated solvents is being documented or monitored. Specifically, this study seeks to answer the question: Can DPT well data be interpreted with (or in lieu of) conventional well data to draw conclusions about NA processes, or do data collected using different types of installation techniques need to be treated separately? If it can be demonstrated that data collected from DPT and conventional wells are comparable and functionally equivalent, the findings of this report will provide support for the use of DPT wells for augmenting or replacing conventional wells for the evaluation and monitoring of NA processes. The primary method used to answer the questions posed in this study was to analyze existing data sets from various United States Air Force (USAF) facilities to determine if colocated conventional and DPT well pairs yielded statistically equivalent data. In cases where data for a given parameter supported the conclusion that conventional and DPT wells were not statistically similar, data were evaluated qualitatively to determine if the statistical differences might be expected to lead to a change in conclusions about monitored natural attenuation (MNA). A second method used to evaluate whether data collected from conventional and DPT wells are comparable was to review data sets from USAF facilities where DPT wells had been installed to supplement existing conventional wells (i.e., DPT and conventional wells were not colocated) to assess whether a combination of conventional and DPT wells installed along the contaminant flow path yielded results that were reasonably consistent over space.

The findings of this study are relevant to on-going and future long-term monitoring (LTM) activities at USAF facilities because the use of DPT techniques for installing temporary or permanent monitoring wells may be faster and less expensive than conventional techniques for shallow (less than 50-foot) and, in some lithologies, intermediate (50 to 100-foot) well installations in unconsolidated sediments. One specific example of cost savings that may be realized from DPT well installations, relative to conventional well installations, is that DPT generates a significantly smaller volume of cuttings that require handling, sampling, analysis, and potentially off-site disposal as hazardous waste. One of the major limitations of DPT well installations is that this technique may not be capable of penetrating stiff or dense formations that can readily be drilled by various conventional techniques.

This report was developed jointly by the Air Force Center for Environmental Excellence, Science and Engineering Division (AFCEE/ERS) (formerly the Technology Transfer Division), the Defense Logistics Agency (DLA), and Parsons.

1.2 BACKGROUND

As described in the *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* (AFCEE, 1995) and the *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water* (United States Environmental Protection Agency [USEPA], 1998), the primary method for documenting and monitoring NA of petroleum hydrocarbons and chlorinated solvents in ground water is to collect water samples from monitoring wells. Recommended analyses of ground water samples for documenting NA processes include both volatile organic compounds (VOCs) and various indicators of geochemical condition that provide insight on local oxidation-reduction (redox) conditions. As described in the USEPA directive on the *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites* (USEPA, 1999), measurement of VOC concentrations can be used in combination with aquifer hydrogeologic parameters (e.g., ground water velocity) to evaluate contaminant plume stability and mass loss (i.e., the first, or primary, line of evidence). The USEPA directive also advocates the collection and interpretation of geochemical indicator parameter data for the purpose of identifying active degradation processes that are used to document NA mechanisms (i.e., the second line of evidence) that act to stabilize and/or decrease the size of the contaminant plume.

Historically, the most common method used to install monitoring wells in shallow, unconsolidated aquifers is with a hollow-stem auger (HSA) technique. During the 1990s, more rapid and inexpensive well installation procedures using DPT were developed and gained popularity. DPT-installed wells are widely accepted and encouraged for initial site characterization (e.g., American Society for Testing and Materials [ASTM], 1998; USEPA, 2000 and 2001), but have not been programmatically accepted by regulatory agencies for longer-term tracking of NA progress and LTM. Regulatory agencies may be more willing to accept DPT wells for purposes other than initial characterization if it can be shown that chemical concentration data collected from DPT and conventional well data are functionally equivalent and comparable.

1.3 REPORT ORGANIZATION

This document contains six sections, including this introduction, and two appendices. Section 2 presents a summary of previous studies and available data sets that were considered as part of this study. Section 3 describes the methods of analysis used in this study, and Section 4 describes the results of these analyses. Section 5 presents a discussion of the findings of this report and how these findings relate to evaluating and/or monitoring MNA-based remedies. Section 5 also summarizes the conclusions developed in this study. Section 6 lists references used in preparing this document. Appendix A provides a detailed description of data evaluation procedures performed during the initial evaluation of data published in a previous study by Farrington *et al.* (2003). Appendix B provides supporting data and figures from a previous MNA assessment at Site 56, MacDill Air Force Base (AFB), Florida.

SECTION 2

PRELIMINARY EVALUATION OF AVAILABLE DATA

A preliminary evaluation of available data sets from sites where ground water chemistry data were available from both conventional and DPT wells was conducted to examine the spatial distribution (laterally and vertically) of available data sets. Based on this review, sites were categorized as having either ‘colocated’ well pairs or ‘non-colocated’ well pairs because the spatial relationship between well types dictated what types of analyses could be applied appropriately. The focus of this section is to provide an overview of available data sets and to describe how preliminary evaluations affected the selection of data sets and analytical methods used in the remainder of this study.

2.1 REVIEW OF SELECTED USAF FACILITIES WITH MNA DATA

Table 2.1 lists 15 USAF sites that Parsons identified where DPT wells were installed to aid the evaluation of MNA. Each of these 15 sites was evaluated for inclusion in this study. At each of the 15 sites, it was noted that DPT wells were installed to fill spatial data gaps between conventional wells. For example, at sites such as Facility 1381, Cape Canaveral Air Station (AS), Florida, it was observed that several DPT wells generally were placed in the same areal location as several existing monitoring wells, but that the newly-installed DPT wells were screened over different depth intervals than the existing conventional wells to fill a spatial data gap in the vertical dimension. At other sites, such as Site FT-29, Patrick AFB, Florida and Site SS27/XYZ, Dover AFB, Delaware, DPT wells were screened across a comparable vertical interval to existing conventional wells, but were used to fill a lateral spatial data gap between existing conventional wells installed in the source area (high concentration areas) and distant downgradient points (low concentration or below detection measurements). For these sites, the absence of conventional monitoring wells in the transitional area between the source area and distant edges of the dissolved plume made it impossible to evaluate how results from DPT wells affected the assessment of NA processes over the areal extent of the contaminant plume because there were no data from conventional wells to compare with the data obtained from DPT wells.

The approach of using DPT wells to fill data gaps is a logical and reasonable approach for minimizing redundancy and maximizing the value of each new data point. For the purpose of this study, however, the use of new DPT points solely to fill existing spatial data gaps led to a statistical conclusion that the two data sets (i.e., DPT well data and conventional well data) were spatially uncorrelated. While this finding was not surprising given that the goal of the supplemental well installations was to fill data gaps (i.e., place DPT monitoring points in locations that were spatially separated from existing conventional wells), a consequence of this finding was that direct statistical comparison of data from the different well types was not possible for any of these 15 sites.

TABLE 2.1
SUMMARY OF SITES CONSIDERED FOR DPT VERSUS CONVENTIONAL
WELL DATA COMPARISON

Site Name ^{a/}	Number of DPT Wells	Number of Conventional Wells	Type of Contamination
Cape Canaveral AS, FT-17	18	32	Fuel/CAH ^{b/}
Cape Canaveral AS, Building 1381	21	45	Fuel/CAH
Westover ARB, Zone 1	16	33	Fuel
Rickenbacker AFB, Building 560	35	10	Fuel
Offutt AFB, FPTA-3	26	10	Fuel
Myrtle Beach AFB, POL Yard	28	18	Fuel
MacDill AFB, Site 56	14	19	Fuel
Pope AFB, FPTA-4	12	11	Fuel
Hill AFB, Building 870	35	32	Fuel/CAH
Patrick AFB, ST-29	41	13	Fuel
Dover AFB, SS27/XYZ	27	16	Fuel
Plattsburgh AFB, FT-002	68	22	Fuel/CAH
Madison (Truax) ANGB, Building 412/POL Yard	20	13	Fuel
Offutt AFB, Tank 349	13	14	Fuel
Eglin AFB, POL, SS-36	56	19	Fuel

^{a/} AFB = Air Force Base; ARB = Air Reserve Base; ANGB = Air National Guard Base; AS = Air Station; FPTA = Fire Protection Training Area; FT = Fire Training; POL = petroleum, oils, and lubricants.

^{b/} CAH = chlorinated aliphatic hydrocarbon.

The data from all 15 sites were reviewed a second time to determine if there were any cases where data were available from at least three conventional wells and three DPT wells that were installed at comparable elevations along a contaminant flow path. The rationale for this approach was that this type of spatial data arrangement had the potential to yield at least a qualitative assessment of whether use of data from DPT wells could significantly alter the conclusions of an MNA assessment performed along the centerline of a contaminant plume. The only site that met these criteria was Site 56, MacDill AFB, Florida (Parsons, 1996), where four DPT wells and six conventional wells had been installed and sampled along a common contaminant flow path. Although the screen lengths of the two types of wells were different (DPT wells were installed with 5-foot screens, whereas conventional wells had 9-foot screens), all ten wells were screened starting at the water table. Based on this preliminary assessment of available site data, Site 56, MacDill AFB was identified as the only site of the original 15 that had data which could be used to support the objectives of the current study.

2.2 PREVIOUS COMPARISON STUDIES OF DATA COLLECTED USING DPT AND CONVENTIONAL WELL INSTALLATIONS

Because the available field data from the original 15 sites where DPT points had been installed as supplements to existing conventional wells yielded only one site where data were available in a spatial distribution that could be used in this study, a literature review was conducted to determine if data and/or results from other studies could be used to help answer the objectives of the current study. The results of this literature search identified the three studies described in this section.

2.2.1 ESTCP Study (Farrington *et al.*, 2003)

In one study, the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) funded a direct-comparison study specifically designed to compare DPT and conventional well data (Farrington *et al.*, 2003). In this study, initiated in 2000 at multiple locations on several USAF facilities, one or more DPT wells were installed as close to the concrete pad of conventionally-installed (e.g., HSA) wells as the DPT drill rig would allow. These researchers attempted to minimize the number of well pair locations where VOC measurements were measured as below detection. The rationale for this approach was that each below detection measurement reduces the power associated with statistical testing results. Therefore, DPT wells were installed adjacent to conventional wells where VOCs had previously been measured between 100 and 1000 micrograms per liter ($\mu\text{g/L}$). DPT wells were installed so that well screen intervals and slot sizes matched the conventional wells to the full extent possible. Up to five rounds of samples were collected over a 15-month period using low-flow sampling techniques. The researchers performed statistical analyses on the differences in results for each analytical parameter and each DPT well type.

Of the five sites that were part of this ESTCP-funded study, the types of contaminant plumes of interest to this study (i.e., aromatic petroleum hydrocarbons and/or chlorinated solvents) were found at three locations: Tyndall AFB, Florida (eight well pairs), Dover AFB, Delaware (six well pairs), and Hanscom AFB, Massachusetts (eight well pairs). The results of the statistical analyses performed by Farrington *et al.* (2003) for MNA parameters of interest (i.e., the contaminants of concern plus measured redox indicator data) are

summarized in [Table 2.2](#). The P-value is the smallest significance at which the null hypothesis can be rejected. For these tests, if the P-value was above 0.05, the null hypothesis was accepted and it was concluded that DPT and conventional wells provide statistically similar results. The power of the test is its ability to distinguish a difference between DPT and conventional well values in the sample should a difference really exist in the general population. In other words, increased power of statistical tests means that there is more statistical certainty that the “accept” conclusion is correct. In summary, Farrington *et al.* (2003) concluded that:

- Petroleum constituent (i.e., benzene, toluene, ethylbenzene, and xylene isomers [BTEX]) concentrations were often statistically higher in the DPT wells than in conventional wells;
- Chloroethene concentrations were generally statistically similar in DPT and conventional wells;
- Redox indicator concentrations (with the exception of ferrous iron and alkalinity) in 2-inch DPT wells were generally higher than their paired conventional well, but lower in 1.5-inch DPT wells than their paired conventional well; and
- Measurements of several parameters that are generally considered to be unaffected by contaminant biodegradation (i.e., sodium, potassium, pH, and temperature), were higher in the 2-inch DPT wells than conventional wells, but were statistically the same when comparing 1.5-inch DPT wells with conventional wells.

The original objective of the Farrington *et al.* (2003) study was to compare the chemical results measured in samples collected from conventionally-installed wells with those measured in DPT wells that were located in very close proximity to the conventional wells. This objective of the Farrington *et al.* (2003) study was expanded midway through the study to include a comparison of the performance of various DPT well designs (i.e., different well diameters, unpacked screens versus several pre-packed screen configurations).

As a result of this expanded scope, statistical tests were run on smaller data sets than originally intended, which resulted in a decreased power and increased probability of type II error for the tests. In this case, a type II error would conclude that DPT and conventional wells provided statistically similar results when in fact they did not. In the original design of this study, Farrington *et al.* (2003) hoped that the data they collected would yield a power of at least 80 percent for their tests. As can be seen in the summarized results of the Farrington *et al.* (2003) study provided in [Table 2.2](#), the increased scope of the original study contributed to a reduction in test power that was almost universally below their original target of 80 percent.

Based on the fact that the data used in the ESTCP study were available to Parsons, and that a variety of ground water parameters, including VOCs and several redox indicator parameters, were measured at a relatively large number of locations, the ESTCP-funded study was considered a useable data set for further analysis in the current study in terms of what the data from the ESTCP study might mean for the evaluation and monitoring of NA processes. Analysis procedures used in the current study for the Farrington *et al.* (2003) data set are described in Section 3.1. The results of the analysis performed in the current study are described in Section 4.1.

TABLE 2.2
SUMMARY OF STATISTICAL RESULTS FROM FARRINGTON *et al.* (2003)

Analyte	DPT Well Diameter (inches)	No. of Well Pairs	Mean Difference [DPT-Conventional Well] (µg/L)	Statistical Test	P-value	Power	Result ^{a/}
<i>Petroleum Compounds</i>							
Benzene	2	38	3.6	Paired t test (log-transformed)	0.603	0.08	Accept
	1.5	28	67.8	Paired t test (log-transformed)	<0.01	0.28	Reject
Toluene	2	27	122.7	Paired t test (log-transformed)	0.048	0.52	Reject
	1.5	26	48.6	Paired t test (log-transformed)	<0.01	0.51	Reject
Ethylbenzene	2	28	3.6	Wilcoxon matched pairs	0.241	0.06	Accept
	1.5	28	47.2	Paired t test (log-transformed)	<0.01	0.69	Reject
Xylene (<i>m,p</i>)	2	35	7.3	Paired t test (log-transformed)	0.765	0.06	Accept
	1.5	29	113.6	Paired t test (log-transformed)	0.018	0.62	Reject
Xylene (<i>o</i>)	2	35	12.3	Paired t test (log-transformed)	0.036	0.57	Reject
	1.5	30	80.4	Paired t test (log-transformed)	0.042	0.60	Reject
<i>Chloroethenes</i>							
PCE	2	30	180.5	Wilcoxon matched pairs	0.821	0.26	Accept
	1.5	8	2.6	Paired t test	>0.15	0.32	Accept
TCE	2	47	191.7	Wilcoxon matched pairs	0.691	0.23	Accept
	1.5	34	73.0	Wilcoxon matched pairs	0.007	0.80	Reject
<i>cis</i> -1,2-DCE	2	44	1913.5	Wilcoxon matched pairs	0.354	0.71	Accept
	1.5	21	-2.1	Wilcoxon matched pairs	0.496	0.10	Accept
<i>trans</i> -1,2-DCE	2	22	14.2	Paired t test (log-transformed)	0.392	0.13	Accept
	1.5	13	-5.6	Wilcoxon matched pairs	0.489	0.10	Accept
VC	2	39	83.5	Wilcoxon matched pairs	0.818	0.39	Accept
	1.5	19	-2.9	Paired t test	>0.15	0.23	Accept
<i>Redox Indicators</i> ^{b/}							
ORP	2	55	61.1	Wilcoxon matched pairs	0.000	NC ^{c/}	Reject
	1.5	44	-19.9	Wilcoxon matched pairs	0.003	NC	Reject
DO	2	112	0.35	Wilcoxon matched pairs	0.000	NC	Reject
	1.5	43	-0.07	Wilcoxon matched pairs	0.395	NC	Accept

TABLE 2.2
SUMMARY OF STATISTICAL RESULTS FROM FARRINGTON *et al.* (2003)
(Concluded)

Analyte	DPT Well Diameter (inches)	No. of Well Pairs	Mean Difference [DPT-Conventional Well] (µg/L)	Statistical Test	P-value	Power	Result ^{a/}
Redox Indicators (concluded)							
Ferrous Iron	2	18	-0.587	Wilcoxon matched pairs	0.433	0.06	Accept
	1.5	21	-0.117	Wilcoxon matched pairs	0.979	0.14	Accept
Manganese (II)	2	28	0.492	Wilcoxon matched pairs	0.017	0.37	Reject
	1.5	24	-0.005	Paired t test (log-transformed)	0.010	0.77	Reject
Sulfate	2	29	4.441	Paired t test	0.013	0.73	Reject
	1.5	24	-4.783	Paired t test	0.004	0.88	Reject
Other Ground Water Quality Indicators							
pH	2	133	-0.16	Wilcoxon matched pairs	0.002	NC	Reject
	1.5	44	11.41	Wilcoxon matched pairs	0.578	NC	Accept
Alkalinity	2	29	12.858	Wilcoxon matched pairs	0.462	0.32	Accept
	1.5	24	1.288	Paired t test	0.772	0.06	Accept
Temperature	2	133	-0.1	Wilcoxon matched pairs	0.046	NC	Reject
	1.5	43	0.00	Wilcoxon matched pairs	0.786	NC	Accept
Sodium	2	29	4.505	Wilcoxon matched pairs	0.000	0.09	Reject
	1.5	21	0.113	Paired t test	0.797	0.06	Accept
Potassium	2	29	-0.149	Wilcoxon matched pairs	0.345	0.06	Accept
	1.5	24	-0.120	Paired t test (logs)	0.991	0.05	Accept

^{a/} Accept = DPT and Conventional wells are statistically similar; Reject = DPT and Conventional wells are statistically different

^{b/} Farrington *et al.* (2003) did not report statistical data for nitrate.

^{c/} NC = power not calculated by Farrington *et al.* (2003)

Notes: DPT = direct push technique; N = number of samples; P = power; *m* = meta; *o* = ortho; *p* = para; PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; VC = vinyl chloride; DO = dissolved oxygen; ORP = oxidation-reduction potential; µg/L = micrograms per liter

2.2.2 BP Corporation/USEPA Regions 4 & 5 Study (2002)

In a collaborative study between BP Corporation and USEPA Regions 4 & 5, twelve 1-inch-diameter DPT wells (without filter packs) were installed (three wells each at four fuel release sites) approximately 2.5 feet west of twelve conventional monitoring wells for the specific purpose of evaluating whether ground water parameter measurements obtained from DPT wells are comparable to those obtained from conventional wells (BP Corporation and USEPA, 2002). These researchers measured ground water elevations, hydraulic conductivity, selected chemical concentrations (BTEX, methyl tert-butyl ether [MtBE], naphthalene, and total suspended solids [TSS]), and selected redox indicator parameters. All parameters in the BP/USEPA study were measured quarterly for one year at each location except for the redox indicator parameters, which were measured at only two of the four sites. Based on statistical analyses of the data collected during the study, researchers from BP Corporation and USEPA (2002) concluded the following:

- Ground water levels measured in DPT wells were nearly identical to those measured in conventional wells;
- Mean hydraulic conductivities measured in conventional wells were, on average, more than four times greater than those measured in DPT wells. The researchers suggest that insufficient development of the DPT wells may have resulted in artificially low measurements of hydraulic conductivity, and cite previous work by Henebry and Robbins (2002) at other sites to support this claim. An alternate explanation for the observed differences in hydraulic conductivity measurements is that the filter pack in the conventional wells impacted measured hydraulic conductivity. For example, the presence of a filter pack that is more transmissive than the surrounding aquifer could cause hydraulic conductivity measurements from conventional wells to be artificially high;
- At three of the four sites, BTEX concentrations were statistically similar in samples collected from DPT and conventional wells. At the fourth site, BTEX concentration measurements were consistently and significantly higher in samples obtained from the DPT wells. These researchers suggested that the screen or DPT borehole may have become contaminated by material in the smear zone during installation of the direct-push well at this one site;
- MtBE concentrations were statistically similar in samples collected from DPT and conventional monitoring wells;
- Naphthalene concentrations were slightly higher in samples from DPT wells relative to those from conventional wells, although these researchers also noted that there was considerable spatial variability in this parameter;
- TSS were significantly higher in samples from DPT wells relative to those from conventional wells. Farrington *et al.* (2003) attributed the increase in TSS in DPT wells to the absence of a filter pack in the DPT wells and/or incomplete DPT well development; and

- Limited measurements of selected redox parameters (dissolved oxygen [DO], carbon dioxide, ferrous iron, nitrate, methane, alkalinity, and sulfate) suggested that there was no difference in concentrations measured in samples obtained from DPT and conventional wells, although significant variability was noted for most of these parameters.

Based on the limited number of locations and total sampling points of the BP Corporation and USEPA (2002) data set, and the lack of access to the raw data used to perform the statistics described in the BP Corporation and USEPA (2002) report, further analysis of this data set was not performed for the current study.

2.2.3 Naval Facility Engineering Command Study (2001)

A study by the United States Navy at Port Hueneme, California compared the ability of conventional wells and various designs of DPT wells to detect MtBE and several inorganic solutes (Naval Facilities Engineering Service Center [NFESC], 2001). The NFESC study involved eight conventional wells, four to a cell. Each conventional well was clustered with two or four DPT wells. Each cluster was screened over a different length and/or interval. The study was designed to permit analysis of spatial variability (differences in concentrations among the same well type but different screen lengths/intervals in a cell) and well type variability (differences in concentrations among different well types in a cluster). NFESC (2001) concluded that the variability between well types was less than that resulting from spatial heterogeneities with differing screen depths. The limitations of the NFESC (2001) study were that 1) the timeframe of measurements was limited to six months and 2) the power of statistical analysis of MtBE concentrations in some wells and clusters was limited because the test locations were located at the leading edge of the MtBE plume, resulting in multiple samples where MtBE concentrations were below the method detection limit.

The Farrington *et al.* (2003) study described in Section 2.1.1 benefited from the results of the NFESC (2001) study in two ways. First, raw data from the Port Hueneme site was included as one of the five test sites analyzed in the more recent Farrington *et al.* (2003) study. Second, the data limitations identified from the NFESC (2001) results were addressed during the experimental design of other sites in the Farrington *et al.* (2003) study, as seen by the longer experimental duration (15 months instead of 6 months) and the selective placement of well pairs in more concentrated portions of plumes to minimize collection of below detection samples. Because the only organic contaminant detected in the Port Hueneme wells was MtBE (i.e., aromatic petroleum hydrocarbons or chloroethenes were not detected), data from the Port Hueneme wells (whether reported by NFESC [2001] or Farrington *et al.*, [2003]) were not used in the data evaluation performed for this study.

SECTION 3

METHODS

Methods of data analysis for comparing conventional and DPT well results are described in this chapter. Methods were developed for assessing variability in contaminant concentrations and redox indicators measurements for both colocated (e.g., Farrington *et al.*, [2003]) and non-colocated (e.g., Site 56, MacDill AFB [Parsons, 1996]) data sets.

3.1 ANALYSIS OF COLOCATED WELL DATA

The Farrington *et al.* (2003) data of interest for this study were collected at Tyndall AFB, Dover AFB, and Hanscom AFB because these were the three sites with aromatic petroleum hydrocarbon and/or chloroethene contaminants. Tyndall AFB conventional wells were paired with a cluster of different DPT well types. The sites at Hanscom AFB and Dover AFB had conventional wells paired with single, two-inch-diameter, unpacked DPT wells. The prepacked DPT wells used in the Farrington *et al.* (2003) study had a sand pack that was manufactured with the well screen and driven as a single unit by the DPT rig. Unpacked DPT wells had well screens driven directly into the ground without any sand-pack.

In preparation for the statistical analyses performed in the current study, the Farrington *et al.* (2003) data set was examined to 1) determine if the sample size could be increased and 2) eliminate any obvious errors or blunders in the data. The method used to create a larger data set than was analyzed by Farrington *et al.* (2003) was to combine the Dover AFB and Hanscom AFB well pair data (i.e., conventional wells paired with 2-inch-diameter unpacked DPT wells) with the most similar well pair data from Tyndall AFB (i.e., conventional wells paired with 1.5-inch-diameter unpacked DPT wells). The implications of this decision were that all of the DPT wells used in the statistical analysis of the current study were unpacked, and that it was assumed that the measured ground water parameters were not sensitive to the half-inch difference in well diameter. Data were closely examined for obvious errors and for any indication of well pairs that should be excluded from the data set. Although several data points appeared that they could have been outliers, no justification for excluding any data points was found and all data points were subsequently included in the statistical and qualitative analyses used in the current study. Details of the analysis for blunders and outliers are provided in Appendix A.

Of the chemical and physical parameters measured by Farrington *et al.* (2003), only those of interest to MNA evaluation or monitoring were considered in this study. Specifically, the parameters of interest were:

- aromatic petroleum compounds (i.e., BTEX);

- chloroethene compounds (i.e., tetrachloroethene [PCE], trichloroethene [TCE], *cis*-1,2-dichloroethene [DCE], *trans*-1,2-DCE, and vinyl chloride [VC]);
- redox indicator parameters (i.e., DO, nitrate, ferrous iron, manganese, sulfate, alkalinity, and oxidation-reduction potential [ORP]); and
- other ground water quality indicators (i.e., sodium, potassium, temperature, and pH) that are largely unaffected by the MNA process, but can be used to indicate whether sampled ground water in paired wells is similar in chemical composition.

Using the combined Farrington *et al.* (2003) data set, several methods were employed to compare data from DPT and conventional wells for drawing conclusions about MNA. These methods included:

- repeating the Farrington *et al.* (2003) hypothesis testing methodology using larger data sets to develop conclusions with increased power (decreased probability of type II errors [see Section 2.2.1]);
- qualitatively evaluating the Farrington *et al.* (2003) data from an MNA perspective through analysis of scatter plots; and
- using a logic diagram to predict the probable terminal electron acceptor process (TEAP) for redox reactions in ground water at each well, given the available redox parameter data, to determine how often the same TEAP conclusion was reached using data from paired (DPT and conventional) wells.

3.1.1 Hypothesis Testing

The statistical null hypothesis (H_0) tested in the current study was that DPT and conventional well values were the same. The alternate hypothesis (H_a) was that they were not the same (i.e., DPT well values could be greater or smaller than the conventional well values). In statistical notation, these hypotheses tests can be expressed as:

$$H_0: \mu_{DPT} - \mu_{CW} = 0$$

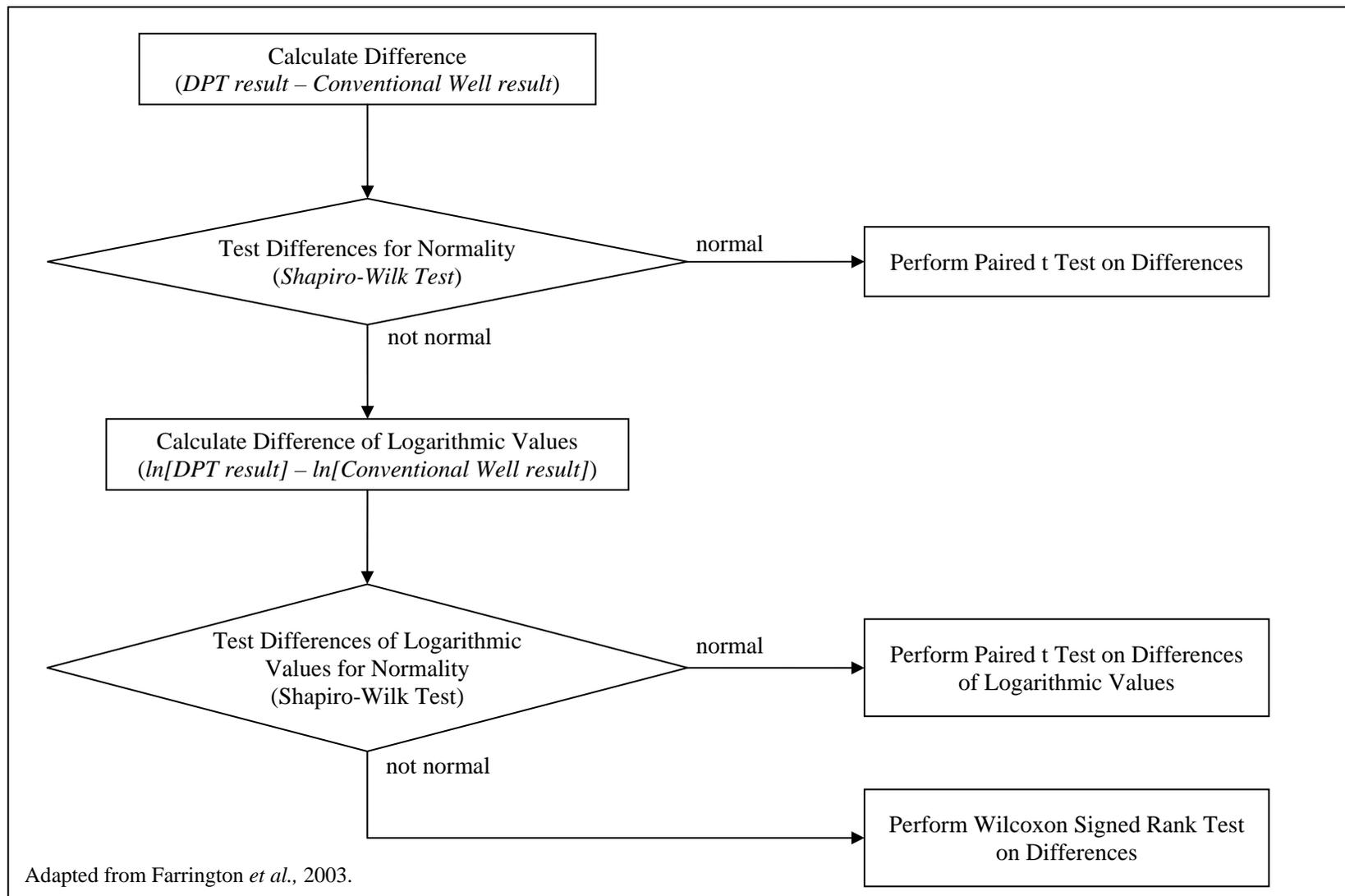
$$H_a: \mu_{DPT} - \mu_{CW} \neq 0$$

where μ_{DPT} is the mean of DPT well values (e.g., chemical concentration, temperature) in a given data set, and μ_{CW} is the mean of conventional well values.

Both parametric and nonparametric tests exist for testing this hypothesis. The applicability of each type of test depends on the distribution of the population, as inferred by the distribution of the random sample. If a parameter was not detected in one of the paired wells, it was assigned a value equal to half the detection limit. If a parameter was not detected in either of the paired wells, it was not included in the data set, resulting in a reduction of degrees of freedom (N) by one for each below-detection tie that was discarded.

The statistical methodology used to evaluate the data was similar to that used by Farrington *et al.* (2003), and is illustrated in **Figure 3.1**. A paired t test was used to evaluate the data if the differences in either the data or the log-transformed data were normally

FIGURE 3.1
FLOW CHART FOR STATISTICAL ANALYSIS OF DATA



distributed. If neither the untransformed nor log-transformed differences were normal, the Wilcoxon Signed Rank Test was performed to statistically evaluate the null hypothesis.

There are two ways of making an incorrect decision in hypothesis testing. Type I errors occur when the sample data reject the null hypothesis even though it is true. Type II errors result in accepting the null hypothesis even though it is false. In this study, a type I error would incorrectly conclude that data from DPT and conventional wells are not statistically equivalent when, in reality, these data are equivalent (i.e., false negative error). A type II error would incorrectly conclude that data from DPT and conventional wells are statistically equivalent data when, in reality, these data are not equivalent (i.e., false positive error). The level of significance (α) is the probability of a type I error, and the confidence of the test is $1 - \alpha$. The standard of performance (to accept the null hypothesis) for this study was 95 percent confidence or $\alpha = 0.05$. The P-value is the smallest α at which the null hypothesis can be rejected for the random sample. At 95 percent, any P-value in excess of 0.05 results in accepting the null hypothesis.

The probability of a type II error is represented by β , and the power of the test ($1 - \beta$) is its ability to distinguish a difference between DPT and conventional well values in the sample should a difference really exist in the general population. The power estimates were calculated as the power of the t test, assuming normally distributed differences of values or log-transformed values.

3.1.2 Scatter Plot Analysis

Scatter plots were created for all data sets in preparation for visual examination of variability of measurements by well type. All data were plotted with values from the conventional wells on the X axis (abscissa) and DPT well values on the Y axis (ordinate). When data ranged over an order of magnitude, data were plotted on a log scale. A solid line (i.e., the identity line) was included in all plots to represent where conventional and DPT values would plot if the values were exactly the same. When data are clustered around the identify line, the conventional wells and DPT wells are providing similar data. Data that are spread widely about the line have more variability between DPT and conventional well data. When data are consistently above the line, DPT results are generally higher than conventional well results. Conversely, when data are consistently below the line, the conventional well results are higher than the DPT well results.

Quantitative assessments of scatter plots were also performed. For VOCs, two methods of quantitative assessment were used to evaluate how often combined use of conventional well and DPT well results would confound assessment of MNA. First, one order of magnitude was chosen as a measure of “significant difference” (no statistical connotation here) between well pair values of VOC concentrations. The basis for this somewhat arbitrary selection of an order of magnitude as a quantitative indication of ‘significant’ was that experience with monitoring MNA sites indicates that measured VOC concentrations in wells often vary over wide ranges (an order of magnitude or more) over both space and time. Based on this experience with spatial and temporal variations in VOC concentrations, it was assumed that, for the purposes of the current study, differences of less than an order of magnitude could possibly be attributed to “noise”, and that differences of an order of magnitude or more could be assumed to be too large to be attributed to noise. Based on this assumption, differences in

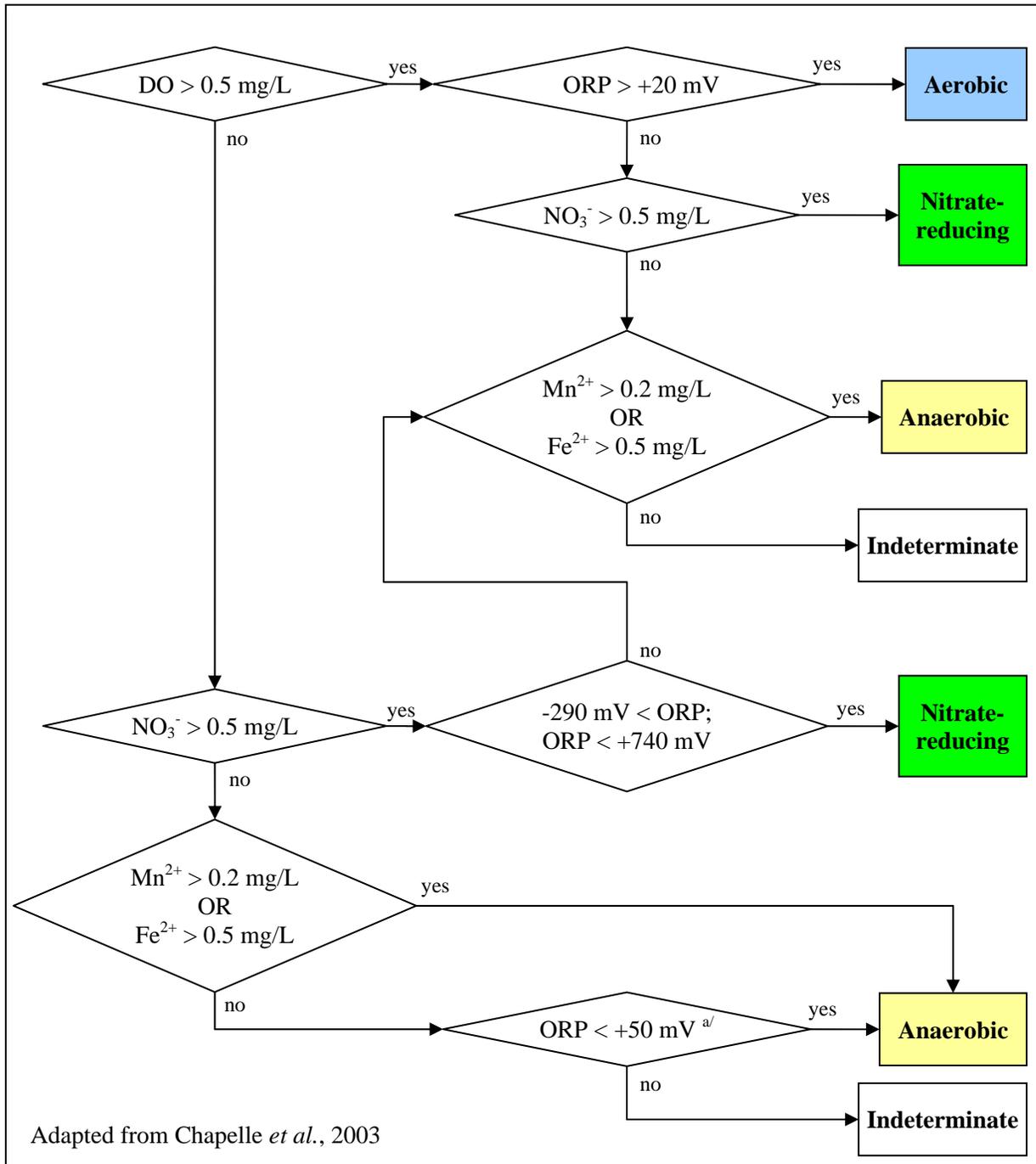
VOC concentrations that were more than an order of magnitude were interpreted to represent real differences in VOC concentrations between colocated well pair samples. Using this approach, the number of well pairs where the difference between DPT and conventional well values was within an order of magnitude was determined and compared with the number of locations where these concentration differences were greater than an order of magnitude (high or low). Second, the impact of the presence (above detection, without regard to the magnitude of detected concentrations) or absence (below detection) of each VOC was evaluated. The basis of this evaluation was a quantification of how many times a VOC was not detected in either a DPT or conventional well sample, but the same VOC was detected in a sample from its paired well.

For the analysis of scatter plots for redox indicators (i.e., DO, ORP, nitrate, ferrous iron, manganese, and sulfate), ‘threshold’ values were selected based on the work of Chapelle *et al.* (2003). Threshold values are concentrations or values which would lead an evaluator to make a different determination about a redox condition. For example, the threshold concentration for DO was designated as 0.5 milligrams per liter (mg/L) for the current study. DO concentrations above 0.5 mg/L were assumed to indicate aerobic conditions (oxygen is the terminal electron acceptor), whereas concentrations below 0.5 mg/L were assumed to indicate anaerobic conditions (some other chemical is the terminal electron acceptor). Using these threshold values for each parameter, the number of well pairs where concentrations in both wells were both above or both below the threshold value (i.e., data from both wells lead to the same conclusion), as well as the number of well pairs where the DPT well value was above the threshold and conventional well value below the threshold or vice versa (i.e., the two wells lead to different conclusions about redox condition) was determined.

3.1.3 Redox Condition Assessment

In addition to looking at scatter plots of individual redox indicator parameters, redox parameters were evaluated in total to determine the apparent TEAP for well pairs with complete redox parameter information. The TEAP condition for each well was determined based on available redox indicator concentrations and ORP measurements using the process illustrated on [Figure 3.2](#). The process for determining the TEAP was adapted from Chapelle *et al.* (2003), which in turn was based on earlier work of Chapelle *et al.* (1995) and Lyngkilde *et al.* (1991). The Chapelle *et al.* (2003) approach uses both chemical concentrations (i.e., DO, nitrate, ferrous iron, reduced manganese, sulfate) and dissolved hydrogen measurements to predict the redox condition. The Farrington *et al.* (2003) data included geochemical indicator measurements for DO, nitrate, ferrous iron, reduced manganese, sulfate, and ORP, but did not include dissolved hydrogen, methane, or carbon dioxide concentration measurements. In lieu of dissolved hydrogen data, ORP data were incorporated into the TEAP determination process of the current study by comparing the measured ORP values with the expected ORP range for a given redox condition. The range of ORP values that were chosen to correspond to each TEAP condition was based on theoretical predictions developed by Stumm and Morgan (1995). Figure 3.2 depicts the process used to select the most probably TEAP condition, based on all available data from the Farrington *et al.* (2003) study. As shown on this figure, identification of TEAP processes in this study was limited to three conditions: aerobic, nitrate-reducing, and anaerobic. For

**FIGURE 3.2
FLOW CHART FOR IDENTIFYING REDOX CONDITION**



^{a/} ORP = +50mV represents the maximum value predicted for ferric oxide reduction. ORP values up to +520 mV are theoretically possible at locations where reduction of manganese(IV) oxide is the dominant TEAP.

Notes: DO = dissolved oxygen; Fe²⁺ = ferrous iron; mV = millivolts; mg/L = milligrams per liter; Mn²⁺ = manganese (II); NO₃⁻ = nitrate; ORP = oxidation-reduction potential

the purposes of the current study, anaerobic conditions were defined to include manganese(VI) reduction, ferric iron reduction, sulfate reduction, and methanogenesis. While it is recognized that distinguishing between anaerobic TEAP conditions can affect significantly the evaluation of biodegradation of some contaminants of concern (especially chloroethenes), the absence of upgradient (background) concentration data for sulfate and the lack of hydrogen sulfide, methane, or carbon dioxide data made it impossible to distinguish between anaerobic biodegradation processes. In spite of this limitation, the ability to distinguish between the three conditions noted above was judged to be significant enough to allow conclusions to be drawn in terms of whether DPT and conventional wells yielded similar interpretations of the local redox condition.

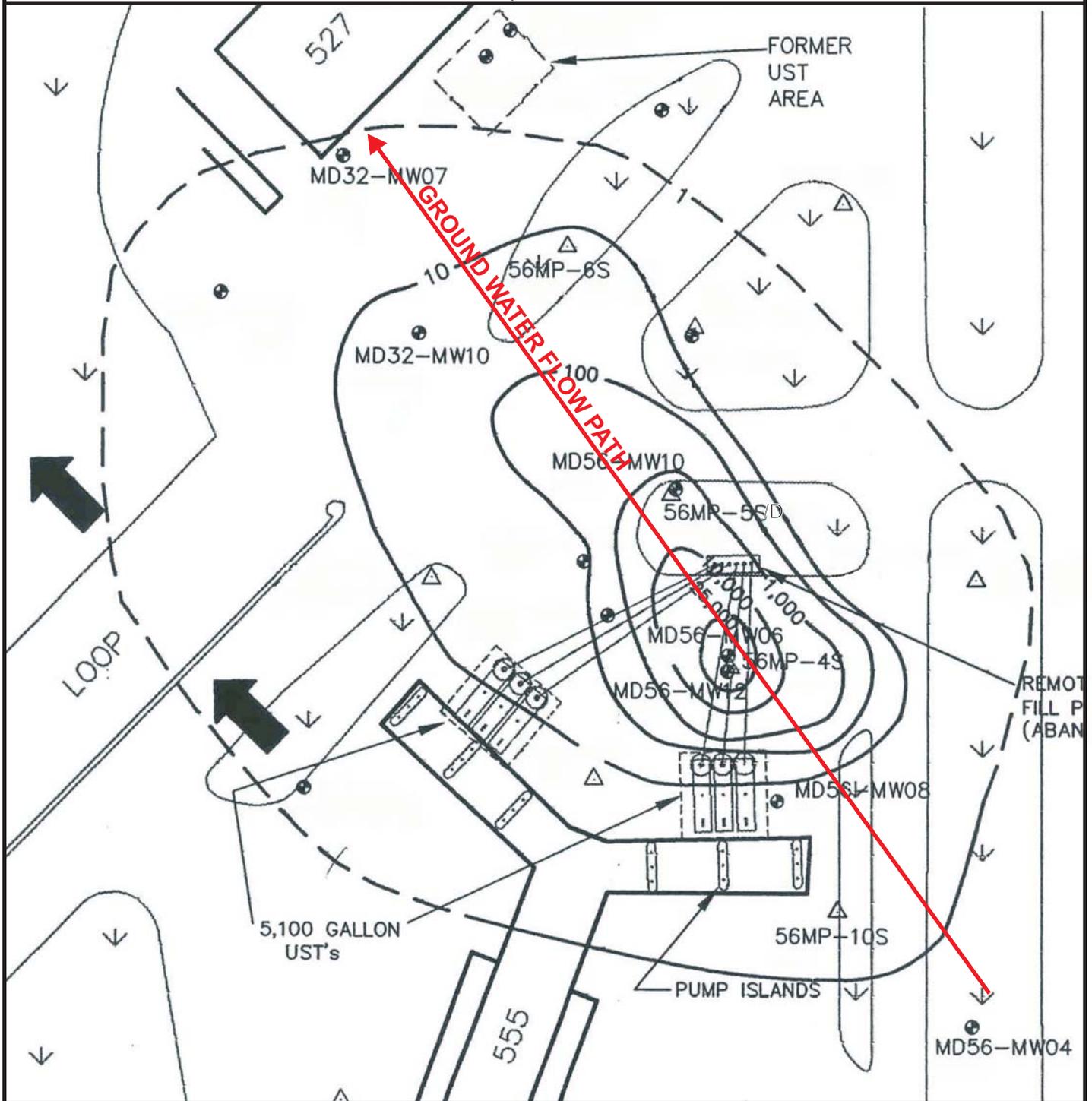
Note that the process for identifying TEAPs shown on Figure 3.2 also allowed for limited evaluation of cases where the chemical concentrations led to a conclusion that was at odds with the ORP data. For example, there were multiple cases where oxygen concentrations were greater than 0.5 mg/L, but ORP was less than 20 millivolts (mV). Rather than categorically labeling each of these occurrences as “indeterminate”, the TEAP identification process used in this study allowed for the assessment of whether there were additional data (i.e., nitrate, ferrous iron, or manganese(II) concentrations) that could be used to support a conclusion that either nitrate reduction or anaerobic conditions may be present. The justification for this approach was that even the most careful adherence to the current state-of-practice for low-flow sampling may still expose the ground water sample to the atmosphere. Field experience has shown that DO and ORP measurements are more sensitive to unintentional introduction of atmospheric oxygen to the sample (prior to measurement) than several of the anaerobic indicator parameters (e.g., nitrate, ferrous iron and manganese).

3.2 ANALYSIS ALONG A CONTAMINANT FLOW PATH

As mentioned in Section 2.1, only one site (Site 56, MacDill AFB, Florida) was found that had multiple DPT and conventional monitoring wells along a common contaminant flow path. MNA data for conventional and DPT wells at this site were plotted along a common ground water flow line to qualitatively evaluate if the data from the different well types showed similar characteristics in contaminant concentrations and redox indicator variation with distance along the flow path. **Figure 3.3** is a plot showing locations of all conventional and DPT wells at Site 56, with the points used in this study shown with labels. Ground water flow is to the northwest (indicated by the red arrow on Figure 3.3). Six shallow conventional wells and four DPT wells were selected along (or close to) a flow line that starts upgradient of the dissolved petroleum contamination and proceeds through the center of the dissolved contamination and the downgradient limit of the plume.

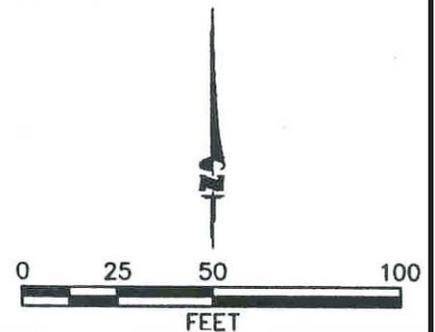
The method of analysis was to plot concentrations of contaminants and redox indicators along the flow path separately for conventional wells and DPT wells. DPT well 56MP-04 was selected as the zero coordinate on the flow line because it appeared to be closest to the source of petroleum contaminants. The positions of the other wells were estimated to be either in the negative direction (upgradient) or positive direction (downgradient) from 56MP-04. As described in Section 4.2, spatial plots were analyzed to determine if similar NA-related conclusions were derived from the two well sets.

**FIGURE 3.3
LOCATIONS OF CONVENTIONAL AND DPT WELLS
AT SITE 56, MACDILL AFB**



LEGEND

- 56MP-8S  DPT MONITORING WELL
- MD56-MW04  CONVENTIONAL MONITORING WELL
-  10 LINE OF EQUAL BTEX CONCENTRATION ($\mu\text{g/L}$)
-  ESTIMATED GROUND WATER FLOW DIRECTION
-  GRASSY AREA



SECTION 4

RESULTS

This chapter describes the results from quantitative and qualitative analysis of the colocated (i.e., Farrington *et al.* [2003]) and non-colocated (i.e., Site 56, MacDill AFB) data sets evaluated in this study.

4.1 RESULTS FROM ANALYSIS OF COLOCATED DATA

4.1.1 Hypothesis Testing

The results of the hypothesis testing for the current study are summarized in [Table 4.1](#). As expected, the results generally mirror those of Farrington *et al.* (2003). For example, statistical tests of whether petroleum compound concentrations were statistically similar between well types were rejected due to higher concentrations in DPT wells with the exception of *m,p*-xylene. In contrast, statistical tests of whether individual chloroethene concentrations were statistically similar were accepted (i.e., DPT and conventional wells yielded statistically similar results for chloroethenes). Using the combined data set, statistical tests on individual redox indicator measurements were accepted as statistically similar between wells for all redox indicators, except for manganese(II). This finding was in contrast to results of using the smaller data groupings in Farrington *et al.* (2003) in that previous results indicated a rejection of the null hypothesis (i.e., the data sets were not statistically the same between wells) for ORP, DO, and sulfate. Concentrations of manganese(II) were rejected as similar in both the current and Farrington *et al.* (2003) studies. Of the other ground water indicators evaluated in the current study, temperature and potassium were accepted as statistically similar, but sodium and pH were rejected.

As mentioned previously, the goal of combining the 2-inch and 1.5-inch wells was to increase the power of the statistical tests (i.e., reduce the chance of a type II error) for the measured parameters by increasing the sample size. Combining these two data sets caused increases in statistical power, relative to the Farrington *et al.* (2003) study for all of the individual BTEX compounds and TCE, but had little effect on the power of statistical tests for *cis*-1,2-DCE. Unexpectedly, combining these two data sets resulted in a decrease in the statistical power for PCE, *trans*-1,2-DCE and VC. Although there was decrease in statistical power for PCE, *trans*-1,2-DCE and VC, neither the original or combined data sets had powers that were approaching the targeted level of 0.80. As for ground water quality indicator parameters, combining the two data sets increased (relative to the Farrington *et al.* [2003]) the statistical power of ferrous iron, manganese(II), and sodium, had a negligible effect on the statistical power for alkalinity and potassium, and decreased the statistical power for sulfate. The Farrington *et al.* (2003) study did not publish power results for several of the remaining redox indicator or other ground water indicator parameters, so no

TABLE 4.1
STATISTICAL TESTING RESULTS OF COMBINED FARRINGTON *et al.* (2003) DATA SETS

Analyte	No. of Well Pairs	Mean Difference [DPT-Conventional Well] (µg/L)	Standard Deviation [DPT - Conventional Well] (µg/L)	Statistical Test	P-Value	Power	Result
<i>Petroleum Compounds</i>							
Benzene	66	30.8	166	Paired t test (log-transformed)	0.0311	0.58	Reject
Toluene	52	88.0	240	Wilcoxon matched pairs	0.00153	0.95	Reject
Ethylbenzene	55	25.8	87.0	Wilcoxon matched pairs	0.0155	0.84	Reject
Xylene(<i>m,p</i>)	63	56.2	203	Wilcoxon matched pairs	0.141	0.73	Accept
Xylene(<i>o</i>)	64	44.3	138	Wilcoxon matched pairs	0.00149	0.98	Reject
<i>Chloroethenes</i>							
PCE	37	147	649	Paired t test (log-transformed)	0.245	0.20	Accept
TCE	80	144	831	Wilcoxon matched pairs	0.0825	0.81	Accept
<i>cis</i> -1,2-DCE	64	1310	4170	Wilcoxon matched pairs	0.264	0.64	Accept
<i>trans</i> -1,2-DCE	35	6.87	45.0	Paired t test (log-transformed)	0.656	0.06	Accept
VC	58	55.2	249	Wilcoxon matched pairs	0.730	0.11	Accept
<i>Redox Indicators</i>							
ORP	83	20.1	106	Wilcoxon matched pairs	0.752	0.39	Accept
DO	82	0.239	2.54	Wilcoxon matched pairs	0.0741	0.13	Accept
Nitrate	39	-0.134	1.05	Wilcoxon matched pairs	0.738	0.04	Accept
Ferrous Iron	39	-0.334	5.82	Wilcoxon matched pairs	0.521	0.46	Accept
Manganese (II)	50	0.255	1.17	Wilcoxon matched pairs	0.0126	0.96	Reject
Sulfate	50	-0.725	8.73	Paired t test	0.560	0.08	Accept
<i>Ground Water Quality Indicators</i>							
pH	83	-0.227	0.809	Wilcoxon matched pairs	0.0172	0.71	Reject
Alkalinity	50	3.78	33.8	Wilcoxon matched pairs	0.807	0.06	Accept
Temperature	82	-0.146	1.71	Wilcoxon matched pairs	0.724	0.11	Accept
Sodium	47	2.27	6.36	Wilcoxon matched pairs	0.00270	0.68	Reject
Potassium	50	-0.280	3.02	Wilcoxon matched pairs	0.709	0.03	Accept

^{a/} Accept = DPT and Conventional wells are statistically similar; Reject = DPT and Conventional wells are statistically different

Notes: DPT = direct push technique; P = power of the statistical test = 1-β; *m* = meta; *o* = ortho; *p* = para; PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; VC = vinyl chloride; DO = dissolved oxygen; ORP = oxidation-reduction potential; µg/L = micrograms per liter

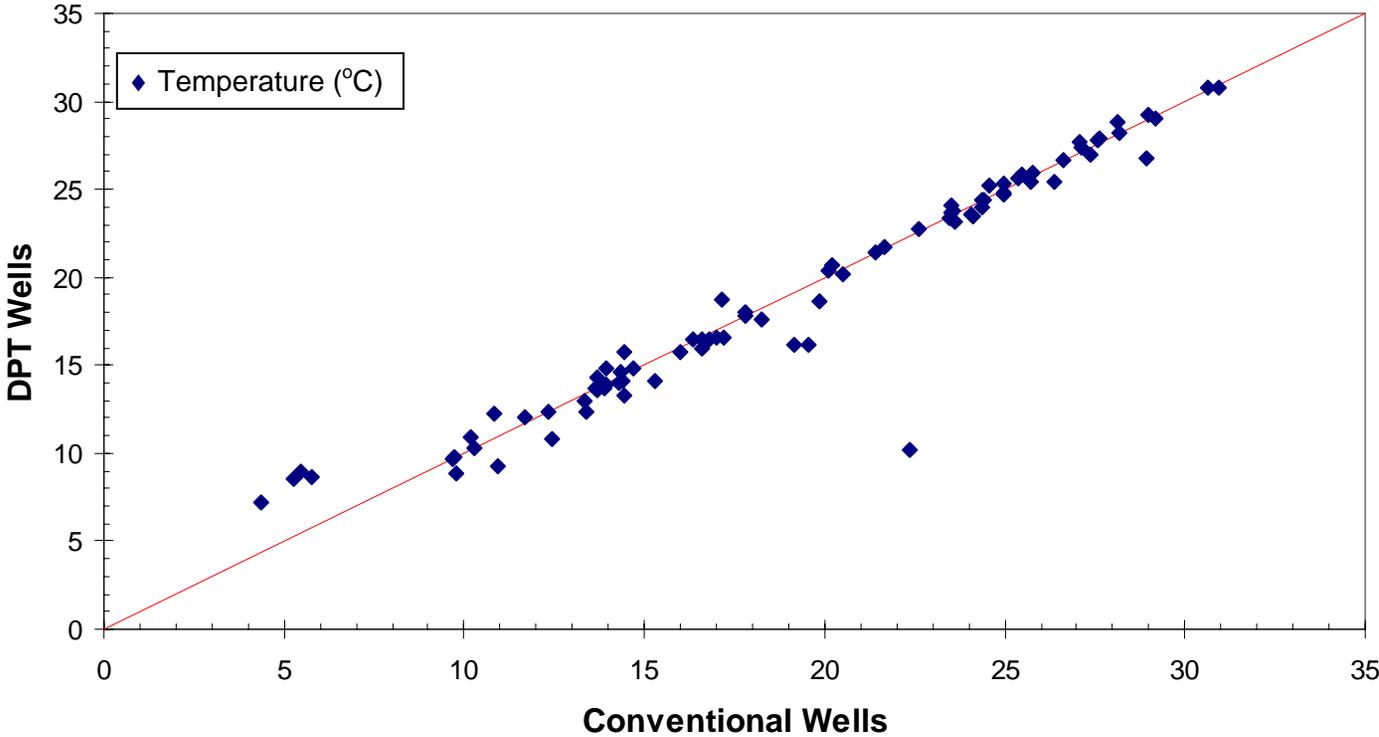
evaluation of the effect of increasing the size of the data set on improvements in power could be made. Note that the Farrington study included ground water indicator parameters from other sites (i.e., Port Hueneme) that were not considered as part of the current study for reasons described previously. The effect of excluding the Port Hueneme data in the current study was that, in some cases, the number of well pairs with ground water indicator measurements was smaller in the current study than was used in the statistical calculations by Farrington *et al.* (2003).

4.1.2 Scatter Plot Analysis

Scatter plots for the ground water indicators temperature, potassium, sodium, and pH are presented on **Figures 4.1 through 4.4**. The solid diagonal line (i.e., the identity line) shows where DPT and conventional well data would plot if the measurements were exactly the same. Qualitatively, temperature (Figure 4.1) and potassium (Figure 4.2) data are clustered closely to the solid line. The sodium (Figure 4.3) data also appear to be fairly closely clustered to the solid line and do not appear visually to be very different from the potassium (Figure 4.2) scatter plot. However, statistical testing of sodium data indicates that the null hypothesis is rejected (i.e., the two data sets are not statistically similar). Note that this statistical testing result for sodium data does not change if the two sodium data points furthest from the solid line are eliminated (see discussion in Appendix A). Closer inspection of the scatter plot reveals that the sodium data set is distributed over a fairly narrow range (less than an order of magnitude) and, even though the data are closely clustered to the solid line, the highest concentrations are consistently above the line. This combination of observed conditions in the sodium data is believed to have produced the statistical conclusion that the DPT and conventional well are statistically different even though the visual qualitative assessment suggests that the measured data were similar. If the range of sodium concentrations had been larger, there may have been a better chance that the data sets would have been calculated as statistically similar. pH data (Figure 4.4) exhibit considerably more scatter than the other ground water quality indicator parameters. One possible explanation for the relatively higher scatter in pH data could be that this parameter is more sensitive to small changes in spatial location. The three data points to the far right of the pH data plot are the Hanscom AFB RAP2-2T well pair data that is discussed in Appendix A.

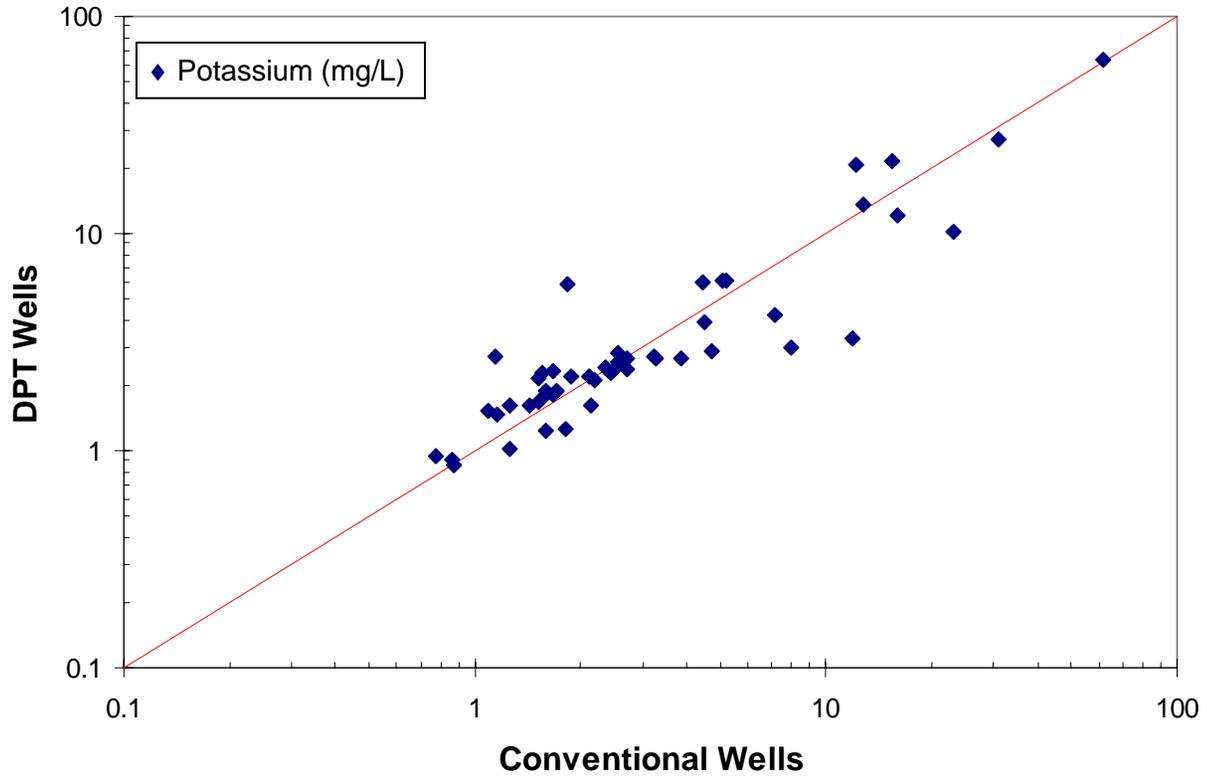
Aromatic petroleum compound and chloroethene data are plotted on **Figures 4.5 and 4.6**, respectively. The solid diagonal line shows where DPT and conventional well data would plot if concentrations were measured as exactly the same. The dashed lines are an order of magnitude above and below this identity line. Of the data that plots outside the dashed lines (i.e., conventional and DPT well data that differ by more than one order of magnitude), the higher concentration was measured more often in the DPT well than in the conventional well. This observation is true both for the BTEX compounds, where the DPT well concentrations were found to be statistically higher than the conventional well concentrations, and for the chloroethenes, where the data sets were generally found to be statistically equivalent. The results of a frequency analysis for the number of occurrences when the contaminant concentration measurements were observed to differ by more than one order of magnitude are presented in **Table 4.2**. As indicated in this table, the fractions of well pair data that were within an order of magnitude of a one-to-one correlation were 72 percent for BTEX compounds and 76 percent for chloroethenes.

FIGURE 4.1
COMPARISON OF TEMPERATURE DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



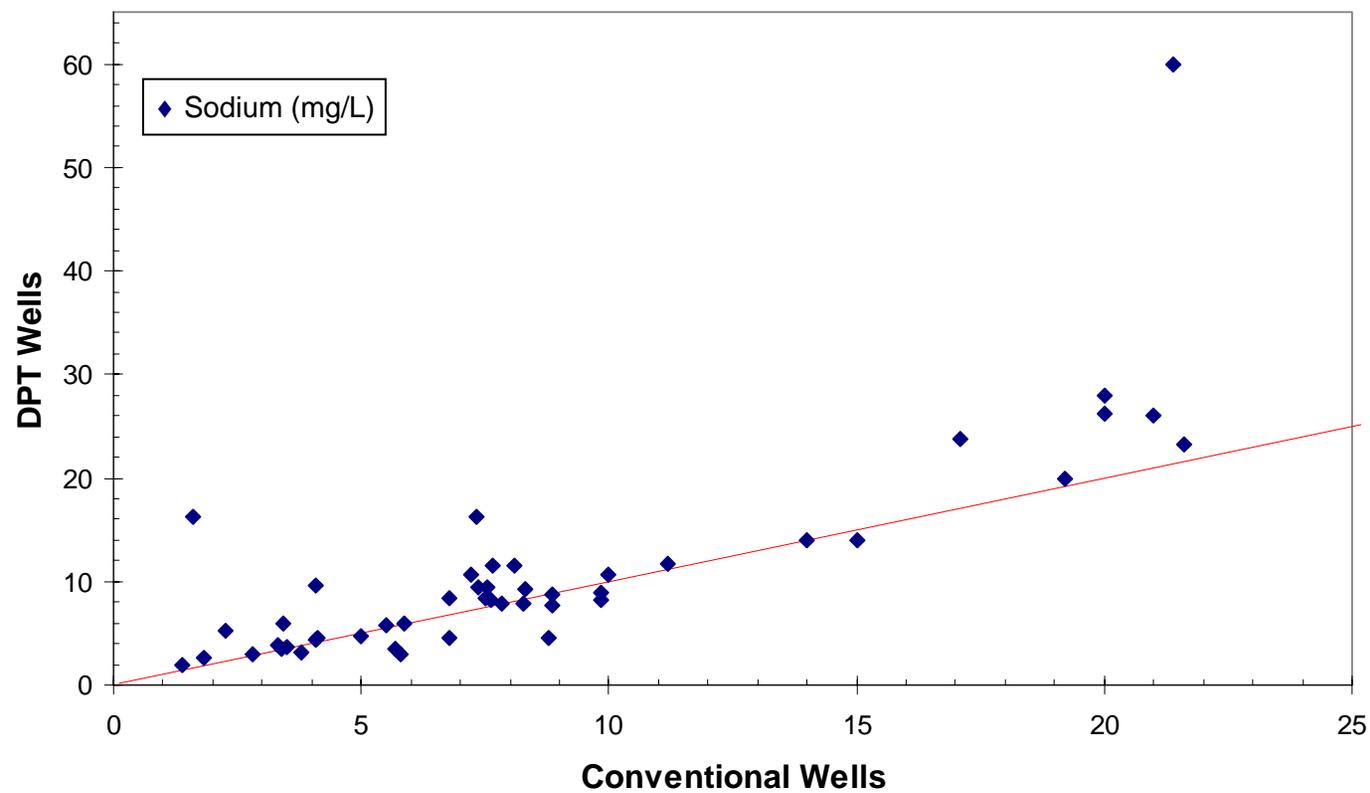
^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.2
COMPARISON OF POTASSIUM DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



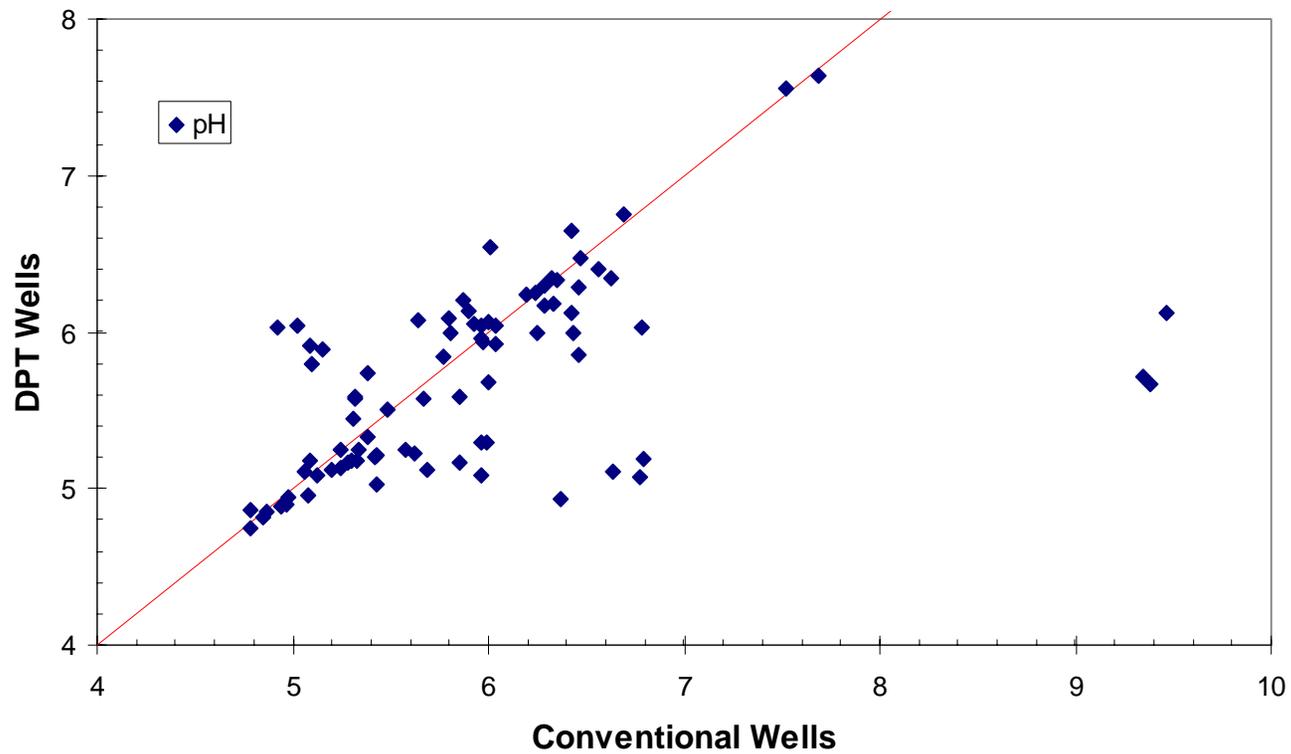
^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.3
COMPARISON OF SODIUM DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.4
COMPARISON OF pH DATA COLLECTED FROM DPT^{a/} AND
CONVENTIONAL WELLS (FARRINGTON et al., 2003)



^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.5
COMPARISON OF BTEX DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)

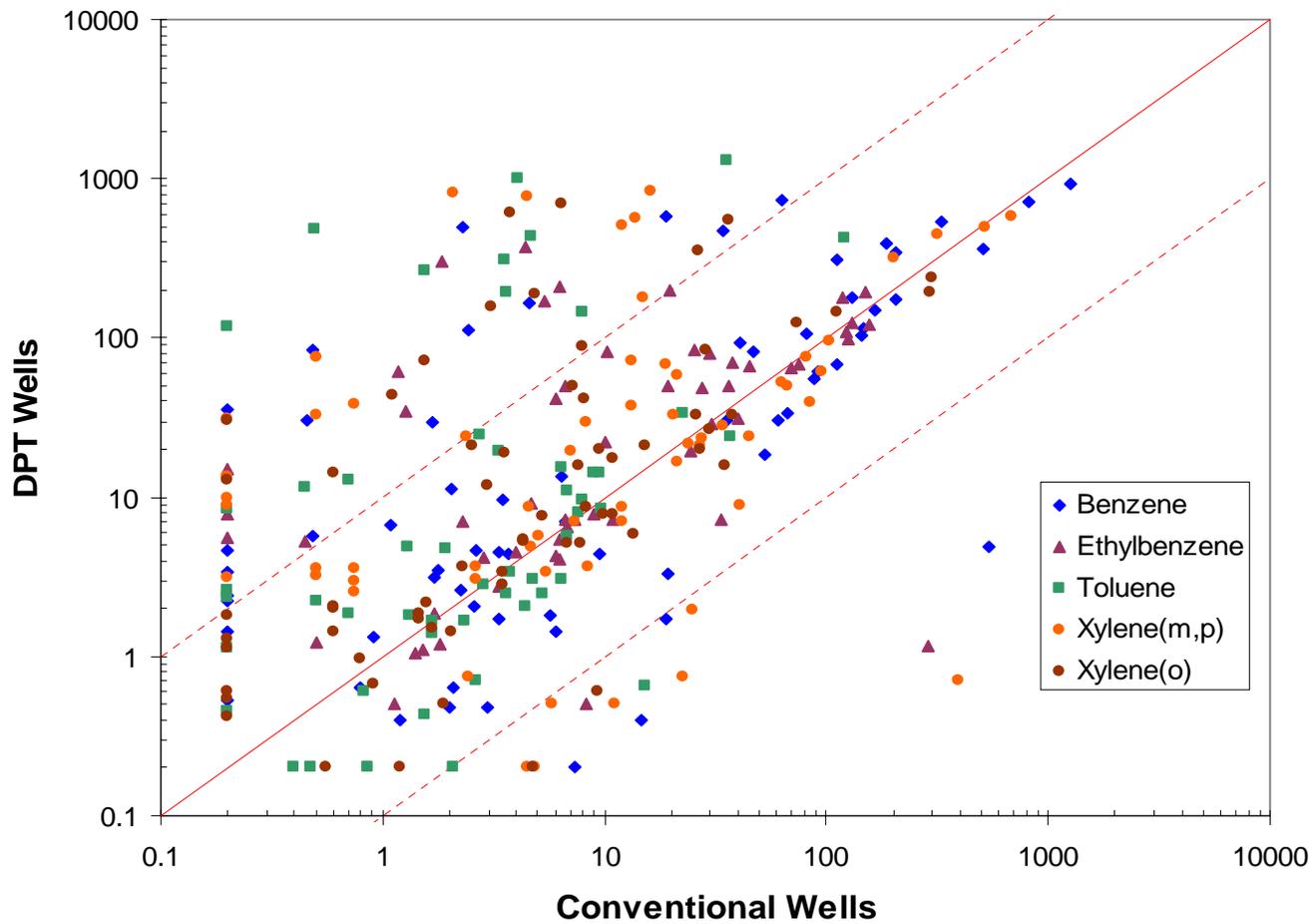
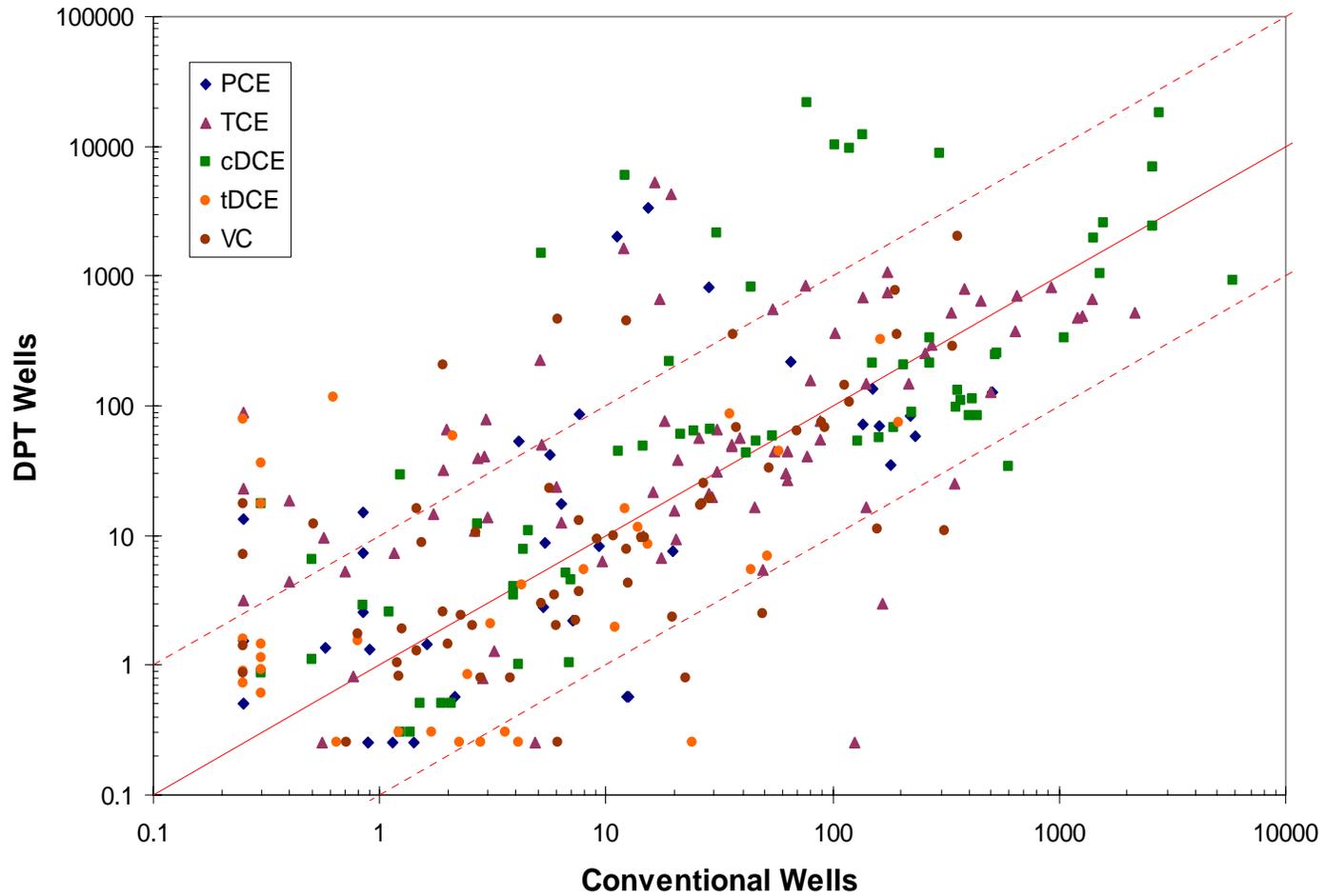


FIGURE 4.6
COMPARISON OF CHLOROETHENE DATA COLLECTED FROM DPT ^{a/}
AND CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

Notes: PCE = tetrachloroethene; TCE = trichloroethene; cDCE = *cis*-1,2-dichloroethene; tDCE = *trans*-1,2-dichloroethene; and VC = vinyl chloride

**TABLE 4.2
COMPARISON OF VOC CONCENTRATIONS WITHIN WELL PAIRS**

Compound/Group	Number of Data Pairs	Number of Data Pairs where VOC Concentration Measurement in:		Percentage of Data Pairs within One Order of Magnitude of 1:1 Correlation
		DPT Well > 10x Conventional Well	Conventional Well > 10x DPT Well	
Benzene	66	15	4	71 %
Toluene	52	14	2	70 %
Ethylbenzene	55	11	2	76 %
Xylene (<i>o</i>)	64	12	2	78 %
Xylene (<i>m,p</i>)	63	16	7	64 %
Total BTEX	300	68	17	72 %
PCE	37	7	2	76 %
TCE	80	18	4	73 %
<i>cis</i> -1,2-DCE	64	13	1	78 %
<i>trans</i> -1,2-DCE	35	5	4	74 %
VC	58	7	5	79 %
Total Chloroethenes	274	50	16	76 %

Notes: *m* = meta; *o* = ortho; *p* = para; BTEX = benzene, toluene, ethylbenzene, and xylene isomers, PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; VC = vinyl chloride

The contaminant concentration data sets and corresponding scatter plots were also evaluated for the occurrence of below detection measurement in one well type but above detection measurement in the corresponding paired well. The results of this analysis are presented in [Table 4.3](#). As reported in [Table 4.3](#), individual BTEX and chloroethene compounds were detected in both paired wells for 77 percent of the measurements. For individual BTEX compounds, there were twice as many below detection measurements in conventional wells as there were in DPT wells. For chloroethenes, the number of below detection measurements was found to be approximately the same. On [Figures 4.5](#) and [4.6](#), the data pairs where measurements were below detection in one well type but not the other are represented by the line of data points shown at 0.25 µg/L and parallel to the X axis (i.e., below detection in the DPT well, above detection in the conventional well) or Y axis (i.e., below detection in the conventional well, above detection in the DPT well).

**TABLE 4.3
SUMMARY OF BELOW DETECTION VOC MEASUREMENTS BY
WELL TYPE**

Compound Group	Number of Data Pairs	Number of BD Measurements Reported in Conventional Well Only	Number of BD Measurements Reported in DPT Well Only	Percentage of Data Pairs with Concentrations above Detection in both Well Types
BTEX	300	47	23	76.7%
Chloroethenes	274	32	31	77.0%

Note: BD = below detection

The observation that more below detection results were found in conventional well samples than DPT well samples for BTEX compounds appears to be consistent with results of other tests performed as part of this study in that tests for statistical equivalence between well type were rejected for these compounds, and that samples that were more than one order of magnitude different in concentration between well pairs were approximately four times as likely to come from DPT wells as they were to come from conventional wells. The observation that the number of below detection measurements for chloroethenes was approximately equivalent between well types appears to be consistent with previous statistical tests that indicated statistical equivalence between measurements for these compounds.

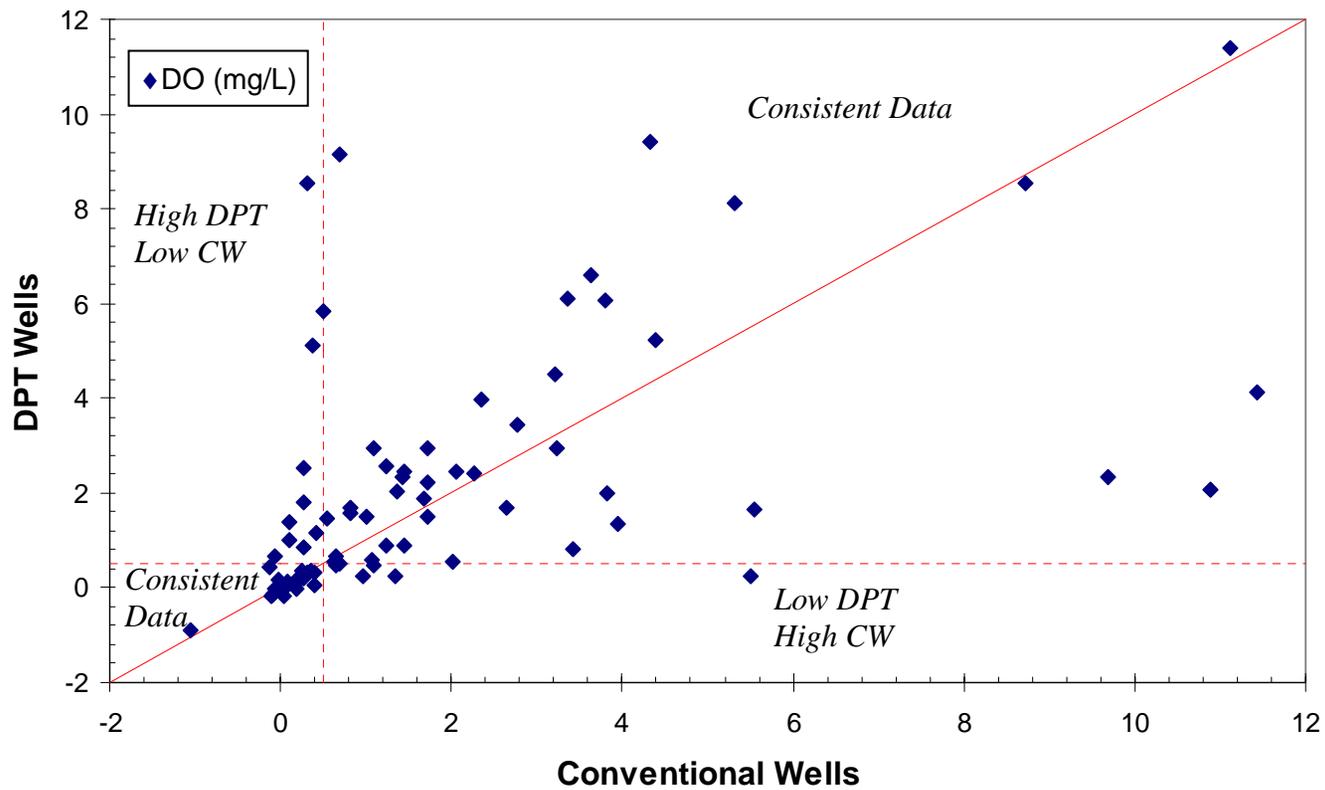
Scatter plots for individual redox indicator parameters are provided as **Figures 4.7 through 4.11**. One way of evaluating the potential influence of well type on MNA evaluation is to compare measured redox indicator concentrations with concentrations that are indicative of different redox conditions. For example, different redox conditions would be indicated if DO concentration was greater than 0.5 mg/L (i.e., indicative of aerobic conditions) in one well type, but less than 0.5 mg/L (i.e., indicative of anaerobic conditions) in the paired well. To facilitate visualization of when data were consistent or inconsistent between well types, dashed lines have been included on each of the redox indicator plots to separate the presented plots into quadrants labeled as “Consistent Data”, “High DPT, Low CW”, and “Low DPT, High CW”. For the DO example described above, this approach indicates that a redox indicator would be “consistent” between well types only if DO concentrations were either both above or both below 0.5 mg/L. As can be observed from visual inspection of the redox indicator figures, the majority of data pairs were consistent between well types for DO (Figure 4.7), nitrate (Figure 4.8), ferrous iron (Figure 4.9), manganese(II) (Figure 4.10), and ORP (Figure 4.11). Although sulfate concentrations were measured for multiple well pairs, this data set was not plotted or subjected to the test for consistency because only one sulfate concentration measurement was reported as below 1.0 mg/L (i.e., only one measurement to clearly indicate sulfate depletion) and background sulfate concentration data were not available to aide in evaluating a site-specific threshold as an alternate method for evaluating ‘significant’ sulfate depletion.

Table 4.4 lists the ‘critical values’ used for each redox indicator parameter and the results of quantitative analysis on data consistency between well types. As can be observed from the results presented in Table 4.4, DO, nitrate, ferrous iron, manganese, and ORP data supported consistent redox determinations for between 83 to 90 percent of the well pairs. Of the data pairs that disagreed regarding values critical to redox condition, values in conventional wells were more often lower than DPT wells for all parameters except ferrous iron.

4.1.3 Redox Condition Assessment

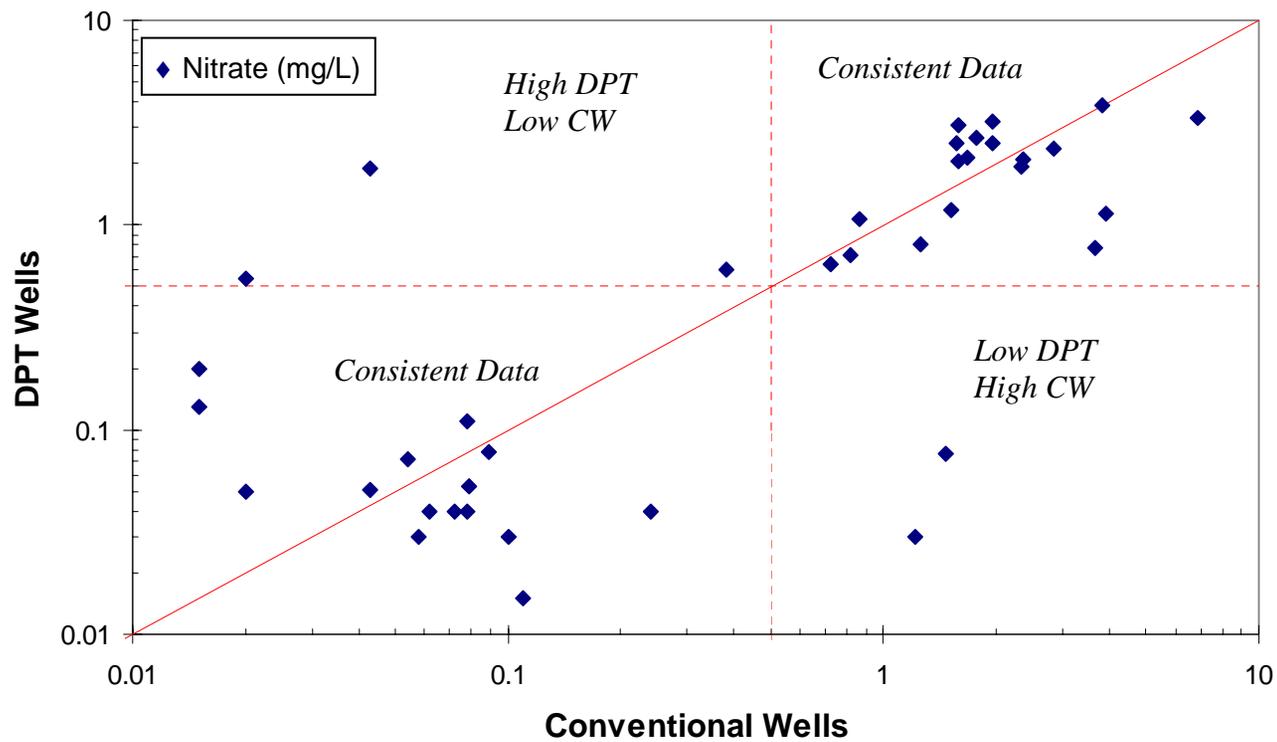
The Farrington *et al.* (2003) data set contained results for DO, nitrate, ferrous iron, manganese, sulfate, and ORP at 46 well pairs (92 ground water samples). Using the process described in Section 3.1.4 and illustrated on Figure 3.2, the TEAP condition for each well was evaluated using the available redox indicator data. The results of this analysis are shown on a well-by-well basis in **Table 4.5**. Of the 92 ground water samples, results for three wells exhibited discrepancies between redox indicator data that prevented determination of the probable TEAP condition. As a result, the TEAP was considered determinate for both well

FIGURE 4.7
COMPARISON OF DISSOLVED OXYGEN (DO) DATA COLLECTED FROM
DPT^{a/} AND CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



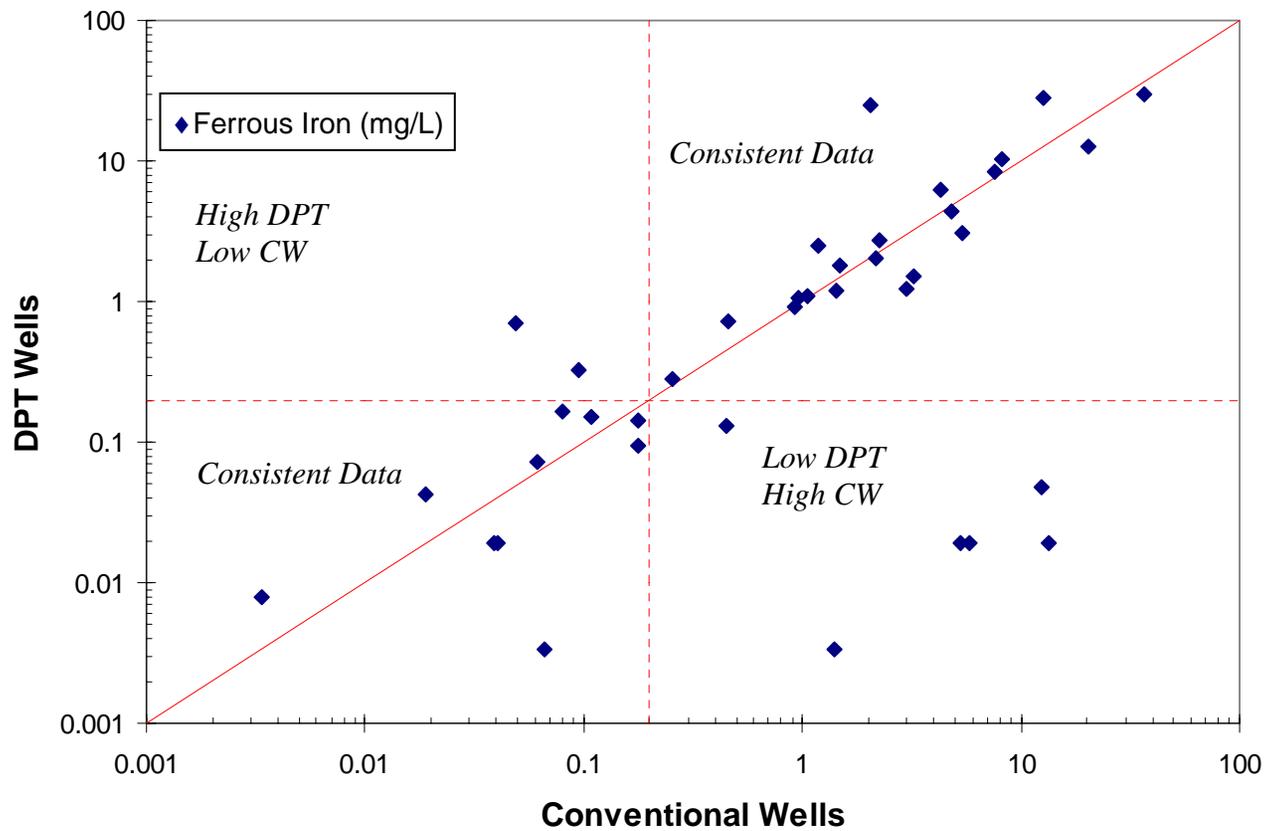
^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.8
COMPARISON OF NITRATE DATA COLLECTED FROM DPT^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



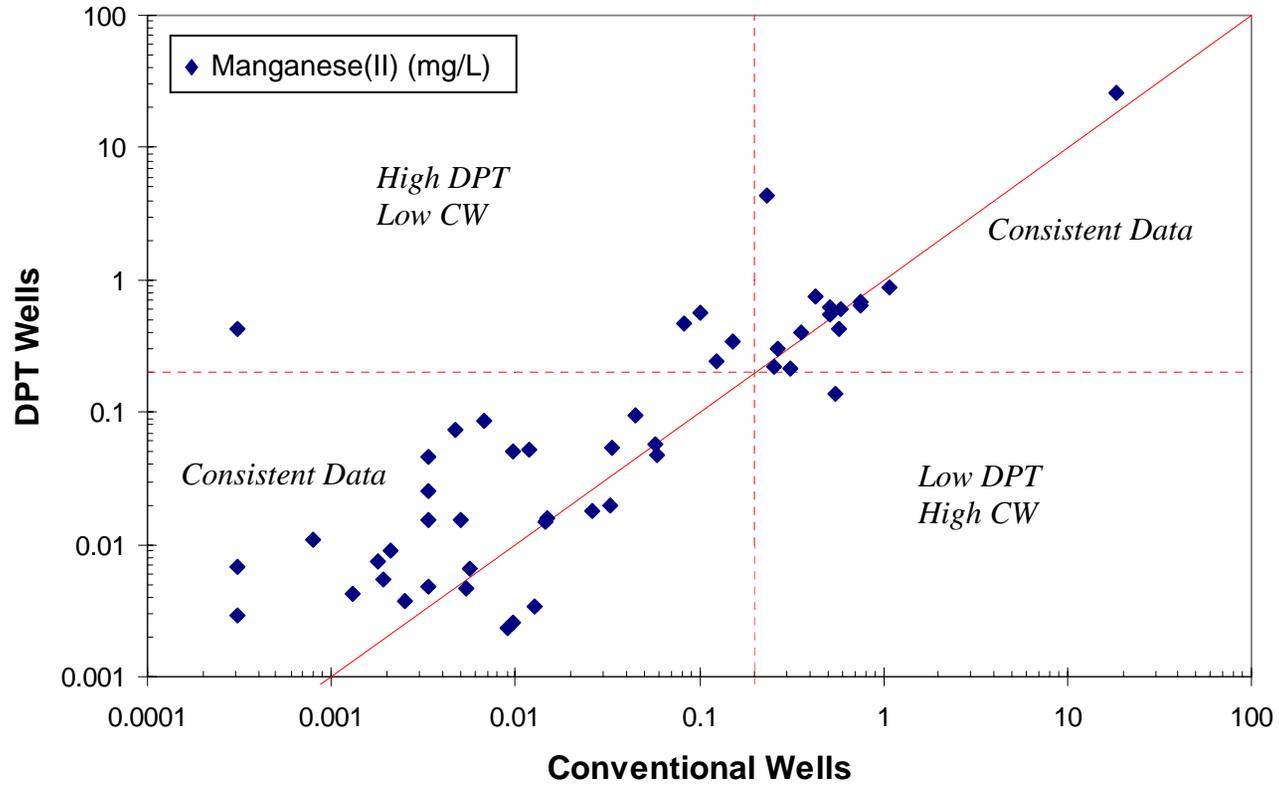
^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.9
COMPARISON OF FERROUS IRON DATA COLLECTED FROM DPT ^{a/}
AND CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



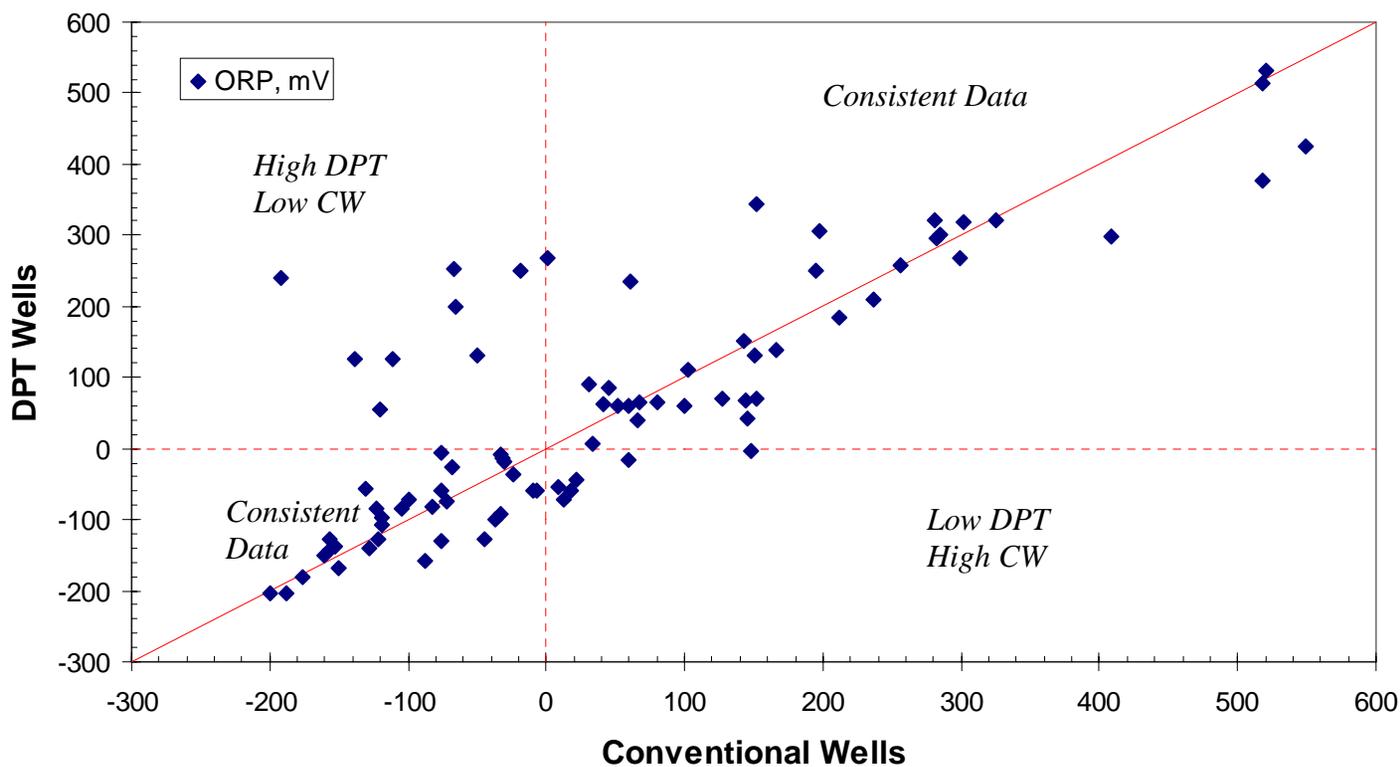
^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.10
COMPARISON OF MANGANESE(II) DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE 4.11
COMPARISON OF OXIDATION- REDUCTION POTENTIAL (ORP) DATA COLLECTED
FROM DPT ^{a/} AND CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

TABLE 4.4
SUMMARY OF RESULTS FROM REDOX INDICATOR DATA ASSESSMENT

Analyte	Critical Value for Redox Determination	Total Data Pairs	Number of Pairs with Low Conventional Well Value and High DPT Well Value	Number of Pairs with Low DPT Well Value and High Conventional Well Value	Percent of Well Pairs Indicating Similar Redox Conditions
DO	0.5 mg/L	82	9	5	83 %
Nitrate	0.5 mg/L	50	3	2	90 %
Ferrous Iron	0.2 mg/L	50	2	6	84 %
Manganese	0.2 mg/L	50	5	1	88 %
ORP	0 mV	83	8	6	83 %

Notes: DPT = direct push technique; DO = dissolved oxygen; ORP = oxidation-reduction potential

types at 44 of the 46 well pairs. Results for both the DPT and conventional wells predicted the same TEAP in 34 of the 44 determinate well pairs (i.e., 77 percent agreement).

4.2 RESULTS FROM ANALYSIS ALONG CONTAMINANT FLOW PATH

Contaminant and redox indicator parameters are plotted for the May 1995 sampling of Site 56, MacDill AFB, on Figures 4.12 through 4.16. The data reported on these figures were collected from monitoring wells located along or near a single contaminant flow path, as shown in Figure 3.3. DPT and conventional wells were purged and sampled during a single sampling event using a peristaltic pump and dedicated tubing to collect samples with identical low-flow sampling procedures. The intake elevation of the dedicated tubing was placed at the approximate mid-point elevation of the saturated portion of the well screen. Conventional well (MW56-MW04, MD56-MW08, MD56-MW10, MD32-MW10, and MD32-MW07) data are plotted using open icons and dashed lines, whereas DPT well (56MP-10S, 56MP-4S, 56MP-5S, and 56MP-6S) data are plotted using filled icons and solid lines. Plots are ordered from the most up-gradient well (MW56-MW04) on the left to the most down-gradient well (MD32-MW07) on the right. **Figure 4.12** shows total BTEX concentrations along the flow path, and **Figure 4.13** is a bar chart showing the concentrations of BTEX and trimethylbenzene (TMB) compounds in conventional and DPT wells. These figures show that the conventional and DPT wells both detect comparable levels of petroleum compound solutes in ground water along a contaminant flow path through the approximate center of the contaminant plume. In particular, the petroleum solute concentrations in paired conventional well MD56-MW06 and DPT well 56MP-4S are very similar, as are the concentrations in well pair MD56-MW10 and 56MP-5S (**Figure 4.13**). These results contrast to the generally higher concentrations of petroleum solutes observed in DPT wells reported in the Farrington *et al.* (2003) data set (see Section 2.2.1).

During review of well completion logs, it was noted that the screens of the MacDill AFB DPT wells are shorter than those of the conventional wells. Because both the DPT and conventional monitoring wells were screened across the water table, the shorter screen length of the DPT well implies that sampling from the DPT wells was likely to preferentially sample ground water from the upper portion of the interval sampled by the longer-screened

TABLE 4.5
REDOX INDICATOR DATA AND INFERRED TEAP CONDITION FOR DPT AND CONVENTIONAL WELLS

DPT-installed Wells								Conventionally-installed Wells									
Well Name	Sample Date	ORP	DO	NO3	Mn ²⁺	Fe ²⁺	SO4	TEAP	TEAP	ORP	DO	NO3	Mn ²⁺	Fe ²⁺	SO4	Sample Date	Well Name
Data from Dover AFB																	
NTS-337S	14-Dec-00	514.2	2.57	2.13	0.003	8.46	33.3	Aerobic	Aerobic	517.6	1.23	1.68	0.003	7.55	30.7	14-Dec-00	DM-337S
NTS-337S	07-May-01	377	5.21	2.5	0.676	0.02	36.9	Aerobic	Aerobic	518	4.4	1.95	0.751	0.02	36.5	07-May-01	DM-337S
NTS-337S	06-Aug-01	425	2.43	2.07	0.635	0.02	32.8	Aerobic	Aerobic	549	2.27	1.59	0.758	0.02	30.6	06-Aug-01	DM-337S
NTS-236D	15-Dec-00	250.9	0.23	0.008	0.046	10.40	20.3	Anaerobic	Aerobic	194.3	5.5	0.11	0.003	8.24	10.3	15-Dec-00	MW-236D
NTS-236D	08-May-01	251	2.35	0.02	0.219	0.05	22.8	Aerobic	Anaerobic	-19	9.69	0.24	0.256	12.30	11.7	08-May-01	MW-236D
NTS-236D	07-Aug-01	253	2.32	0.02	0.216	0.02	23.8	Aerobic	Anaerobic	-67	1.43	0.02	0.314	13.40	20.5	07-Aug-01	MW-236D
NTS-235D	15-Dec-00	269.1	0.21	2.35	0.0257	6.19	10.3	NO3	NO3	298.7	0.27	2.84	0.003	4.30	3.7	15-Dec-00	DM-235D
NTS-235D	08-May-01	301	2.06	2.1	0.015	0.02	11.3	Aerobic	Aerobic	285	10.88	2.35	0.014	0.02	3.6	08-May-01	MW-235D
NTS-235D	07-Aug-01	210	1.67	1.93	0.0156	0.04	11.5	Aerobic	Aerobic	236	5.55	2.32	0.015	0.02	3.4	07-Aug-01	DM-235D
NTS-354D	18-Dec-00	257.3	1.7	2.68	0.052	3.03	2.7	Aerobic	Aerobic	255.6	0.81	1.77	0.012	5.35	0.75	18-Dec-00	DM-354D
NTS-354D	08-May-01	318	4.49	2.5	0.0177	0.02	1.7	Aerobic	Aerobic	302	3.21	1.57	0.026	0.02	1.8	08-May-01	DM-354D
NTS-53S	19-Dec-00	-60.1	0.25	0.13	25.6	27.90	3.8	Anaerobic	Anaerobic	17.6	1.34	0.02	18.400	12.60	18.4	18-Dec-00	DM-53S
NTS-53S	09-May-01	-60	2.45	0.02	0.601	29.50	2.4	Anaerobic	Anaerobic	-76	2.06	0.02	0.592	36.50	12.2	09-May-01	DM-53S
NTS-237S	09-May-01	-26	2.94	0.02	0.561	25.10	25.6	Anaerobic	Anaerobic	-68	3.23	0.02	0.102	2.05	5.1	09-May-01	MW-237S
Data from Hanscom AFB																	
OW2-2-DPT	31-Oct-00	-100	0.3	0.015	4.4	2.49	6.8	Anaerobic	NO3	-36.3	0.24	1.21	0.234	1.18	11.1	31-Oct-00	OW2-2-CON
OW2-6-DPT	02-Nov-00	200.5	5.84	1.9	0.301	0.00	18.3	Aerobic	Aerobic	-65.2	0.51	0.04	0.266	1.40	13.5	03-Nov-00	OW2-6-CON
OW2-6-DPT	02-May-01	131.4	2.04	0.71	0.62	0.02	39.2	Aerobic	Anaerobic	-50.1	1.37	0.82	0.510	5.26	25.4	02-May-01	OW2-6-CON
OW2-6-DPT	27-Jul-01	126.7	1.17	0.61	0.752	0.02	32.6	Aerobic	Anaerobic	-111	0.42	0.38	0.426	5.86	40.8	24-Jul-01	OW2-6-CON
RAP2-2T-DPT	01-Nov-00	-56.2	0.48	0.015	0.427	0.00	15.9	Anaerobic	Anaerobic	-131	0.64	0.02	0.580	0.07	17.0	01-Nov-00	RAP2-2T-CON
RAP2-2T-DPT	01-May-01	111.1	2.94	0.02	0.463	0.02	20.7	Aerobic	Aerobic	102.6	1.73	0.06	0.082	0.04	10.7	01-May-01	RAP2-2T-CON
RAP2-2T-DPT	25-Jul-01	85.1	1.8	0.02	0.0938	0.02	29.9	Aerobic	Anaerobic	45.7	0.28	0.08	0.045	0.02	10.8	25-Jul-01	RAP2-2T-CON
RFW-11-DPT	02-Nov-00	185.2	4.14	0.64	0.0862	0.01	15.7	Aerobic	Aerobic	211.7	11.43	0.72	0.007	0.00	17.2	02-Nov-00	RFW-11-CON
RFW-11-DPT	02-May-01	150.5	11.4	3.81	0.0034	0.02	27.7	Aerobic	Aerobic	143.3	11.12	3.84	0.013	0.02	26.6	02-May-01	RFW-11-CON
RFW-11-DPT	26-Jul-01	131.3	8.55	3.19	0.0075	0.02	20.3	Aerobic	Aerobic	150.7	8.72	1.95	0.002	0.02	18.3	26-Jul-01	RFW-11-CON
Data from Tyndall AFB																	
MW-1-P15	08-Dec-00	-60.4	-0.19	0.015	0.242	1.22	11.1	Anaerobic	Anaerobic	-10.1	0.04	0.10	0.123	2.99	22.5	08-Dec-00	MW-1-C
MW-1-P15	23-May-01	-142.1	0.17	0.02	0.0026	0.13	4.1	Anaerobic	Anaerobic	-156.6	-0.03	0.02	0.010	0.45	4.7	23-May-01	MW-1-C
MW-1-P15	22-Aug-01	-138.2	0.21	0.077	0.0023	0.10	4.0	Anaerobic	NO3	-153.1	0.27	1.47	0.009	0.18	24.9	22-Aug-01	MW-1-C
MW-2-P15	22-May-01	125.6	0.68	0.55	0.0066	1.06	9.9	Aerobic	Anaerobic	-138.1	-0.07	0.02	0.006	0.96	3.9	22-May-01	MW-2-C
MW-2-P15	23-Aug-01	-84.3	0.45	0.078	0.0046	0.90	6.4	Anaerobic	Anaerobic	-104.9	-0.13	0.09	0.005	0.92	2.5	23-Aug-01	MW-2-C
MW-5-P15	11-Dec-00	64.9	0.02	1.14	0.0153	1.50	17.1	NO3	NO3	80.9	0.06	3.92	0.003	3.24	28.2	11-Dec-00	MW-5-C
MW-5-P15	21-May-01	138.3	0.55	0.78	0.0067	0.02	13.6	Aerobic	Aerobic	165.7	2.01	3.66	0.0003	0.02	26.5	21-May-01	MW-5-C
MW-5-P15	21-Aug-01	69	0.8	3.31	0.0029	0.02	10.8	Aerobic	Aerobic	152.5	3.42	6.88	0.0003	0.02	22.4	21-Aug-01	MW-5-C
MW-8-P15	11-Dec-00	69.8	0.01	0.8	0.0511	1.79	15.1	NO3	NO3	127.4	0.01	1.26	0.010	1.49	17.1	11-Dec-00	MW-8-C
MW-8-P15	21-May-01	60.3	2.46	1.08	0.0037	0.02	13.8	Aerobic	Aerobic	99.5	1.45	0.86	0.003	0.02	13.2	21-May-01	MW-8-C
MW-8-P15	21-Aug-01	42.4	0.33	1.18	0.009	0.02	12.5	NO3	NO3	145.7	0.4	1.52	0.002	0.04	14.0	21-Aug-01	MW-8-C
MW-9-P15	07-Dec-00	-18.2	-0.05	0.015	0.403	1.18	17.6	Anaerobic	Anaerobic	-31	-0.01	0.058	0.359	1.42	28.5	07-Dec-00	MW-9-C
MW-9-P15	22-May-01	-97.5	0.12	0.02	0.073	0.73	29.4	Anaerobic	Anaerobic	-119.5	0.08	0.02	0.005	0.46	21.6	22-May-01	MW-9-C
MW-9-P15	23-Aug-01	67.2	0.5	0.02	0.0151	0.32	18.2	Aerobic	Aerobic	143.8	0.69	0.072	0.005	0.10	27.5	23-Aug-01	MW-9-C
MWD-9-P15	12-Dec-00	6.6	-0.01	0.072	0.136	2.05	19.6	Anaerobic	Anaerobic	33.6	-0.01	0.054	0.554	2.16	25.6	12-Dec-00	MWD-9-C
MWD-9-P15	23-May-01	-128.7	0.53	0.02	0.0108	0.28	17.9	Indeterminate	Indeterminate	-45	0.62	0.02	0.001	0.26	25.6	23-May-01	MWD-9-C
MWD-9-P15	20-Aug-01	61.9	0.37	0.053	0.0042	0.14	22.2	Indeterminate	Anaerobic	41.8	0.35	0.079	0.001	0.18	26.5	20-Aug-01	MWD-9-C
MWD-11-P15	12-Dec-00	-36.1	-0.14	0.11	0.345	2.75	13	Anaerobic	Anaerobic	-23.6	-0.09	0.078	0.153	2.25	17.9	12-Dec-00	MWD-11-C
MWD-11-P15	23-May-01	-157.8	0.85	0.02	0.0055	0.15	4.5	Anaerobic	Anaerobic	-88.1	0.26	0.02	0.002	0.11	21.5	23-May-01	MWD-11-C
MWD-11-P15	20-Aug-01	-72.5	0.31	0.051	0.0048	0.17	18.1	Anaerobic	Anaerobic	12.4	0.32	0.043	0.003	0.08	18.5	20-Aug-01	MWD-11-C
T6-5-P15	08-Dec-00	-150.7	-0.17	0.015	0.0541	4.40	2.4	Anaerobic	Anaerobic	-160.1	-0.1	0.02	0.033	4.77	7.2	08-Dec-00	T6-5-C
T6-5-P15	22-Aug-01	-203.9	-0.02	0.05	0.0578	0.69	3.7	Anaerobic	Anaerobic	-199.2	-0.07	0.02	0.057	0.05	1.9	22-Aug-01	T6-5-C

Notes:

- Numerical values in italics indicate solute was not detected above analytical detection limits. For these measurements, a value equal to one-half the analytical detection limit was assigned.
- ORP = oxidation-reduction potential; DO = dissolved oxygen; NO3 = nitrate; Mn2+ = manganese(II); Fe2+ = ferrous iron; SO4 = sulfate; TEAP = terminal electron acceptor

FIGURE 4.12
BTEX CONCENTRATIONS ALONG A FLOW PATH AT SITE 56, MACDILL AFB (MAY 1995)

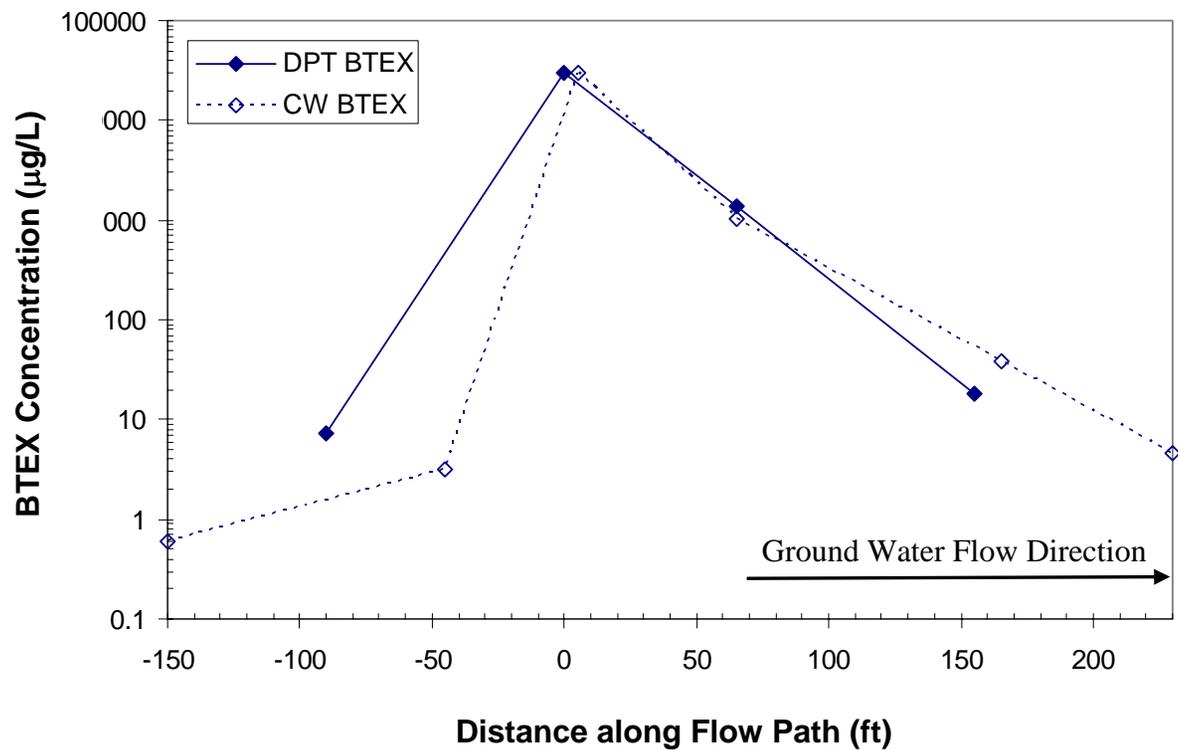
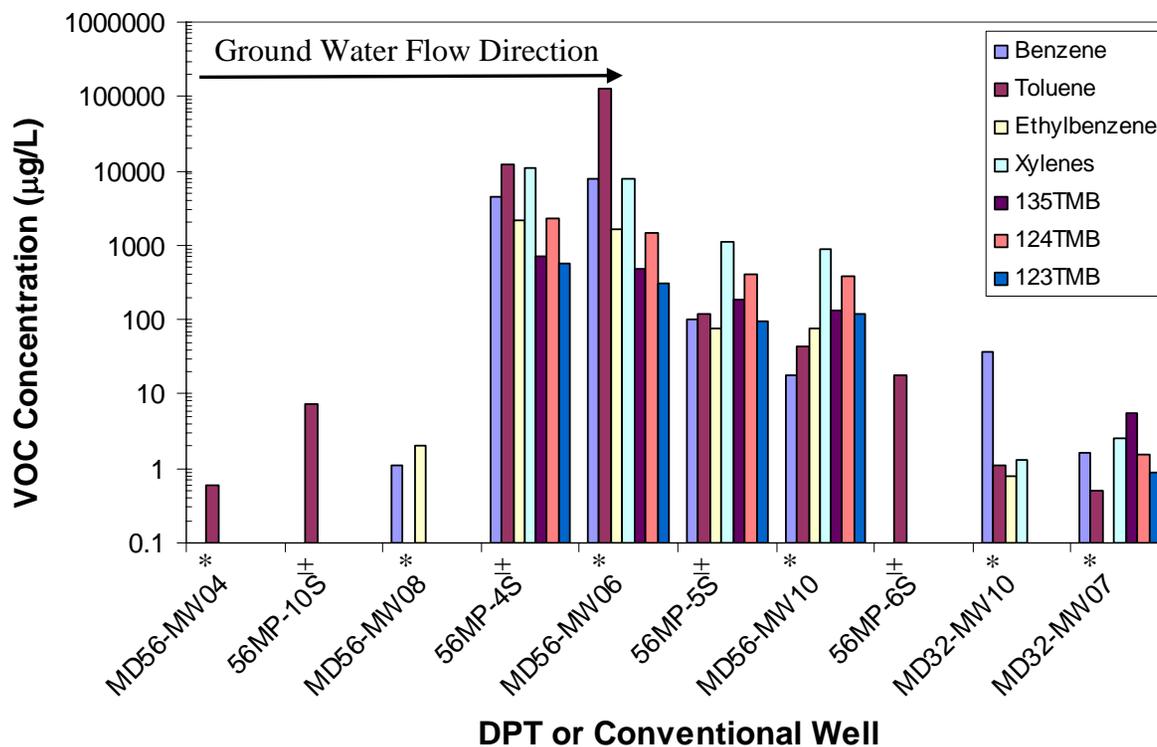


FIGURE 4.13
PETROLEUM HYDROCARBON CONCENTRATIONS IN SELECTED WELLS AT SITE 56, MACDILL AFB (MAY 1995)



Notes: 1. * Indicates conventional well; ± indicates DPT well
 2. TMB = trimethylbenzene

FIGURE 4.14
DISSOLVED OXYGEN (DO) CONCENTRATIONS ALONG A FLOW PATH
AT SITE 56, MACDILL AFB (MAY 1995)

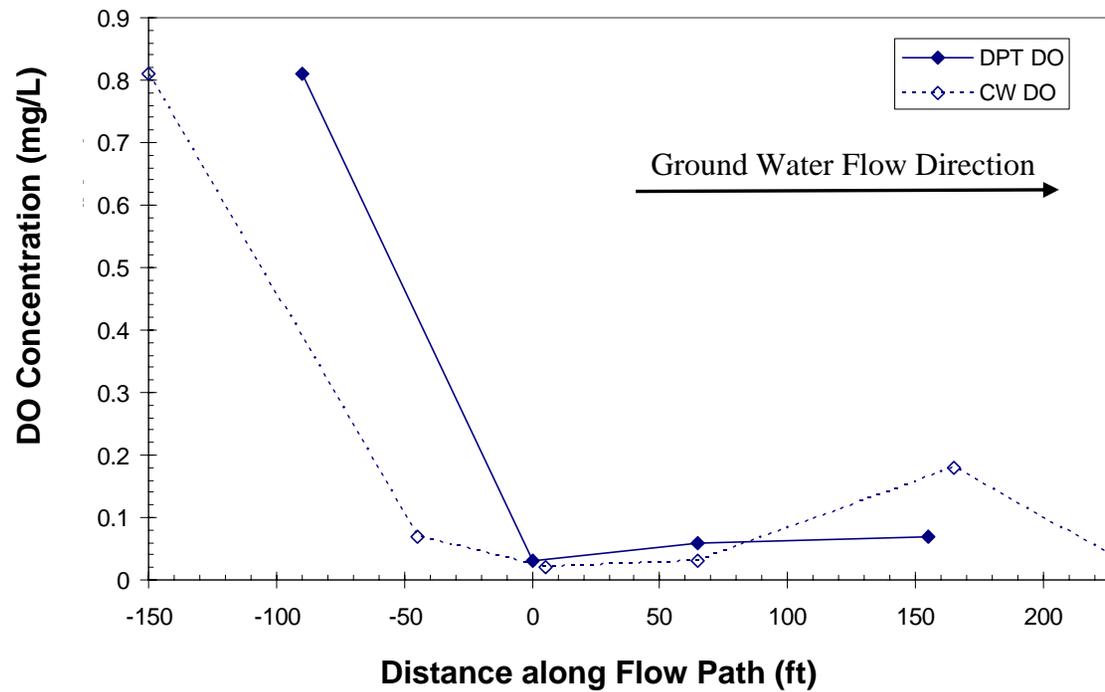


FIGURE 4.15
OXIDATION-REDUCTION POTENTIAL (ORP) VALUES ALONG A FLOW PATH AT SITE 56,
MACDILL AFB (MAY 1995)

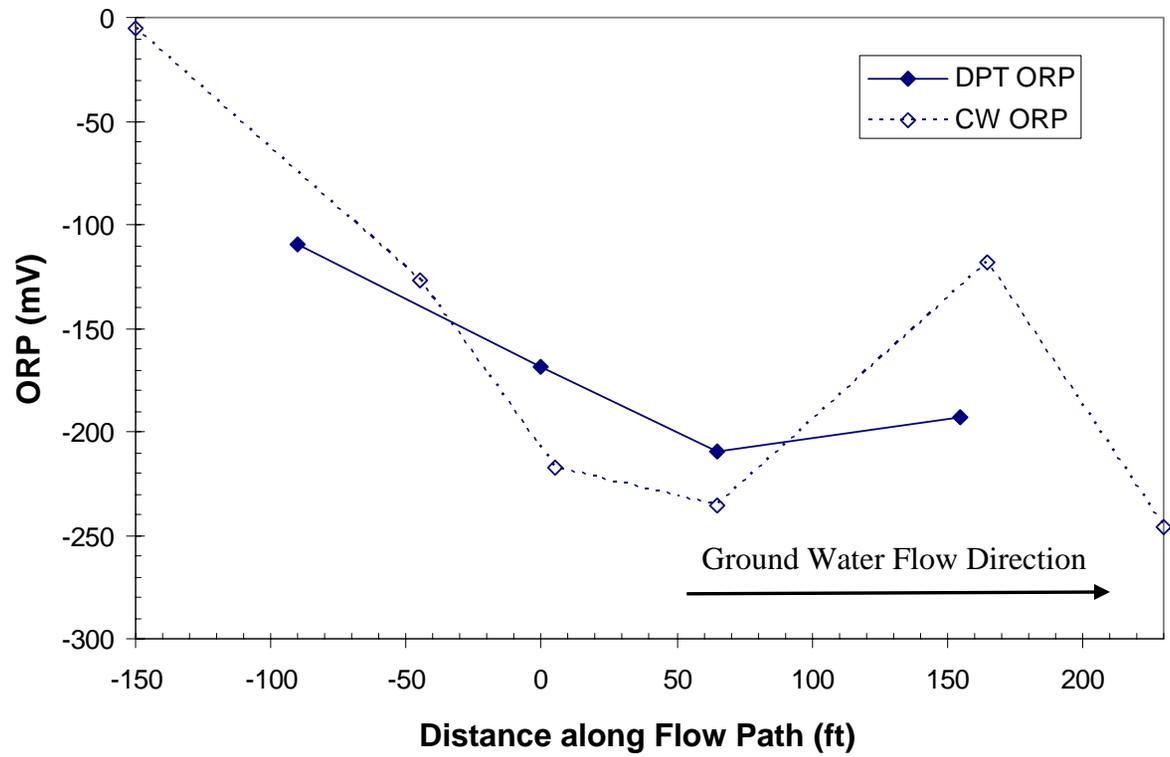
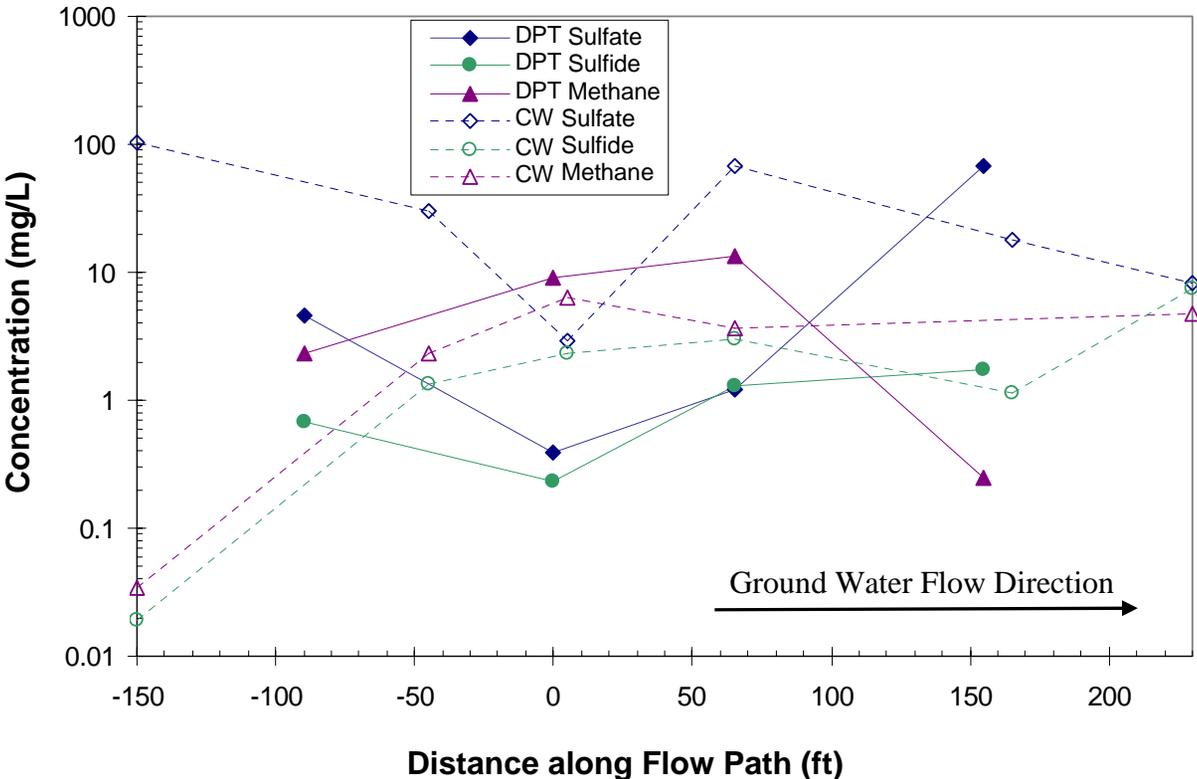


FIGURE 4.16
SULFATE, SULFIDE, AND METHANE CONCENTRATIONS ALONG A FLOW PATH AT
SITE 56, MACDILL AFB (MAY 1995)



conventional wells. This physical difference in well completion makes the observed similarity of petroleum compound concentrations even more remarkable, as preferential sampling of shallower (and presumably higher contaminant concentration) ground water in the DPT wells might have been expected to lead to higher overall petroleum hydrocarbon concentration measurements than would be measured in the longer-screened conventional wells. In terms of overall MNA assessment, however, evaluators of MNA data would not be expected to find any significant difference between VOC concentrations in the different well types installed at this site.

Geochemical indicator data and the identification of dominant TEAPs at Site 56 were also evaluated as part of this study. As described below, available data on redox indicator parameters suggests that the dominant TEAP within the contaminant plume is sulfate reduction and/or methanogenesis. For the purposes of this study, the importance of this finding is that geochemical data from both conventional and DPT wells resulted in the identification of similar trends and conditions in the inferred dominant TEAPs along the selected flow path for Site 56. Although trends and conditions in the local TEAP were generally consistent between well types, it is also important to recognize that there are observable local variations in redox indicator measurements and/or TEAP interpretation between well types.

Dominant TEAP conditions were identified using the redox indicator measurements along the selected ground water flow path. DO concentrations (Figure 4.14) indicate that the two most upgradient wells (conventional well MD56-MW04 and DPT well 56MP-10S) are slightly aerobic, whereas all other wells indicate anaerobic conditions. Although, the observation of negative ORP measurements (Figure 4.15) in all wells suggests anaerobic conditions along the entire contaminant flow path, the observation of elevated DO (Figure 4.14) and sulfate concentrations (Figure 4.16), combined with the absence of both sulfide and methane in MD56-MW04 suggests that background ground water conditions are mildly aerobic. Nitrate, ferrous iron, and manganese(II) concentrations were universally low, and therefore were not graphed (see Appendix B for reported values). Low nitrate concentrations (maximum concentration = 0.99 mg/L) suggests that nitrate is not present at this site in sufficient concentrations to act as significant TEAP. Low concentrations of manganese(II) (maximum concentration = 0.4 mg/L) and ferrous iron (concentrations less than 0.6 mg/L at all but two locations), the reaction end products of manganese- and iron-reduction, respectively, suggest that these biodegradation processes occur in isolated locations, and are generally not significant TEAPs at this site.

Sulfate, sulfide, and methane concentrations are plotted on Figure 4.16. As shown on this figure, the lowest sulfate concentrations are within the center of the contaminant plume, with higher concentrations both upgradient and within the downgradient edges of the plume. For sulfide and methane (reaction end products of sulfate-reduction and methanogenesis, respectively), concentrations are low in upgradient locations, generally highest in the center of the plume, and elevated above background at downgradient locations within the contaminant plume. The occurrence of decreased sulfate concentrations (relative to background) and elevated sulfide concentrations within the plume suggests that sulfate-reduction is occurring, or has occurred, across much of the site. In locations where sulfate is still available for reduction, sulfate-reduction is likely to be the dominant TEAP in these areas. In the center of the plume where sulfate has been depleted and methane concentrations

are elevated (i.e., MD56-MW06 and 56MP-5S), methanogenesis is the most likely TEAP. It appears that methanogenic conditions are also the dominant TEAP in the most downgradient well (MD32-MW07), but this may be due to influences of contamination from an adjacent release site and/or normal variations in site geochemistry and hydrogeology which may cause the TEAP condition to periodically switch between sulfate reduction and methanogenesis.

Although overall TEAP trends at this site were generally consistent between well types, it was possible to use available data to provide limited insight on local variations of inferred TEAP conditions. An example of observed differences in geochemical indicators at a given location can be found by comparing results from DPT wells 56MP-5S (shown on Figure 3.3) and 56MP-5D (colocated with 56MP-5S) with results from conventional well MD56-MW10 (shown on Figure 3.3). These three wells are located within close proximity to each other, with the screen intervals of DPT wells 56MP-5S and 56MP-5D corresponding to the top and bottom portions, respectively, of the single screen interval of MD56-MW10. Table 4.6 lists screen intervals and selected geochemical indicator parameters for 56MP-5S, 56MP-5D, and MD56-MW10. A review of DO, nitrate, ferrous iron, and ORP measurements indicates that these measurements are virtually identical between these three wells, with values that suggest that redox conditions are reducing (anaerobic) with a dominant TEAP of either sulfate-reduction or methanogenesis. A review of sulfate, sulfide, and methane data suggests that the dominant TEAP in the shallow ground water sampled from 56MP-5S (low sulfate concentration, high methane concentration) is methanogenesis, while the TEAP in the slightly deeper ground water sampled from 56MP-5D (high sulfate, high sulfide, low methane) is more likely to be sulfate-reduction. A review of total BTEX concentrations for these two wells provides an explanation for this observed difference in redox condition in that the continued presence of BTEX in 56MP-5S suggests that sufficient electron donor (i.e., BTEX) is present to consume available sulfate and produce methanogenic conditions, whereas the absence of BTEX in 56MP-5D suggests that there is insufficient electron donor reaching ground water that flows into this well to completely overcome the available supply

**TABLE 4.6
WELL SCREEN INTERVAL AND REDOX INDICATOR DATA FOR SELECTED
WELLS AT SITE 56, MACDILL AFB**

Measured Parameter (Units)	Well Name		
	56MP-5S	56MP-5D	MD56-MW10
Screen Interval (feet bgs)	2.0 – 7.0	10.0 – 10.5	3.0 – 12.0
Total BTEX (µg/L)	1305	ND	1018
DO (mg/L)	0.06	0.03	0.03
Nitrate (mg/L)	0.08	ND	ND
Ferrous Iron (mg/L)	0.36	0.34	0.17
Sulfate (mg/L)	1.2	50.4	68.6
Sulfide (mg/L)	1.3	3.1	3.0
Methane (mg/L)	13.6	0.6	3.7
ORP (mV)	-210	-235	-236

- Notes: 1. Total BTEX = Total concentration of benzene, toluene, ethylbenzene, and xylene isomers; DO = dissolved oxygen; ORP = oxidation-reduction potential; bgs = below ground surface; ND = measurement below analytical method detection limit
2. 56MP-5S and 56MP-5D installed using DPT; MD56-MW10 installed using conventional drilling.

of sulfate as an electron acceptor. Results for sulfate, sulfide, and methane in the water sample from MD56-MW10 indicate a mixture of sulfate-reducing and methanogenic conditions in that sulfate and sulfide concentrations are relatively high (indications of continuing sulfate-reduction), but methane concentrations are also relatively high (indication of methanogenesis). The conclusion that a 'mixture' of TEAP conditions appears to be present in conventional well MD56-MW10 is consistent with the DPT well data from the 56MP-5S/5D cluster in that ground water sampled from MD56-MW10 can be expected to represent a mixture of ground water chemistry across from the entire screened interval of MD56-MW10.

In summary, the Site 56, MacDill AFB DPT and conventional wells generally provide a consistent interpretation of the dominant TEAP conditions at this site despite differences in well screen length and off-sets from a common flow line. The data clearly show similar VOC concentration trends, and redox conditions that transition from mildly aerobic (upgradient of the plume) through sulfate-reducing and methanogenic conditions within and immediately downgradient of the plume. Data from two DPT and one conventional well located in close areal proximity at this site suggests that well screen depth may introduce differences in TEAP interpretation that are more significant than the differences in TEAP interpretation that could be caused by different well construction methods.

SECTION 5

DISCUSSION AND CONCLUSIONS

The goal of this study was to evaluate whether monitoring wells installed using DPT provide ground water chemical data that is of comparable data quality to conventionally-installed wells at sites where NA of dissolved petroleum hydrocarbons and/or chlorinated solvents is being evaluated and/or monitored. The primary method used to answer the questions posed in this study was to analyze existing data sets from various USAF facilities to determine if colocated conventional and DPT well pairs yielded statistically equivalent data. In cases where data for a given parameter supported the conclusion that conventional and DPT wells were not statistically similar, data were evaluated qualitatively to determine if the observed differences might be expected to lead to a change in conclusions about MNA. A second method used to evaluate whether data collected from conventional and DPT wells are comparable was to review data sets from USAF facilities where DPT wells had been installed to supplement existing conventional wells (i.e., the DPT and conventional wells were not colocated) to assess whether a combination of conventional and DPT wells installed along the contaminant flow path yielded results that were reasonably consistent over space.

The efforts of the current study lead to several conclusions that are relevant to providing a technical basis for using DPT wells either in conjunction with, or in lieu of, conventional wells. Using data collected by Farrington *et al.* (2003), chloroethene concentration data from colocated conventional and DPT well pairs were shown to be statistically equivalent. This finding of statistical equivalence provides scientific evidence that DPT and conventional monitoring wells can be used to collect ground water samples that yield chloroethene concentration data of equal quality. This finding of statistical equivalence for chloroethene concentrations is also consistent with statistical analysis performed by Farrington *et al.* (2003), with the current study offering the advantage of increased certainty in these results. The increased certainty of results in the current study is quantified by a general increase in statistical power that was achieved by increasing data set size through combination of data sets collected from both 1.5-inch and 2-inch DPT wells. Additional analysis of chloroethene concentrations in the Farrington *et al.* (2003) data set also supported the conclusion that chloroethene concentration data was functionally equivalent between well type in that there was an approximately equal occurrence of below detection measurements in one well type but detectable concentrations in the other well type. Furthermore, variation of chloroethene concentration within a well pair was found to be less than one order of magnitude in more than 72 percent of measured cases. It was interesting to note, however, that when chloroethene concentrations differed by more than an order of magnitude between well pair samples, it was three times more likely that the concentration in the DPT well was higher than the concentration in the conventional well.

For petroleum hydrocarbons, the results of statistical analysis performed in this study confirmed previous findings Farrington *et al.* (2003) and BP Corporation and USEPA (2002) in that concentrations of petroleum compounds in DPT wells were found to be statistically different (i.e., greater) than concentrations measured in conventional wells. Analysis of petroleum hydrocarbon data from the Farrington *et al.* (2003) study indicated that individual BTEX concentrations varied less than one order of magnitude in more than 63 percent of the well pairs. However, in the cases where there was more than one order of magnitude of variation between BTEX concentrations in a well pair, DPT wells were more than four times as likely to be the well type where the higher concentration was found. In addition, it was twice as likely to find a detectable BTEX concentration in a DPT well when the corresponding conventional well sample was below detection as it was to find the opposite case of a detectable BTEX concentration in a conventional well when the DPT well was below detection.

Various theories have been postulated to explain observations of higher petroleum hydrocarbon concentrations in DPT wells relative to conventional wells. Some researchers have suggested that insufficient well development and/or the absence of a filter pack results in a turbidity-induced effect on data quality. Analysis performed as part of the current study suggests that turbidity is not the governing factor because high turbidity in one well type did not consistently correspond with higher or lower VOC concentrations. This conclusion is consistent with experiments performed by Paul and Puls (1997) that found turbidity does not consistently impact chloroethene concentrations. Another possibility is that the act of driving a DPT well using techniques that expose the well screen to soil (i.e., placing the well screen on the outside, rather than inside, of the driving rod) could cause petroleum-impacted soils to become lodged within the well screen if the well is driven through a section of aquifer material that a “smear” zone that contains contaminated soils and/or residual free product. If this is the case, elevated petroleum compounds would be expected only in DPT wells installed through a smear zone and in manner that exposes the screen to the smeared product. Note that the researchers in the Farrington *et al.* (2003) study attempted to minimize contaminant concentration measurements that were below detection by installing wells in locations where VOC concentrations were anticipated to be above analytical method detection limits, while simultaneously trying to avoid potential problems with contaminated soils from the unsaturated zone becoming lodged within the screen of the unpacked DPT wells during installation by avoiding areas thought to contain light non-aqueous phase liquid (LNAPL). In spite of these efforts, it may be possible that some of the wells were installed through smear zones of residual LNAPL, thereby causing the observed elevated concentrations of petroleum hydrocarbons in the Farrington *et al.* (2003) data. Based on the information available for the current study, it is not possible to confirm or refute this theory.

For redox and other geochemical indicator parameters, results of statistical testing for individual parameters and qualitative examination of likely TEAP conditions led to a conclusion that data obtained from DPT and conventional wells generally provide data that are functionally equivalent. This conclusion is supported by both statistical analysis of individual parameters and qualitative analysis on how often the combined results of geochemical data would lead to the selection of the same TEAP for colocated wells. Specifically, all individual redox indicator measurements, except manganese, were shown to be statistically similar between well types. Of the other ground water indicators, temperature and potassium were also determined to be statistically equivalent, but sodium and pH were

not. The results of a more qualitative assessment of functional equivalence of redox parameters between well type, based on interpreted TEAP condition for 46 colocated well pair measurements performed as part of the Farrington *et al.* (2003) study, suggested that the same TEAP was indicated in nearly 80 percent of the well pairs.

The current study also attempted to identify several case study sites that could be used to examine whether monitoring well type had an observable effect on MNA assessment. Based on a review of available data for 15 USAF sites, only one site was identified that had a comparable distribution of well types along a defined contaminant flow path. The results of data review for this site (Site 56, MacDill AFB) concluded that well type does not appear to affect MNA assessment in this case. Specifically, this case study found that both VOC (petroleum hydrocarbon) concentrations and TEAP identification would lead to similar conclusions regarding the site-specific effectiveness of MNA. The observed similarity in petroleum hydrocarbon concentrations between well types was of particular interest, as this finding was in contradiction to the statistical differences documented in the statistical analyses of this and other previous studies on the effect of well type on measured petroleum hydrocarbon concentrations. Data from three wells (one conventional and two DPT) located in close areal proximity at this site confirm previous observations by others (e.g., Hurt *et al.*, 2001) that differences in the length and depth of the well screen can exert a significant influence on measured VOC concentrations. Furthermore, VOC and redox indicator data from these three wells suggests that the choice of well screen interval (i.e., length and depth) can produce differences in observed VOC concentrations and interpreted TEAP condition that are more significant than the differences caused by variation in well construction method. Given the current state of knowledge and uncertainty on whether DPT installation through zones of soil contamination may lead to artificially high concentrations of petroleum hydrocarbons in samples collected from these wells, it is recommended that measures be taken during DPT installation to prevent the DPT well screen from coming into direct contact with soils that may contain residual LNAPL, that vigorous well development (comparable with that typically used following well installation using conventional techniques) be performed following DPT well installation, and that proper well-purging procedures be followed immediately prior to sampling. Note that current DPT well installation technology allows well screens to be installed from inside the push rod. By installing the DPT well inside the push rod, the likelihood that DPT well screen will come into contact with contaminated soils during installation is greatly reduced. Therefore, DPT well installations at locations where soil contamination is known or suspected to be present above the desired well screen installation depth should be performed using 'protected screen' techniques.

In terms of areas for further study, the findings of this report could be strengthened if the case study assessment that was performed on the Site 56, MacDill AFB data could be repeated using data sets from other sites where a combination of DPT and conventional wells have been installed and sampled along a contaminant flow path. Ideally, these additional case studies would include a variety of hydrogeologic conditions and contaminant types. Although this type of data may seem readily available for multiple sites, the authors of the current study found that data from only one of 15 USAF sites where a combination of DPT and conventional wells was installed and sampled was appropriate for the analysis method used in this study. In addition, a study that is specifically designed to collect data for quantifying the impact of local heterogeneity on VOC concentration and redox indicator measurements through the use of closely-spaced, identically-installed conventional wells is

recommended. Although local spatial and temporal variations are likely to affect MNA assessments (e.g., Hurt *et al.*, 2001), the authors of the current study are unaware of published research which quantifies the statistical differences in VOC or redox indicator parameter measurements on a scale that could be used to evaluate whether the differences and similarities between well types observed in the Farrington *et al.* (2003) data set are comparable with the variability that may be present in colocated well pairs that were installed using identical well construction techniques. Considering that other studies have demonstrated significant local variation in contaminated soil and discrete ground water sample concentrations (e.g., Libelo *et al.*, 1997; Schumacher and Minnich, 2000; Hurt *et al.*, 2001), a study designed specifically to quantify statistical variation in ground water chemical concentrations in identically-installed, colocated conventional wells may be able to support a statistical demonstration that local heterogeneity in contaminant distribution will, at many sites, cause variations in observed contaminant concentrations that are as large or larger than have been observed in colocated conventional and DPT well pairs described in this and other studies.

In summary, the results of this study provide strong evidence that DPT and conventional wells can be used interchangeably for assessing and/or monitoring MNA of chloroethenes and for evaluating local TEAP conditions at both petroleum hydrocarbon and chlorinated solvent sites. The results of this study are inconclusive, however, with respect to the interchangeable use of DPT wells and conventional wells at petroleum hydrocarbon sites. Because results of statistical analysis in this and other previous studies suggests that samples collected from DPT wells are more likely to have higher petroleum hydrocarbon concentrations than samples from conventional wells, use of petroleum hydrocarbon concentration data from DPT wells is likely to result in more 'conservative' assessments of MNA than conventional wells if the higher concentrations in DPT wells are more representative of petroleum hydrocarbon concentrations than is currently being realized through the use of conventional wells. If, however, the higher petroleum hydrocarbon concentrations in the DPT wells are an artifact of installation procedures (e.g., entrapment of contaminated soil in the 'smear zone' into the DPT well screen), the use of petroleum hydrocarbon concentration data from DPT wells may be inappropriately conservative for MNA assessment and/or performance monitoring.

SECTION 6

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APPENDIX A

ASSESSMENT OF FARRINGTON *et al.* (2003) DATA

The Farrington *et al.* (2003) data set was closely examined for obvious errors or other indications that data should be excluded from the data set. The following minor errors were discovered and corrected

- two cases of incorrectly paired wells;
- one case of an obvious typographical error in pH and temperature data; and
- a few well pairs where database queries returned multiple results for a single sampling event.

The error in pH data was apparently unobserved by the Farrington *et al.* (2003) research team and accounts for the large mean difference in pH in the 1.5-inch DPT data set reported in that study.

Turbidity data were examined for potential influence on VOC concentration measurements. Turbidity was mentioned by Farrington *et al.* (2003) as potentially impacting the results of the Tyndall AFB unpacked DPT data, and was also a concern for BP Corporation and USEPA (2002). For the current study, all turbidity measurements were plotted, and there was no obvious correlation between outlier data (large difference in DPT and paired conventional well turbidity data) and any particular site (Figure A.1). There were 17 instances where the turbidity in the DPT well differed by either more than 100 nephelometric turbidity units (NTUs) or more than a factor of 10 from the conventional well value. Differences in turbidity values were also investigated by comparing differences in log-transformed benzene, xylene (*m,p*), TCE and *cis*-1,2-DCE concentrations between DPT and conventional wells for well pairs with the greatest differences in turbidity readings (Figure A.2). Note that if the remaining data pairs were plotted in Figure A.2, these points would be clustered along the Y axis because the difference in turbidity values between well types is close to zero. For the data transformation presented on Figure A.2, a negative correlation (i.e., data plotting in the upper left and lower right quadrants) would indicate that higher turbidity is correlated with lower organic contaminant concentrations. Conversely, a positive correlation (i.e., data plotted in the upper right and lower left quadrants) would indicate that higher turbidity is correlated to higher organic contaminant concentrations. Based on a review of data presented on Figure A.2, no obvious trend (positive or negative) was noted, as data plotted in all quadrants. Based on this qualitative analysis, it was concluded that turbidity did not appear to impact VOC concentrations in the Farrington *et al.* (2003) data set, and therefore is not responsible for the statistically higher petroleum hydrocarbon concentrations in the DPT wells. These results are consistent with those of Paul and Puls (1997), who concluded that turbidity does not impact concentrations of TCE, *cis*-1,2-DCE, or VC. In fact, the well pair with the greatest turbidity differences (Hanscom AFB RAP2-2T well pair, data points to the far right of the graph) had no significant differences in VOC concentrations.

Scatter plots for parameters that should be uninfluenced or only weakly influenced by biodegradation processes were examined to look for trends among outlier data. The parameters examined were calcium, magnesium, chloride, sodium, potassium, temperature, pH, and total dissolved solids (TDS). Considering that the DPT and conventional well pairs were installed with screens over comparable depth intervals, it was reasoned that there should

FIGURE A.1
FARRINGTON *et al.* (2003) TURBIDITY RESULTS BY BASE

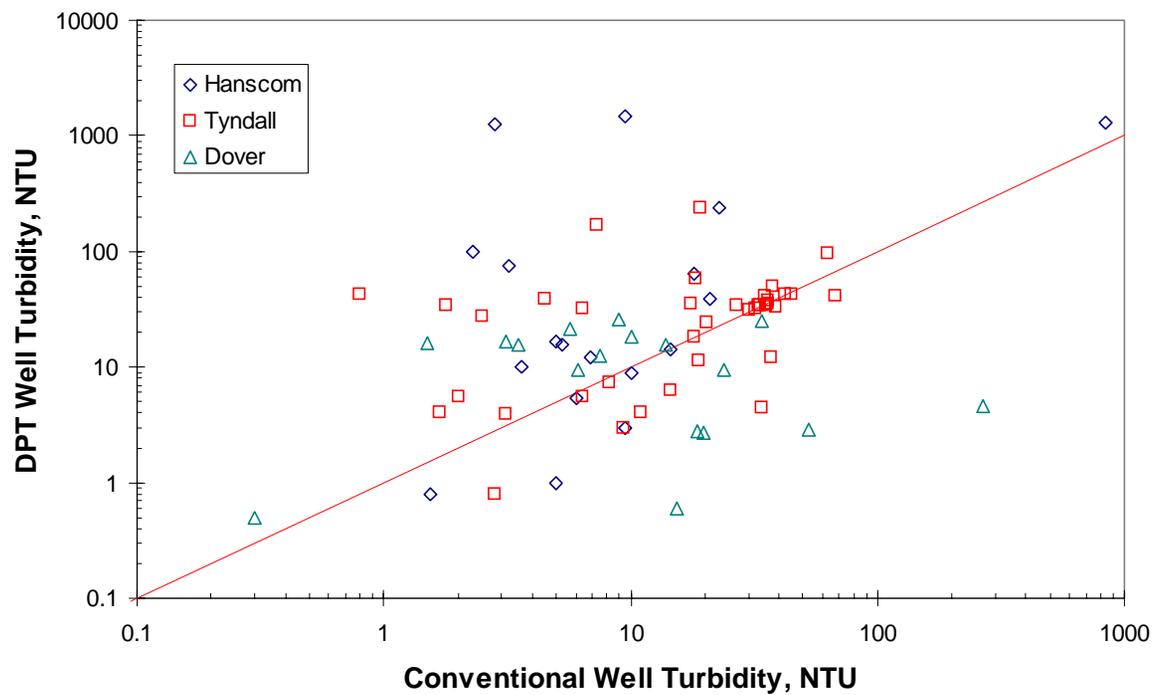
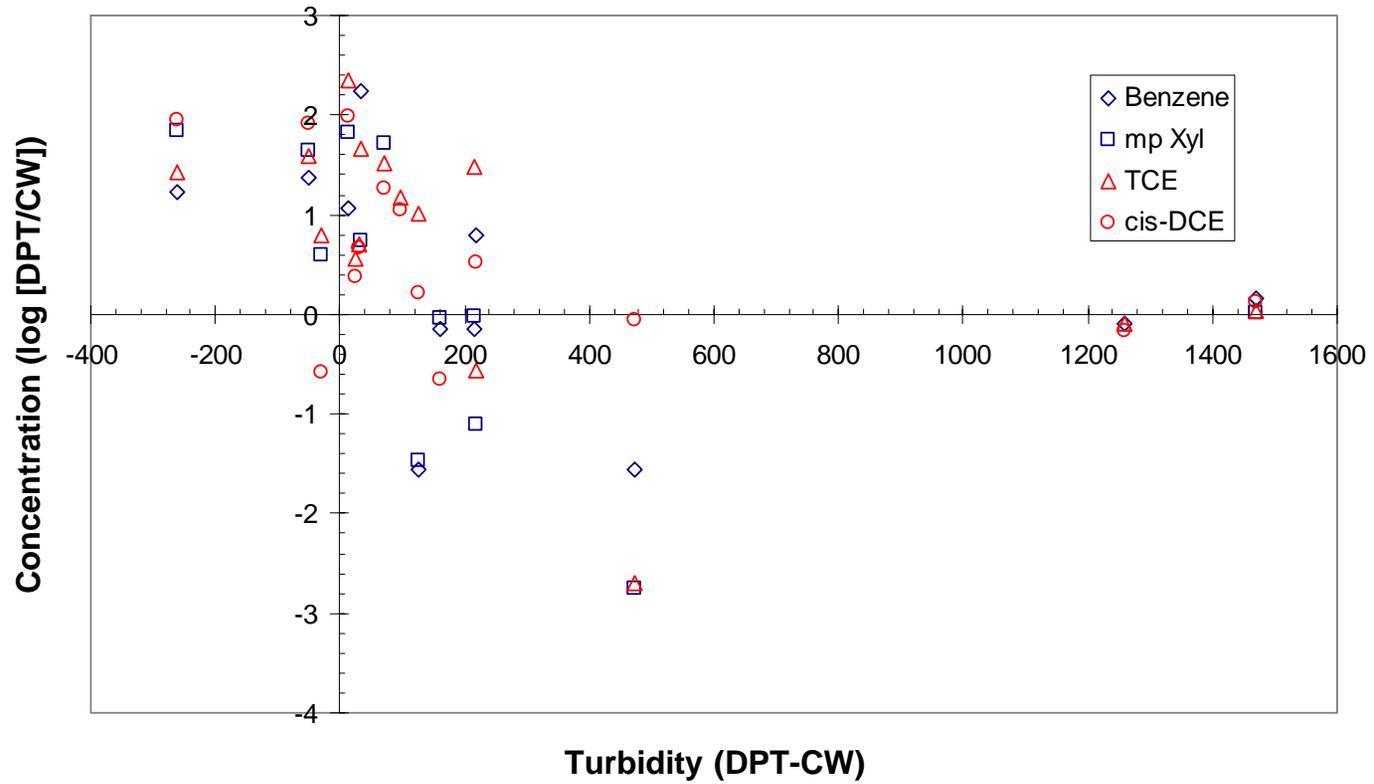


FIGURE A.2
IMPACT OF GREATEST TURBIDITY DIFFERENCES ON VOC CONCENTRATIONS
IN FARRINGTON *et al.* (2003) DATA SET

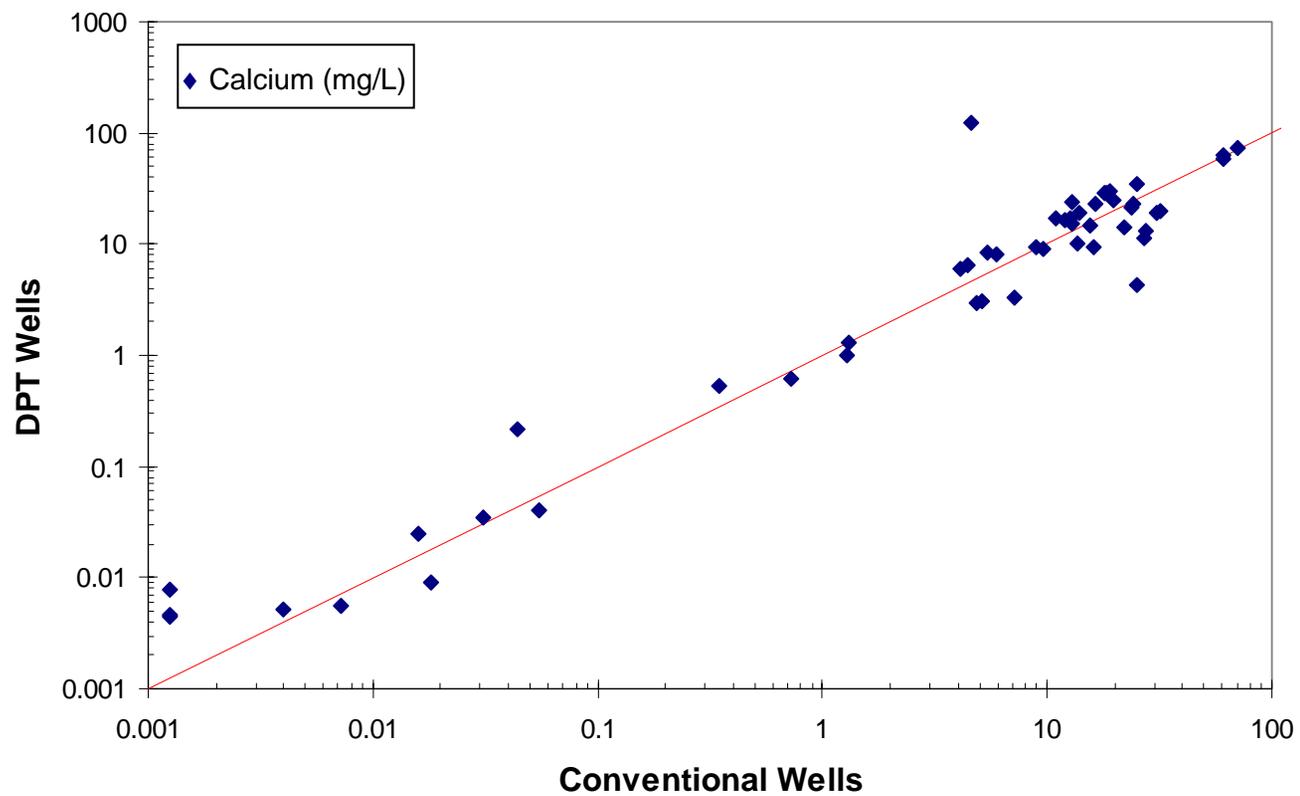


be no significant difference in the values of these parameters because the well pairs should be sampling ground water from roughly the same location. Based on experience with MNA assessments at many sites, and on the knowledge that the aforementioned parameters are not directly involved in electron transfer during VOC degradation, it was assumed that monovalent cations (i.e., sodium and potassium), temperature, and pH were least likely to be affected by geochemical changes caused by biodegradation. Scatter plots for pH, temperature, sodium, and potassium are presented in the main report as Figures 4.1 through 4.4. Scatter plots for calcium, magnesium, chloride, and TDS are presented as Figures A.3 through A.6, respectively. Table A.1 lists the well pairs that were identified as exhibiting potential for outliers in one or more measured parameter. Three well pairs exhibited concentration trends that required further evaluation to determine if data outliers were present:

- For well pair OW2-2-DPT and OW2-2-CON at Hanscom AFB, higher values were measured in the DPT well for calcium, magnesium, chloride, sodium, and TDS. This well pair was sampled only once for inorganic compounds. Therefore, it was impossible to determine if the anomalous results were limited to a single sampling event or if the two wells were actually sampling significantly different ground water. Exclusion of this data point from the sodium data set (along with the RFW-11 well pair discussed below) did not significantly improve the results of hypothesis testing for sodium (described in Sections 3.1.1 and 4.1.1).
- For well pair RFW-11-DPT and RFW-11-CON at Hanscom AFB, higher values were measured in the DPT well for sodium and chloride during the 2 May 2001 sampling event. This well pair was sampled three times for inorganic compounds. Several analytes, including sodium, chloride, calcium, and sulfate, showed increases in concentration during the 2 May 2001 sampling event. Some analyte concentrations increased in both the DPT and conventional wells, while others showed an increase only in the conventional well. The variation in inorganic concentrations in the RFW-11 well pair was attributed to natural fluctuations in ground water quality and was assumed not to indicate significantly different ground water.
- Large variations in pH measurements at the Hanscom AFB RAP2-2T well pair were not observed in the first two sampling rounds, but were observed during the last three events (see Table A.1). The pH results were sufficiently anomalous that measurement errors were initially suspected. However, concentrations of calcium, magnesium, sulfate, and chloride exhibited fluctuations consistent with the pH change (increased concentration for more acidic conditions, decreased concentration for the more alkaline conditions). Because the pH variability was consistent across multiple sampling events and also consistent with some of the inorganic chemical data, the results were assumed to be error free.

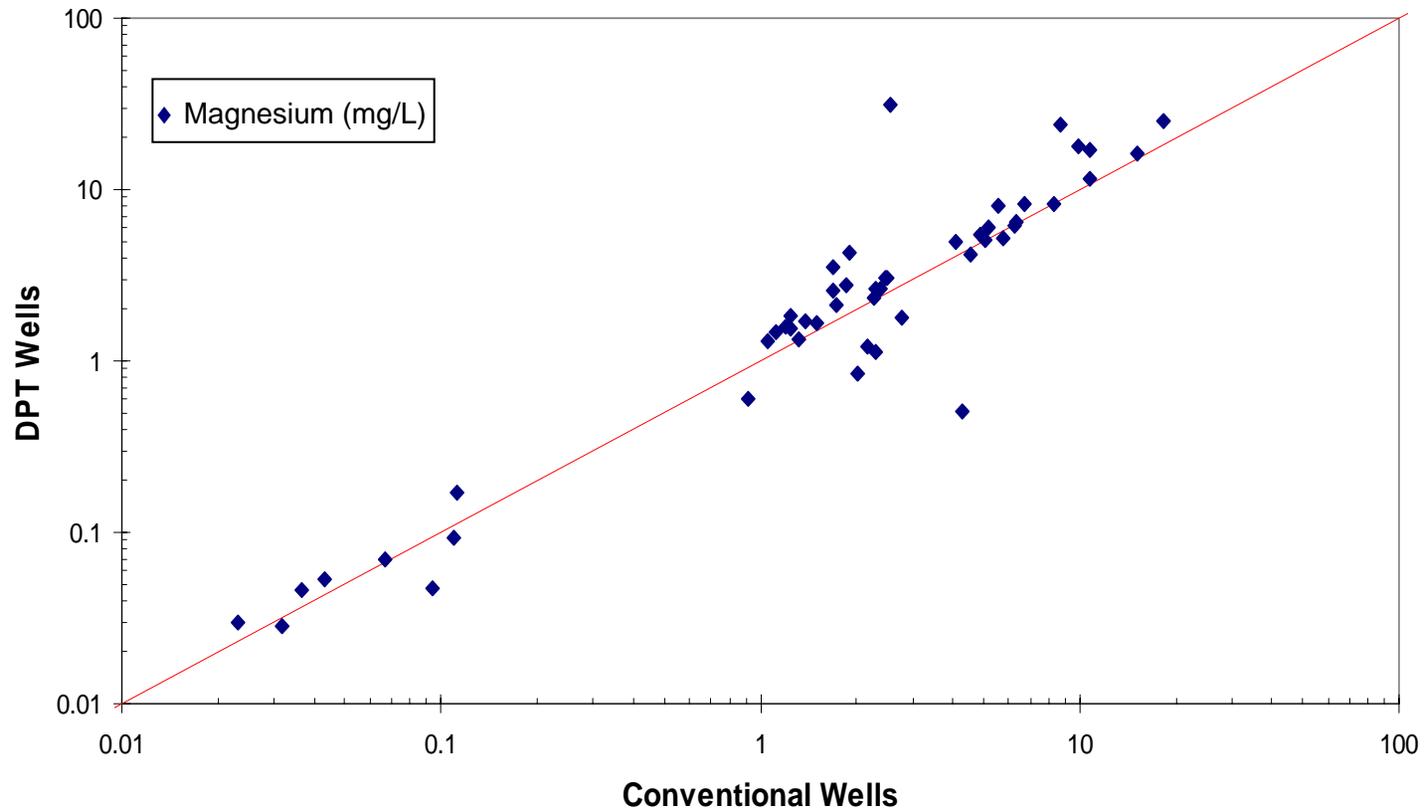
Based on this analysis for obvious data outliers, no data were excluded from the data set prior to performing the statistical or qualitative analyses.

FIGURE A.3
CALCIUM DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



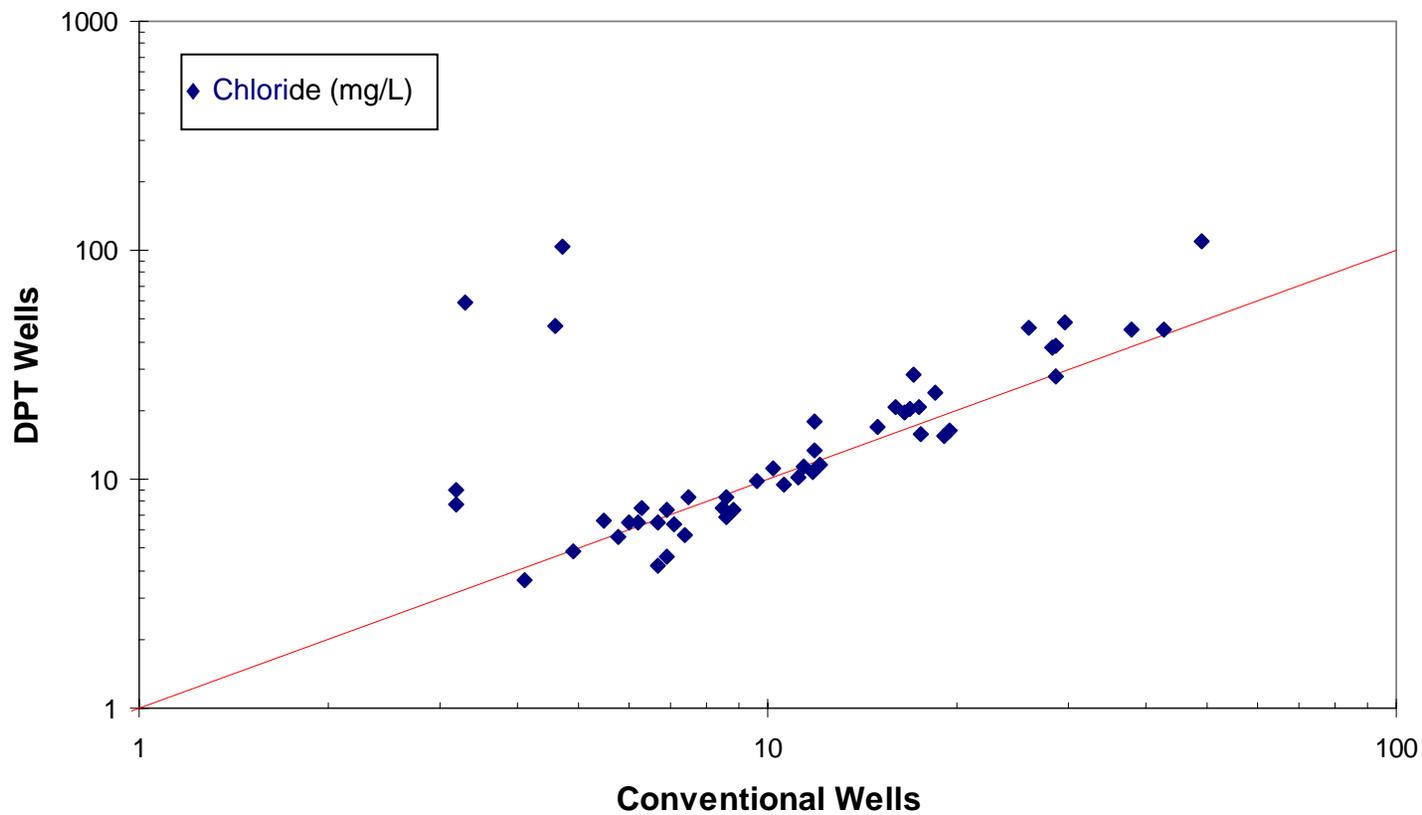
^{a/} Data shown for “DPT Wells” is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE A.4
MAGNESIUM DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



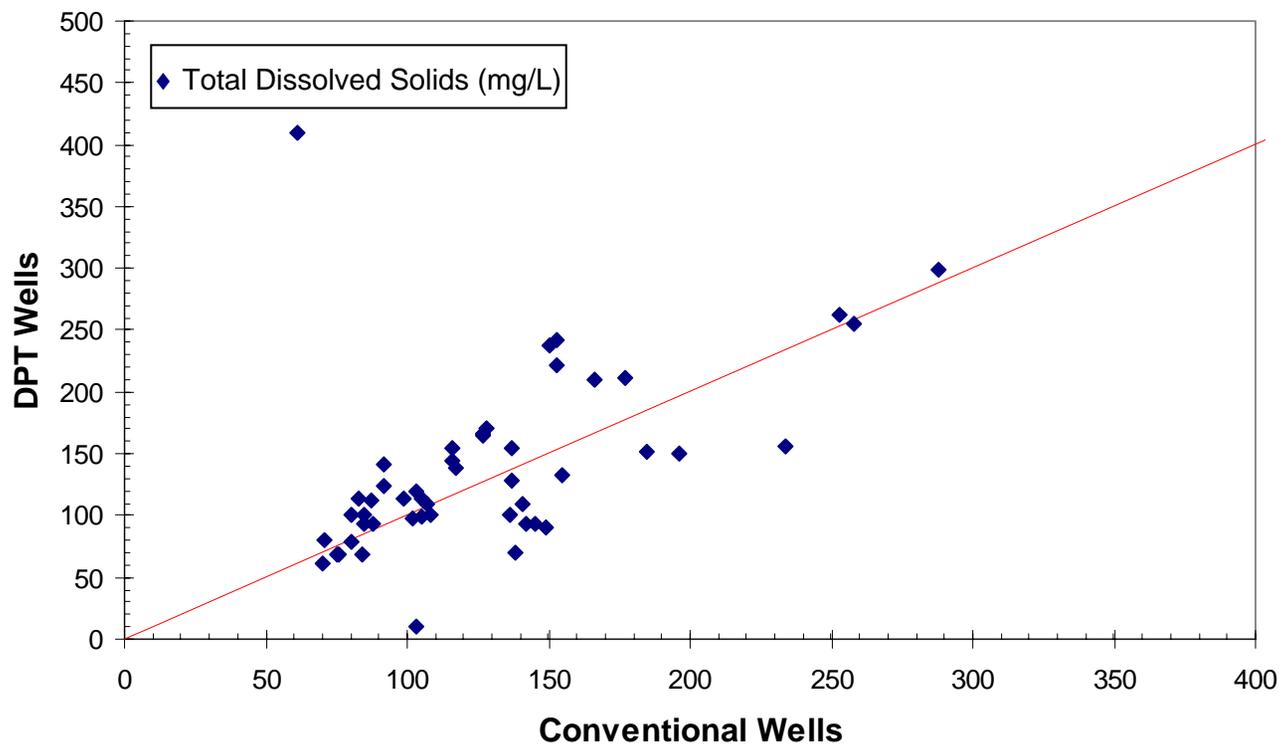
^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE A.5
CHLORIDE DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

FIGURE A.6
TOTAL DISSOLVED SOLIDS DATA COLLECTED FROM DPT ^{a/} AND
CONVENTIONAL WELLS (FARRINGTON *et al.*, 2003)



^{a/} Data shown for "DPT Wells" is from unpacked, 2.0- and 1.5-inch diameter wells.

TABLE A.1
SUMMARY OF POTENTIALLY ANOMALOUS DATA FROM
FARRINGTON *et al.* (2003)

Parameter (Units)	Well Pair	Sampling Date	DPT Value	Conventional Well Value
Calcium (mg/L)	Hanscom OW2-2	31 Oct 2000 ^{a/}	125	4.6
Magnesium (mg/L)	Hanscom OW2-2	31 Oct 2000 ^{a/}	31.4	2.55
	Tyndall MW-1	22 Aug 2001	0.502	4.29
Chloride (mg/L)	Hanscom OW2-2	31 Oct 2000 ^{a/}	103	4.7
	Hanscom RFW-11	2 May 2001	110	49
	Dover 236D	15 Dec 2000	47.1	4.6
	Dover 237S	9 May 2001	59	3.3
Sodium (mg/L)	Hanscom OW2-2	31 Oct 2000 ^{a/}	16.3	1.61
	Hanscom RFW-11	2 May 2001	60	21.4
Potassium (mg/L)	-	-	-	-
Temperature (°C)	Dover 237S	8 Aug 2001	10.24	23.25
pH (Standard Units)	Hanscom RAP2-2T	1 May 2001 ^{b/}	6.12	9.47
	Hanscom RAP2-2T	25 Jul 2001 ^{b/}	5.67	9.38
	Hanscom RAP2-2T	30 Oct 2001 ^{b/}	5.71	9.35
Total Dissolved Solids (mg/L)	Hanscom OW2-2	31 Oct 2000 ^{a/}	409	61
	Dover 337S	7 May 2001	10.3	103

^{a/} Well pair OW2-2 was sampled only once for inorganic parameters.

^{b/} Well pair RAP2-T2 had anomalous pH readings for three of five sampling events. In the other two sampling events, the pH of both wells was between 7.5 and 7.7.

APPENDIX B

**SELECTED DATA FROM MNA ASSESSMENT AT SITE 56,
MACDILL AFB, FLORIDA**

(Source: Parsons, 1996)

TABLE 2.1
MONITORING POINT AND WELL COMPLETION DATA
SITE 56
INTRINSIC REMEDIATION TS
MACDILL AFB, FLORIDA

Well Identification	Installation Date	Northing	Easting	Well Diameter (Inches)	Borehole Diameter (Inches)	Total Depth (ft bgs) ^{a/}	Sandpack Interval (ft bgs)	Screened Interval (ft bgs)	Elevation TOC (ft msl) ^{b/}	Elevation Ground (ft msl)
56MP-1S	3/17/95	1281421.044	498655.269	0.5	2.0	7.0	1.0-2.0	2.0-7.0	7.922	8.072
56MP-2S	3/17/95	1281310.072	498567.034	0.5	2.0	8.0	1.0-3.0	3.0-8.0	8.002	8.096
56MP-3S	3/17/95	1281491.160	498598.739	0.5	2.0	6.0	0.5-1.0	1.0-6.0	6.719	6.752
56MP-3D	3/17/95	1281491.160	498598.739	0.375	1.0	13.5	NP ^{c/}	13.0-13.5	NM ^{d/}	6.752
56MP-4S	3/20/95	1281460.443	498703.610	1.0	2.0	7.0	NP	2.0-7.0	7.556	7.752
56MP-5S	3/20/95	1281519.716	498682.892	1.0	2.0	7.0	1.0-2.0	2.0-7.0	6.546	6.916
56MP-5D	3/20/95	1281519.716	498682.892	0.375	1.0	10.5	5.0-10.0	10.0-10.5	NM	6.916
56MP-6S	3/20/95	1281603.306	498646.493	1.0	2.0	7.0	NP	2.0-7.0	6.582	6.582
56MP-6D	3/20/95	1281603.306	498646.493	0.375	1.0	10.5	NP	10.0-10.5	NM	6.582
56MP-7S	3/20/95	1281490.048	498789.932	1.0	2.0	7.0	NP	2.0-7.0	7.162	7.236
56MP-7D	3/20/95	1281490.048	498789.932	0.375	1.0	11.0	NP	10.5-11	NM	7.236
56MP-8S	3/20/95	1281618.629	498743.107	1.0	2.0	7.0	1.0-2.0	2.0-7.0	6.549	6.522
56MP-9D	3/20/95	1281575.481	498691.202	0.375	1.0	15.0	NP	14.5-15.0	6.226	6.439
56MP-10S	3/20/95	1281375.800	498740.865	1.0	2.0	7.0	NP	2.0-7.0	7.462	7.602
MD56-MW01	10/24/93	1281573.102	498690.350	2.0	9.8	13.5	1.50-13.50	2.53-11.51	6.359	6.439
MD56-MW02	11/2/93	1281267.489	498701.790	2.0	9.8	13.5	1.70-13.50	2.48-11.46	7.649	7.879
MD56-MW03	11/2/93	1281189.545	498572.792	2.0	9.8	14.0	1.50-14.00	2.50-11.42	5.836	6.012
MD56-MW04	11/2/93	1281336.240	498788.477	2.0	9.8	13.5	1.60-13.50	2.35-11.33	7.319	7.562
MD56-MW05	11/3/93	1281417.781	498553.956	2.0	9.8	13.5	1.75-13.50	2.50-11.48	6.846	7.059
MD56-MW06	11/21/93	1281464.341	498702.891	2.0	9.8	13.5	1.75-13.50	2.50-11.48	7.572	7.752
MD56-MW07	11/21/93	1281477.791	498660.564	2.0	9.8	13.5	1.75-13.50	2.50-11.48	7.296	7.549
MD56-MW08	6/22/94	1281413.687	498720.014	2.0	11.0	13.5	1.9-13.5	2.9-11.87	7.439	7.632
MD56-MW09	6/21/94	1281490.924	498741.734	2.0	11.0	13.5	1.45-13.5	2.2-11.18	6.869	7.062
MD56-MW10	6/21/94	1281520.775	498684.409	2.0	11.0	13.5	2.0-13.5	3.0-11.96	6.686	6.916
MD56-MW11	6/22/94	1281495.927	498652.517	2.0	11.0	13.5	1.9-13.5	2.9-11.87	6.882	7.006
MD56-MW12	7/10/94	1281458.591	498702.952	2.0	11.0	35.7	24.22-35.7	27.74-32.05	7.609	7.752
MD32-MW01	9/7/90	1281586.889	498525.260	2.0	9.8	12.2	1.0-12.10	2.0-11.68	9.672	6.749
MD32-MW03	9/7/90	1281650.178	498679.710	2.0	9.8	12.5	1.0-12.4	2.0-12.2	9.466	6.746
MD32-MW06	10/28/93	1281673.787	498620.758	2.0	9.8	13.0	1.34-13.0	2.31-11.31	6.852	7.019
MD32-MW07	6/23/94	1281634.222	498567.734	2.0	11.0	13.5	1.5-13.5	2.25-11.23	6.719	6.872
MD32-MW09	7/9/94	1281677.071	498626.007	2.0	11.0	27.0	16.6-27.0	19.14-23.48	6.826	7.019
MD32-MW10	8/25/95	1281573.227	498594.143	2.0	9.8	13.5	1.79-13.5	2.54-11.51	6.276	6.489

a/ ft bgs = feet below ground surface.

b/ ft msl = feet above mean sea level.

c/ NP = no sandpack.

d/ NM = not measured.

TABLE 4.3
1995 GROUNDWATER QUALITY DATA FOR BTEX AND TMB COMPOUNDS
SITE 56

INTRINSIC REMEDIATION IS
MACDILL AIR FORCE BASE, FLORIDA

Sample Location	Sample Date	Benzene (µg/L) ^v	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	TVH ^v (mg/L) ^v	TOC ^v (mgC/L) ^v	Chloro- Benzene (µg/L)	1,3,5- TMB ^v (µg/L)	1,2,4- TMB ^v (µg/L)	1,2,3- TMB ^v (µg/L)	1,2,3,4 TMB ^v (µg/L)
56MP-1S	3/28/95	ND ^y	7.2	ND	ND	7.2	ND	NA ^v	ND	ND	ND	1.3	ND
56MP-2S	3/29/95	ND	10B ^v	ND	ND	10B	ND	NA	ND	0.4	ND	ND	ND
56MP-3S	3/28/95	ND	11	ND	ND	11	ND	10.2	ND	ND	ND	ND	ND
56MP-3S dup	3/28/95	NA	NA	NA	NA	NA	NA	10.2	NA	NA	NA	NA	NA
56MP-3D	3/28/95	ND	ND	ND	1.4	1.4	ND	NA	0.5	0.7	ND	ND	ND
56MP-4S	3/27/95	4,500	11,936	2,200	11,000	29,636	94E ^{mv}	NA	ND	720	2,300	560	140
56MP-4S dup	3/27/95	NA	NA	NA	NA	NA	93E	NA	NA	NA	NA	NA	NA
56MP-5S	3/27/95	100	120	75	1,100	1,395	8.6	NA	20	190	400	96	130
56MP-5D	3/27/95	ND	ND	ND	ND	ND	ND	NA	ND	1.5	0.7	0.9	30
56MP-15D (dup)	3/27/95	ND	ND	ND	ND	ND	0.2	NA	ND	0.8	0.6	0.9	29
56MP-6S	3/26/95	ND	18	ND	ND	18	ND	NA	ND	ND	ND	ND	0.7
56MP-6D	3/26/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
56MP-7S	3/29/95	ND	5.9B	ND	ND	5.9B	ND	ND	ND	ND	ND	ND	ND
56MP-7D	3/27/95	ND	0.4	ND	ND	0.4	ND	NA	ND	1.4	ND	ND	0.9
56MP-8S	3/26/95	ND	1.6	ND	ND	1.6	ND	NA	ND	ND	ND	ND	ND
56MP-10S	3/26/95	ND	7.3	ND	ND	7.3	ND	NA	ND	ND	ND	ND	ND
MD56-MW1	3/26/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
MD56-MW21 (dup)	3/26/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
MD56-MW2	3/26/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
MD56-MW4	3/29/95	ND	0.6B	ND	ND	0.6B	ND	10.5	ND	ND	ND	ND	ND
MD56-MW5	3/28/95	ND	ND	ND	1.5	1.5	ND	NA	ND	ND	ND	ND	ND
MD56-MW6	3/27/95	7,600	12722	1600	7,700	29,622	91E	NA	ND	490	1,500	310	ND
MD56-MW7	3/28/95	80	47B	81	98	306B	2.1	NA	2.5	33	32	19	15
MD56-MW8	3/26/95	1.1	ND	2	ND	3.1	0.2	NA	ND	ND	ND	ND	ND
MD56-MW9	3/27/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
MD56-MW10	3/27/95	18	43	77	880	1,018	5.1	NA	2.7	130	390	120	74

TABLE 4.3 (Continued)
1995 GROUNDWATER QUALITY DATA FOR BTEX AND TMB COMPOUNDS
SITE 56

INTRINSIC REMEDIATION TS
MACDILL AIR FORCE BASE, FLORIDA

Sample Location	Sample Date	Benzene (µg/L) ^y	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	TVH ^v (mg/L) ^w	TOC ^w (mgC/L) ^z	Chloro- Benzene (µg/L)	1,3,5- TMB ^g (µg/L)	1,2,4- TMB ^g (µg/L)	1,2,3- TMB ^g (µg/L)	1,2,3,4 TMB ^g (µg/L)
MD56-MW11	3/28/95	5.9	ND	29	3.9	38.8	0.5	NA	0.5	0.5	ND	0.4	11
MD56-MW12	3/27/95	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND
56 - FIELD BLANK	3/28/95	0.6	0.8B	ND	1.3	2.7B	NA	NA	ND	ND	ND	ND	ND
56 - RINSAATE BLANK	3/28/95	ND	0.5B	ND	1	1.5B	NA	NA	ND	0.5	ND	1.1	ND
MD32-MW1	3/28/95	ND	0.4B	0.5	1.9	2.8B	0.8	NA	1.2	1	ND	ND	ND
MD32-MW21 (dup)	3/28/95	ND	ND	0.6	2.5	3.1	1	NA	0.9	0.9	ND	ND	ND
MD32-MW3	3/24/95	ND	ND	ND	ND	ND	ND	8.55	ND	ND	ND	ND	ND
MD32-MW7	3/28/95	1.6	0.5B	ND	2.5	4.6	0.1	NA	5.5	1.5	0.9	ND	0.8
MD32-MW10	3/26/95	36	1.1	0.8	1.3B	39.2	1	NA	4.3	ND	ND	ND	1.8
MD32-MW10 dup	3/26/95	38	1.2	0.9	1.5B	41.6	NA	NA	5.9	ND	ND	ND	2

a/ TVH = total volatile hydrocarbons.

b/ TOC = total organic carbon.

c/ 1,3,5-TMB = 1,3,5 trimethylbenzene.

d/ 1,2,4-TMB = 1,2,4 trimethylbenzene.

e/ 1,2,3-TMB = 1,2,3 trimethylbenzene.

f/ 1,2,3,4-TMB = 1,2,3,4 tetramethylbenzene.

g/ µg/L = micrograms per liter.

h/ mg/L = milligrams per liter.

i/ mgC/L = milligrams of carbon per liter.

j/ ND = not detected.

k/ NA = compound not analyzed for.

l/ B = compound detected in blank.

m/ E = laboratory extrapolated value.

Note: Analysis methods included SW8015M for TEH and TVH, and SW8020 for aromatic volatile organic compounds, including TMB compounds.

TABLE 4.4
1995 GROUNDWATER GEOCHEMICAL DATA
SITE 56

INTRINSIC REMEDIATION TS
MACDILL AIR FORCE BASE, FLORIDA

Sample Location	Water Temp (°C)	pH	Conductivity (µs/cm) ^a	Dissolved Oxygen (mg/L) ^b	Redox Potential (mV) ^c	Total Alkalinity (mg/L)	Chloride (mg/L)	Ferrous Iron (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Total Iron (mg/L)	Sulfate (mg/L)	Manganese (mg/L)	Sulfide (mg/L)	Ammonia (ppm) ^d	Carbon Dioxide (ppm)	Methane (ppm)
56MP-1S	26.2	6.55	1470	0.08	-145.1	460	34.7	5.08	ND ^e	ND	4.94	395	0.4	0.14	2	205	0.161
56MP-2S	24.4	6.34	1290	0.10	-39.0	420	45.3	0.66	ND	ND	0.77	331	ND	0.111	1	<100	0.03
56MP-3S	25.1	7.14	570	0.61	-147.1	260	18.3	2.49	ND	ND	2.44	31.6	ND	0.285	1	<100	0.092
56MP-3D	25.7	6.76	590	0.04	-224.9	220	30.5	0.23	ND	ND	0.19	51.7	0.2	8.9	10	175	1.069
56MP-4S	27.1	6.88	970	0.03	-168.7	520	15.3	0.09	ND	ND	0.02	0.395	ND	0.2341 ^f	NA ^g	<100	8.968
56MP-5S	26.9	6.48	880	0.06	-209.6	460	10.7	0.36	0.08	ND	0.27	1.21	ND	1.285	10	225	13.574
56MP-5D	27.0	6.45	460	0.03	-235.2	160	16.9	0.34	ND	ND	0.25	50.4	0.3	3.135	4	128	0.368
56MP-6S	26.2	6.46	520	0.07	-193.0	180	27.5	0.18	ND	ND	0.12	67.3	ND	1.735	NA	<100	0.245
56MP-6D	25.0	6.87	830	0.06	-163.9	200	41.7	0.17	ND	ND	0.11	183	ND	0.458	1	<100	0.086
56MP-7S	22.5	6.28	600	0.16	-111.6	160	32.8	0.39	ND	ND	0.34	108	ND	1.025	2	120	NA
56MP-7D	24.0	6.76	460	0.06	-176.8	140	24.1	0.22	ND	ND	0.22	65.1	ND	0.32	1	<100	0.067
56MP-7D dup	24.0	6.76	460	0.06	-176.8	140	24	0.24	ND	ND	0.17	65.4	ND	0.055	1	<100	NA
56MP-8S	23.8	6.98	1070	0.44	-83.8	120	28.2	0.05	ND	ND	0.04	108	ND	0.053	0.4	<100	0.032
56MP-8S dup	NA	NA	NA	NA	NA	NA	28.5	NA	NA	ND	NA	107	NA	NA	NA	NA	NA
56MP-10S	28.6	6.93	540	0.81	-109.6	240	7.9	0.34	ND	ND	0.34	4.61	ND	0.675	0.8	<100	2.288
56-MP-15D	NA	NA	NA	NA	NA	NA	16.4	NA	ND	ND	NA	52.9	NA	NA	NA	NA	0.548
MD56-MW1	25.2	6.87	590	0.20	-121.5	200	28.3	0.15	0.992	ND	0.21	80	ND	0.555	1	<100	0.442
MD56-MW1 dup	25.2	6.87	590	0.20	-121.5	200	27.8	0.16	0.992	ND	0.17	79.4	ND	0.535	1	<100	NA
MD56-MW2	26.8	6.39	510	0.07	-142.8	200	24.7	0.05	ND	ND	0.03	46.3	0.2	1.88	2	120	0.492
MD56-MW4	23.3	6.78	610	0.81	-4.9	200	24.9	0.02	0.195	ND	0.59	104	ND	0.019	0.2	<100	0.034
MD56-MW4 dup	23.3	6.78	610	0.81	-4.9	180	NA	0.04	NA	NA	0.36	NA	ND	0.017	0.2	<100	NA
MD56-MW5	26.9	7.03	1410	0.02	-237.9	520	59	0.09	1.32	ND	0.07	194	ND	1.735	6	150	0.136
MD56-MW6	27.8	6.83	1040	0.02	-217.5	440	21.5	0.56	ND	ND	0.45	2.92	ND	2.29	10	155	6.324
MD56-MW7	26.7	7.01	660	0.05	-188.5	320	25.7	0.03	ND	ND	ND	2.64	0.4	4.688	81	152	7.953
MD56-MW8	25.5	6.55	450	0.07	-126.7	180	10.8	0.13	ND	ND	0.11	29.7	ND	1.33	2	145	2.298
MD56-MW8 dup	25.5	6.55	450	0.07	-126.7	180	NA	0.16	NA	NA	0.1	NA	ND	0.91	2	142	NA
MD56-MW9	25.4	6.31	500	0.15	-48.8	200	17.6	0.65	0.608	ND	0.77	58.7	ND	0.079	2	130	0.739
MD56-MW10	27.1	6.37	590	0.03	-235.6	200	23.4	0.17	ND	ND	0.17	68.6	0.1	2.975	5	140	3.711
MD56-MW11	26.2	6.82	490	0.08	-126.8	220	37.8	0.03	ND	ND	ND	3.23	0.1	2.69	61	152	5.279
MD56-MW12	28.3	7.32	980	2.40	-12.8	240	147	ND	0.394	ND	0.06	42.4	ND	0.012	0.1	<100	0.014
MD32-MW1	25.2	6.67	420	0.03	-228.9	200	17.1	0.04	ND	ND	ND	14.4	0.4	7.7125	7	180	2.634
MD32-MW21 (dup)	NA	NA	NA	NA	NA	NA	15.8	NA	ND	ND	NA	15.3	NA	NA	NA	NA	NA
MD32-MW3	26.0	6.81	680	0.08	-146.9	180	32.8	0.13	ND	ND	0.14	99.2	ND	0.08	0.4	<100	0.137
MD32-MW3 dup	26.0	6.81	680	0.08	-146.9	180	NA	0.1	NA	NA	0.11	NA	0.1	0.055	0.4	<100	NA
MD32-MW7	25.8	6.62	570	0.03	-246.4	240	49.2	0.02	ND	ND	0.03	8.1	0.3	7.5625	3	160	4.749
MD32-MW10	25.5	6.36	440	0.18	-118.1	200	11.5	0.04	0.202	ND	0.03	17.8	0.1	1.155	4	125	NA

a/ µs/cm = microscms per centimeter. c/ mV = millivolts. e/ ND = not detected. g/ NA = not analyzed for.
b/ mg/L = milligrams per liter. d/ ppm = parts per million. f/ 1 = potential turbidity interference. NOTE: See Table 2.2 for analysis methods.

