

FINAL REPORT

Assessing the Long-term Performance and Impacts of ISCO and
ISBR Remediation Technologies

ESTCP Project ER-201585

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ACRONYMS AND ABBREVIATIONS

cis-1,2-DCE	cis-1,2-dichloroethene
AFP44	Air Force plant 44
CET	Contaminant elution test
CHL	Chloroform
CMD	Contaminant mass discharge
CDMR-MR	Contaminant mass-discharge reduction vs mass reduction
COC	Contaminant of concern
DNAPL	Denser-than-water non-aqueous phase liquid
DO	Dissolved oxygen
DOD	Department of Defense
EAC	Enhanced aerobic cometabolism
EPA	Environmental Protection Agency
ERD	Enhanced reductive dechlorination
ESTCP	Environmental Security Technology Certification Program
FE-ISBR	Fracturing-enhanced in situ biological reduction
FE-ISCR	Fracturing-enhanced in situ chemical reduction
ICET	Integrated contaminant elution and tracer test
ISBR	In situ biological reduction
ISCO	In situ chemical oxidation
ISCR	In situ chemical reduction
PCE	Tetrachloroethene
OOM	Order of Magnitude
ORP	Oxidation-reduction potential
RA	Remedial action
ROD	Record of decision
RPM	Remedial project manager
SERDP	Strategic Environmental Research and Development Program
SVE	Soil vapor extraction
TCE	Trichloroethene
TIAA	Tucson International Airport Area
VC	vinyl chloride

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ABSTRACT

INTRODUCTION AND OBJECTIVES

There is a critical need to conduct accurate, quantitative performance assessments over longer time scales. This is especially important for the many complex sites that contain DNAPL source zones and large groundwater contaminant plumes comprising persistent contamination, which are recognized to present the most difficult challenges to site closure. The implementation of longer-term performance assessments is expected to reduce the risk and costs associated with remediation and management of these complex sites.

The overall goal of this project was to demonstrate the effectiveness of longer-term performance assessments for evaluating the benefits of remedial actions. The specific objectives of the project were as follows:

1. Assess the long-term performance of fracturing-enhanced ISBR remediation for a specific application site.
2. Compare the observed performance of the FE-ISBR project to the prior ISCO project conducted at the same site.
3. Compare the observed performance of the FE-ISBR project to other projects that have employed fracturing to enhance amendment delivery for ISBR or ISCR.
4. Compare the observed performance of the FE-ISBR project to other ISBR projects.
5. Evaluate the effectiveness of alternative methods for assessing performance.
6. Develop an integrated approach for conducting contaminant elution and tracer tests to support site characterization and performance assessments.

TECHNOLOGY DESCRIPTION

The project was conducted using data and information obtained for RAs conducted at the Air Force Plant 44 site, which is part of the Tucson International Airport Area federal Superfund site located in Tucson, AZ. The TIAA site comprises several primary source zones and a large, several kilometer long, groundwater contaminant plume that resides in the regional aquifer. Trichloroethene and 1,4-dioxane are the primary contaminants of concern (COC) for the regional groundwater plume. Chromium is also present in localized zones.

Two separate remediation projects have been conducted at the three designated DNAPL source zones of the AFP44 site, ISCO and fracturing-enhanced ISBR. Both projects focused on the interface between the vadose zone and saturated zone. This interface region, which consists of primarily lower-permeability (clay) media, has been identified as the primary location for remaining COC. Slow release of COC from this domain is considered to be the primary cause of the observed delayed attainment of cleanup objectives. The two remediation projects were conducted by different contractors working with the U.S. Air Force.

PERFORMANCE ASSESSMENT

The project was designed to accomplish a robust, long-term assessment of the performance of ISCO and fracturing-enhanced ISBR remediation technologies, and to compare performance to other RA projects. The objectives of the project were met. Performance monitoring data were obtained for a period of greater than 3 years after completion of ISBR RAs at AFP44. The %-reductions obtained for the RAs conducted at AFP44 are consistent with results reported for prior RAs.

PUBLICATIONS

Guo, Z. and M.L. Brusseau, 2017. The impact of well-field configuration and permeability heterogeneity on contaminant mass removal and plume persistence, *J. Hazard. Mater.* 333, 109–115.

Guo, Z. and M.L. Brusseau, 2017. The impact of well-field configuration on contaminant mass removal and plume persistence for homogeneous versus layered systems. *Hydrol. Proc.* 31, 4748–4756.

Brusseau, M.L. and Z. Guo, 2018. The integrated contaminant elution and tracer test toolkit, ICET3, for improved characterization of mass transfer, attenuation, and mass removal. *J. Contam. Hydrol.* 208, 17–26.

EXECUTIVE SUMMARY

INTRODUCTION

Contaminated groundwater is the single largest liability in the Defense Environmental Restoration Program; thousands of military sites are contaminated with chlorinated solvents, 1,4-dioxane, perchlorate, and other hazardous compounds (SERDP, 2015). Several established technologies exist to remediate these sites. The performances of these technologies have been demonstrated by numerous site installation restoration projects and SERDP/ESTCP-funded projects. However, performance assessments are generally conducted over short time scales comprising typically a few months to a year. It is anticipated that such short-term analyses may be subject to a high degree of uncertainty due to several factors including time required for system stabilization and potential rebound effects.

There is a critical need to conduct accurate, quantitative performance assessments over longer time scales. This is especially important for the many complex sites that contain DNAPL source zones and large groundwater contaminant plumes comprising persistent contamination, which are recognized to present the most difficult challenges to site closure (NRC, 2013; SERDP, 2013). The implementation of longer-term performance assessments is expected to reduce the risk and costs associated with remediation and management of these complex sites.

OBJECTIVES

The overall goal of this project was to demonstrate the effectiveness of longer-term performance assessments for evaluating the benefits of remedial actions. The specific objectives of the project were as follows:

1. Assess the long-term performance of fracturing-enhanced ISBR remediation for a specific application site.
2. Compare the observed performance of the FE-ISBR project to the prior ISCO project conducted at the same site.
3. Compare the observed performance of the FE-ISBR project to other projects that have employed fracturing to enhance amendment delivery for ISBR or ISCR.
4. Compare the observed performance of the FE-ISBR project to other ISBR projects.
5. Evaluate the effectiveness of alternative methods for assessing performance.
6. Develop an integrated approach for conducting contaminant elution and tracer tests to support site characterization and performance assessments.

TECHNOLOGY DESCRIPTION

The project was conducted using data and information obtained for RAs conducted at the Air Force Plant 44 site, which is part of the Tucson International Airport Area federal Superfund site located in Tucson, AZ. The TIAA site was placed on the EPA National Priorities List in 1983. The TIAA site comprises several primary source zones and a large, several kilometer long, groundwater contaminant plume that resides in the regional aquifer (see Figure ES-1). Trichloroethene and 1,4-dioxane are the primary contaminants of concern (COC) for the regional groundwater plume. Chromium is also present in localized zones.

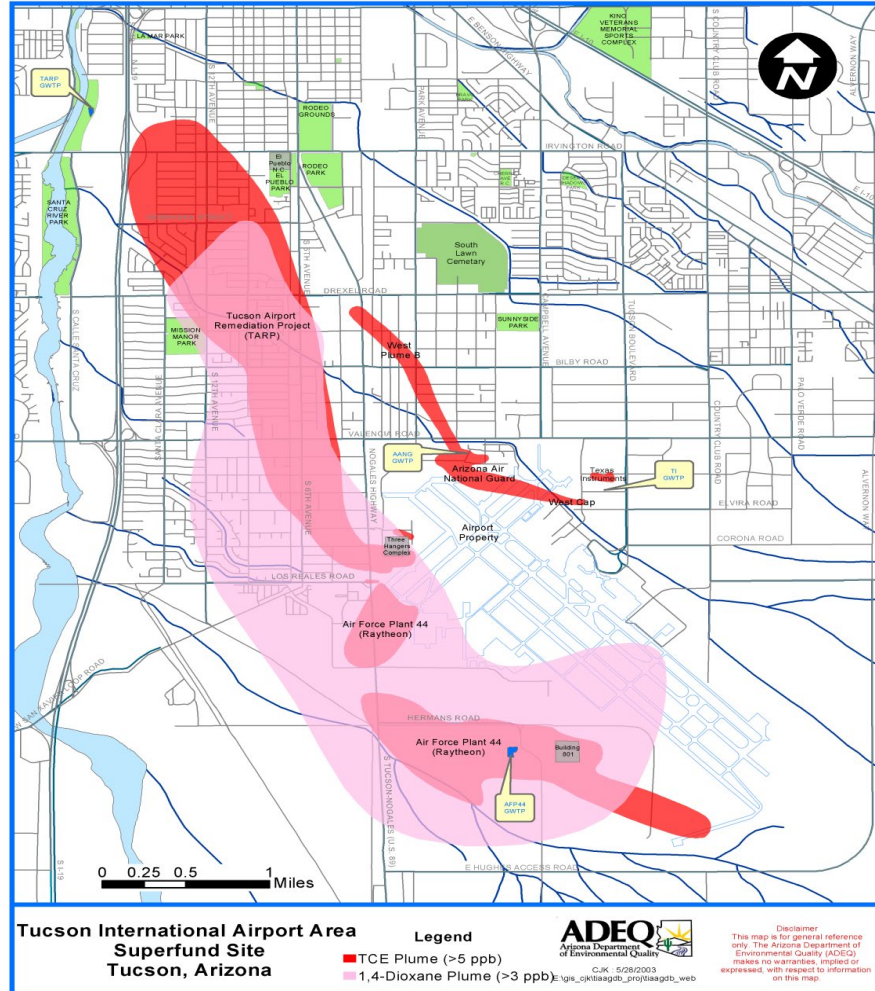


Figure ES-1. Map of TIAA Site.

Two separate remediation projects have been conducted at the three designated DNAPL source zones of the AFP44 site, ISCO and fracturing-enhanced ISBR. Both projects focused on (i) the saturated-zone portion of the sources (below the regional groundwater surface) and (ii) the interface between the vadose zone and saturated zone. This interface region, which consists of primarily lower-permeability (clay) media, has been identified as the primary location for remaining COC. Slow release of COC from this domain is considered to be the primary cause of the observed rate-limited mass removal and delayed attainment of cleanup objectives (Brusseau et al., 2007, 2013; URS, 2013). The two remediation projects were conducted by different contractors working with the U.S. Air Force.

ISCO was implemented at source zones DP002 and DP003, and completed in 2006. The objective of the remediation operation was to significantly reduce the concentration of TCE within the sources zones, and reduce the mass flux of TCE into the plume. ISBR was implemented at source zones DP002, DP003, and DP005. These operations were conducted several years after ISCO was completed, at a point at which all lines of evidence indicated that site conditions had stabilized. The objective of the remediation operation was to significantly reduce the concentrations of TCE, dioxane, and chromium within the sources zones, and reduce the mass flux of the COCs into the plume.

PERFORMANCE ASSESSMENT

The project was designed to accomplish a robust, long-term assessment of the performance of ISCO and fracturing-enhanced ISBR remediation technologies, and to compare performance to other RA projects. Specific technical questions to be addressed included:

- What is the long-term performance of fracturing-enhanced ISBR remediation for this specific application site?
- Was rebound observed for the ISBR RA?
- How does the observed performance of the FE-ISBR project compare to the prior ISCO project conducted at the same site?
- How does the observed performance of the FE-ISBR project compare to other projects that have employed fracturing to enhance amendment delivery for ISBR or ISCR?
- How does the observed performance of the FE-ISBR project compare to other ISBR projects?
- Do the alternative methods for assessing performance provide consistent results?

Three metrics were used for the performance assessment:

(I) change in COC concentration for groundwater samples collected from 1-4 monitoring wells located within the treatment zone before and after the remedial action;

(II) change in aggregate COC concentration for groundwater samples collected from multiple monitoring wells located within the treatment zone before and after the remedial action;

(III) change in COC concentration based on samples collected from extraction wells located downgradient of the treatment zone before and after the remedial action.

PROJECT RESULTS

A total of 9-10 sample sets were collected over the ~3-year monitoring period for TCE, dioxane, and chromium for the designated performance monitoring wells. It is observed that concentrations declined for most COCs for most wells. However, increases were observed for some sampling periods.

The %-reduction performances of the ISBR RAs based on assessment of the COC data collected for the contractor-designated performance-monitoring wells are presented in Table ES-1.

ERD-ISBR was observed to be very effective for TCE treatment in site DP003, with a 94% reduction, equivalent to a 1.2 order-of-magnitude reduction in concentration. It was also effective for chromium, with an 83% reduction. The %-reduction for dioxane was 36%. The %-reduction for TCE and chromium for sites DP002 and DP005 are lower than observed for site DP003.

The observation of cis-1,2-dichloroethene, vinyl chloride, ethene, and ethane in groundwater samples after the RA implementation supports that reductive dechlorination was initiated in the treatment zone (see Figure ES-2).

Table ES-1. Performance of ISBR at AFP44 Based on Designated Monitoring-well Data

	TCE	Dioxane	Chromium
Site 3 ERD-ISBR			
% Reduction	94	36	83
OOM Reduction	1.2	0.2	0.8
Site 3 EAC-ISBR			
% Reduction	60	92	0
OOM Reduction	0.4	1.1	0.0
Site 2 ERD-ISBR			
% Reduction	34	-	13
OOM Reduction	0.2	-	0.1
Site 5 ERD-ISBR			
% Reduction	20	-	38
OOM Reduction	0.1	-	0.2

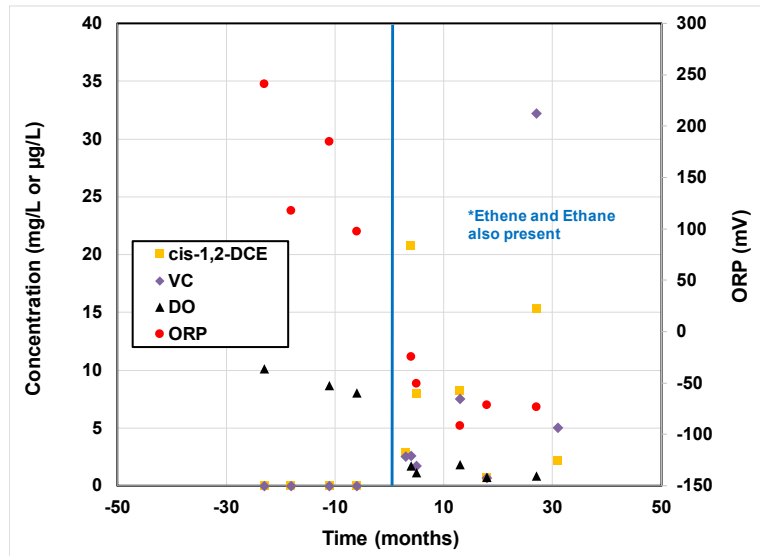


Figure ES-2. Concentrations of Various Analytes Before and After Implementation of ERD-ISBR at Site DP003.

Dissolved oxygen (DO) is in mg/L units; cis-1,2-DCE and VC are in µg/L units.

EAC-ISBR was used in a localized section of site DP003 to address high concentrations of dioxane present. It was very effective for this purpose, with a reduction of 92% achieved. It was moderately effective for TCE, with a 60% reduction. It is noteworthy that the concentrations of chromium remained essentially unchanged over the course of the EAC-ISBR treatment. This indicates that the generation of aerobic conditions had no measurable impact of chromium levels in groundwater.

The contractor for the ISCO RA project selected 17 monitoring wells in the treatment zone of site DP003 to use for performance assessment for TCE remediation. Data were collected for these same wells to conduct an equivalent performance assessment for ISBR at site DP003 (Metric II). These results are presented in Table ES-2.

Table ES-2. Performance of ISBR at Site DP003 Based on Data Reported for 17 Monitoring Wells

TCE [µg/L]	Before	After
MW	2011-2014	July 2018
E14	100	102
E15	110	35
E19	58	10
E21	27	20
M104	16	8
M102	374	1300
M101	345	251
M100	317	1
M98	451	160
M97	100	120
M96	218	86
M95	161	9
M94	330	15
M93	50	10
M92	47	-
M53	48	44
M05	7	40
Geomean	96	37
% Reduction	62	

A reduction of 62% is obtained for TCE for site DP003. This is lower than the 94% decrease observed for ERD-ISBR at site DP003 based on the three designated performance-monitoring wells.

ISCO was conducted at site DP003 years prior to ISBR implementation. An aggregate reduction in TCE concentrations of 68% was reported by the contractor based on data collected from the selected 17 monitoring wells in the treatment zone. This value was calculated using arithmetic means of the individual monitoring-well concentrations.

The %-reduction was recalculated for the present study using geometric means to be consistent with the ISBR data analysis. The recalculated %-reduction is 75%. It is noteworthy that this value is identical to the reduction determined by Brusseau et al. (2011) using CMD tests conducted in the DP003 treatment zone. This provides confidence in the robustness of the %-reductions determined using concentration data obtained from a relatively large number of monitoring wells located within the treatment zone.

The %-reduction performances of ISCO and ISBR at site DP003 are in a similar range, 75% versus 62%.

It is noted that the %-reductions for the two RAs conducted at site DP003 and the one conducted at site DP002 are all greater than the %-reduction for DP005 (see Table ES-1). Recall that ISCO was conducted prior to the ISBR RAs at sites DP003 and DP002, but not at site DP005. These results may indicate that ISBR was more effective at the locations at which ISCO was conducted previously. However, it is also noted that the initial concentrations of TCE at sites DP003 (494 µg/L) and DP002 (227 µg/L) were significantly greater than at site DP005 (45 µg/L). Hence, the greater %-reductions observed for DP003 and DP002 may reflect the higher initial concentrations.

It is observed that the %-reduction for TCE reported for site DP002 is substantially lower than that reported for DP003, even though ISCO was previously conducted at both sites. One possible reason for this disparity is that site DP002 has a much greater proportion of lower permeability media present compared to DP003. However, it should be noted that the performance reported for site DP002 is based on a small number of monitoring wells.

A literature search revealed only a few case studies of prior applications of fracturing for enhancing amendment delivery for ISBR or ISCR conducted in unconsolidated media. The performance comparison of the projects is presented in Table ES-3.

Table ES-3. Comparison of Remediation Performance for Fracturing-enhanced RAs

Site	COC	RA	Performance Period (yr)	% Reduction	Source
Site 3 AFP44	TCE	ISBR	3.4	62	This study
Site 2 AFP44	TCE	ISBR	3.2	34	This study
Site 5 AFP44	TCE	ISBR	3.4	20	This study
FEW AFB	TCE	ISBR	3	84	URS 2008, 2011
Hunters	CHL	ISCR	1	98	NAVFAC 2014
Danish	TCE	ISCR	0.5	>50	Wragg et al. 2016
MCC AFB	TCE	ISCR	0.25	28	Dyson et al. 2019

A range of %-reductions are observed. It is noted that the value reported for the MCC AFB site is likely to be smaller than the actual longer-term reduction.

McGuire et al. (2016) conducted a meta-analysis of enhanced anaerobic bioremediation projects conducted for sites wherein the original COCs were either PCE or TCE. The median concentration reduction was 90% for 34 sites for which the performance monitoring period was at least 3 years.

Tillotson and Borden (2017) conducted a meta-analysis of enhanced reductive dechlorination bioremediation projects conducted for 37 sites with chlorinated ethene contamination. The post-treatment monitoring periods ranged from 4 months to 11 years. Only 4 sites overlapped with the analysis conducted by McGuire et al. (2016). The median reduction in PCE and TCE concentrations was ~90%, identical to that reported by McGuire et al.

The combined studies provide a data set of 67 sites for ISBR performance for PCE and TCE treatment. It is observed that the %-reductions reported for AFP44 in Table ES-1 range from below to similar to the median 90% literature value.

The objectives of the project were met. Performance monitoring data were obtained for a period of greater than 3 years after completion of ISBR RAs at AFP44. The %-reductions obtained for the RAs conducted at AFP44 are consistent with results reported for prior RAs.

Concentrations of the COCs measured after >3 years of monitoring were approximately 50% lower than the values measured after 3 months for a majority of the sampling points. Therefore, an inaccurate assessment of performance would have been obtained based on the typical short-term assessment period. This demonstrates the advantage of conducting longer-term performance assessments.

The results of this project indicate that concentrations stabilized prior to the 3-year monitoring period. Thus, the 3-year timeframe appears to have been sufficient to obtain a robust assessment of performance. This is consistent with the results of the meta-analysis conducted by McGuire et al. (2016), which indicated that 3 years was a sufficient period of monitoring for effective performance assessment. Thus, it is suggested that future RA projects involving ISBR or ISCO/R employ a 3-year monitoring period to produce robust performance assessments.

The project has generated information that will benefit RPMs and other end-users at sites impacted by persistent groundwater contamination. The dissemination of this information will improve the effective implementation of these technologies, which has the potential to substantially reduce the DoD cost burden for management of groundwater-contaminated sites. It is anticipated that the project outcomes will be relevant to RPMs, regulators, and other stakeholders for these sites.

1.0 INTRODUCTION

1.1 BACKGROUND

Contaminated groundwater is the single largest liability in the Defense Environmental Restoration Program; thousands of military sites are contaminated with chlorinated solvents, 1,4-dioxane, perchlorate, and other hazardous compounds (SERDP, 2015). Several established technologies exist to remediate these sites. The performances of these technologies have been demonstrated by numerous site installation restoration projects and SERDP/ESTCP-funded projects. However, performance assessments are generally conducted over short time scales comprising typically a few months to a year. It is anticipated that such short-term analyses may be subject to a high degree of uncertainty due to several factors including time required for system stabilization and potential rebound effects.

There is a critical need to conduct accurate, quantitative performance assessments over longer time scales. This is especially important for the many complex sites that contain DNAPL source zones and large groundwater contaminant plumes comprising persistent contamination, which are recognized to present the most difficult challenges to site closure (NRC, 2013; SERDP, 2013). The implementation of longer-term performance assessments is expected to reduce the risk and costs associated with remediation and management of these complex sites.

Remediation performance assessment is typically based on analysis of changes in contaminant concentrations for groundwater samples collected from one or more monitoring wells within the treatment zone. The effectiveness of this point-sampling-based method may be limited in some cases for large, complex sites characterized by high degrees of heterogeneity. Alternative methods are available, such as the use of contaminant mass discharge as a more integrative measure of the performance of source-zone remediation efforts.

A multiple-method approach was used by Brusseau and colleagues to conduct a long-term assessment of ISCO performance for a TCE-contaminated site in Arizona (Brusseau et al., 2011). The standard analysis of changes in groundwater concentrations for monitoring-well samples was supplemented with the application of source-zone and plume-scale CMD tests. The results demonstrated excellent agreement among the three methods. This work serves as an illustration of the benefits of employing alternative methods for performance assessments.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall goal of this project was to demonstrate the effectiveness of longer-term performance assessments for evaluating the benefits of remedial actions. The specific objectives of the project were as follows:

1. Assess the long-term performance of fracturing-enhanced ISBR remediation for a specific application site.
2. Compare the observed performance of the FE-ISBR project to the prior ISCO project conducted at the same site.

3. Compare the observed performance of the FE-ISBR project to other projects that have employed fracturing to enhance amendment delivery for ISBR or ISCR.
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6. Develop an integrated approach for conducting contaminant elution and tracer tests to support site characterization and performance assessments.

The project has generated information that will benefit RPMs and other end-users at sites impacted by persistent groundwater contamination. The dissemination of this information will improve the effective implementation of these technologies, which has the potential to substantially reduce the DoD cost burden for management of groundwater-contaminated sites. It is anticipated that the project outcomes will be relevant to RPMs, regulators, and other stakeholders for these sites.

1.3 REGULATORY DRIVERS

As a result of past operation and disposal practices, chlorinated-solvent liquid is or was present at many of the chlorinated-solvent DNAPL sites managed by the DOD. In addition, dissolved and sorbed contaminant mass is often sequestered in poorly-accessible domains within the subsurface. These factors contribute to the overall risk posed by the site, and greatly increase the cost-time burden for the attainment of groundwater cleanup goals and eventual site closure. This project will address three COCs at the site- TCE, dioxane, and chromium. The comparative evaluations will focus on TCE, given that a great majority of prior assessments have focused on chlorinated-solvent compounds such as PCE and TCE.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Source-zone Remediation Technologies

Two separate remediation projects have been conducted at the three designated DNAPL source zones of the AFP44 site, in-situ chemical oxidation and fracturing-enhanced in-situ biological remediation. Both projects focused on (i) the saturated-zone portion of the sources (below the regional groundwater surface) and (ii) the interface between the vadose zone and saturated zone. This interface region, which consists of primarily lower-permeability (clay) media, has been identified as the primary location for remaining COC. Slow release of COC from this domain is considered to be the primary cause of the observed rate-limited mass removal and delayed attainment of cleanup objectives (Brusseau et al., 2007, 2013; URS, 2013).

The two remediation projects were conducted by different contractors working with the U.S. Air Force.

ISCO: ISCO was implemented at source zones DP002 and DP003, and completed in 2006. The objective of the remediation operation was to significantly reduce the concentration of TCE within the sources zones, and reduce the mass flux of TCE into the plume.

For both source zones, the injections were conducted in increments and involved 22-24 injection wells. The injection wells were screened across the interface between the vadose zone and groundwater. Injections were conducted primarily under gravity feed, for three to five wells at a time, with an interval of approximately one month between each set of injections. A second round of injections was conducted approximately 1.5 years after the first round at each site, employing a subset of the initial injection locations. Potassium permanganate was used as the sole oxidant, with concentrations for the injection solutions ranging from approximately 0.2 to 2%. A total of approximately 25,000 and 12,500 kg of potassium permanganate was injected for DP002 and DP003, respectively.

An initial performance assessment of the ISCO project has been conducted (Brusseau et al., 2011). Three metrics were used- (I) change in aggregate TCE concentration for groundwater samples collected from multiple monitoring wells located within the treatment zone; (II) change in contaminant mass discharge based on CMD tests conducted in the treatment zone before and after the ISCO; (III) change in plume-scale composite TCE CMD based on continuous monitoring of groundwater extracted with the pump-and-treat system. The performance assessment showed that the ISCO project was successful, resulting in reductions of 68%, 75%, and 70% for metrics I, II, and III, respectively (Brusseau et al., 2011). The results obtained for all three metrics are illustrated in Figures 1, 2, and 3, respectively. A reduction of 86% was reported for DP002 for metric I.

ISBR: Enhanced ISBR was implemented at source zones DP002, DP003, and DP005 (URS, 2013). These operations were conducted several years after ISCO was completed, at a point at which all lines of evidence indicated that site conditions had stabilized. The objective of the remediation operation was to significantly reduce the concentrations of TCE, dioxane, and chromium within the sources zones, and reduce the mass flux of the COCs into the plume.

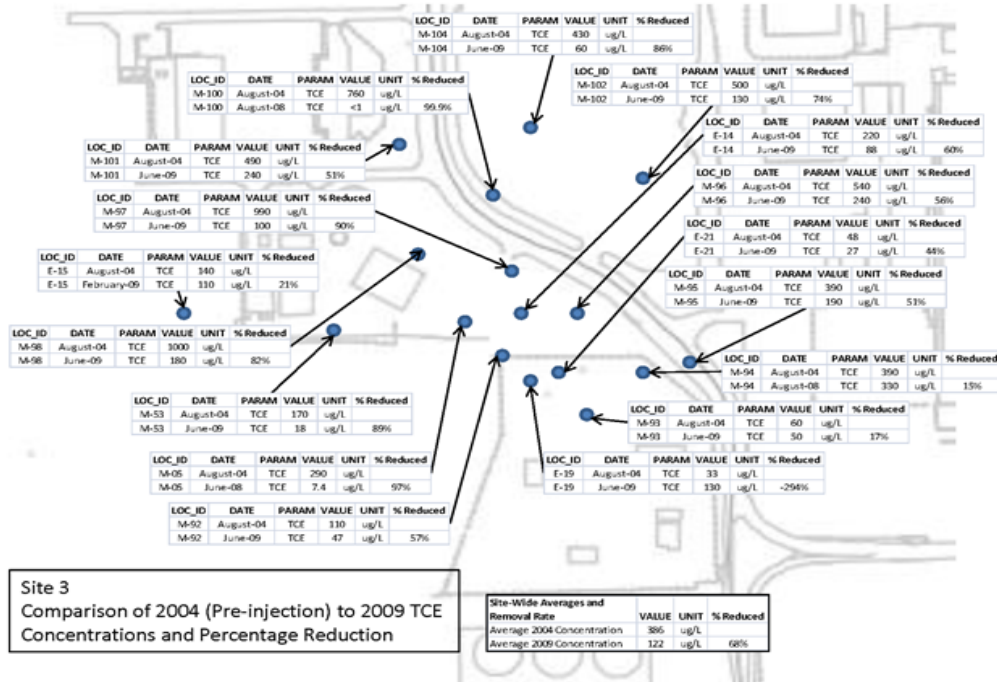


Figure 1. Metric I: Comparison of COC Concentrations in Groundwater Sampled via Monitoring Wells Located Within the Treatment Zone at DP003.

Data from Brusseau et al., 2011.

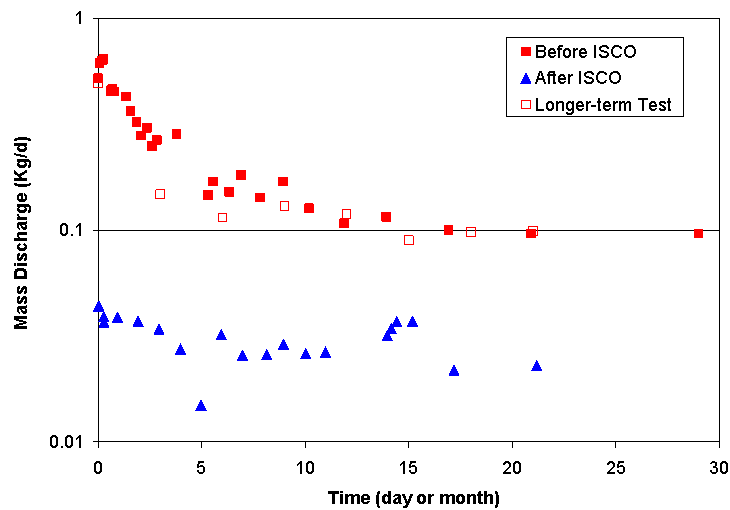


Figure 2. Metric II: Results of TCE CMD Tests Conducted at Source Zone DP003 Before and After ISCO.

The tests labeled “Before ISCO” and “After ISCO” have a time scale of days; the longer-term test (conducted before ISCO, and at a higher flow rate) has a time scale of months. From Brusseau et al., 2011.

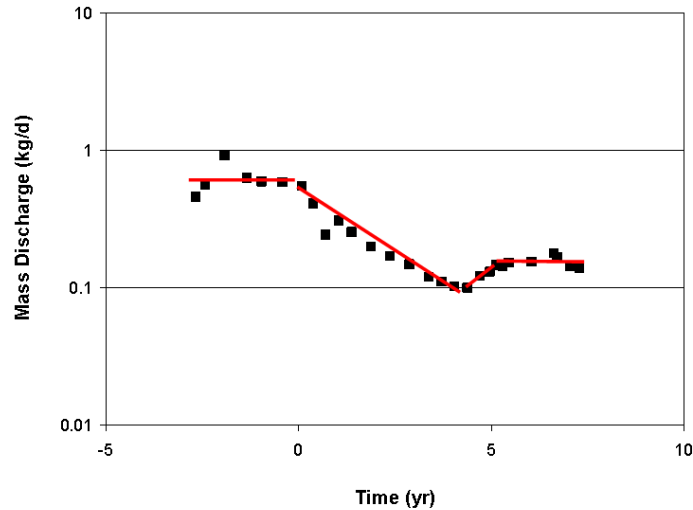


Figure 3. Metric III: Results of Composite CMD Obtained from Analysis of the Plume-scale Pump-and-treat System Operation Data.

Thus the CMD includes contributions from the source zones and the aqueous-phase contaminant plume. Time zero denotes the start of ISCO; ISCO ends at year 4. The rebound is attributed primarily to diffusion of TCE from low-K zones. The lines are included for visualization purposes only. From Brusseau et al., 2011.

The ISBR operations involved innovative application of hydrofracturing to improve delivery of the amendments into the lower-permeability zones. Two different ISBR technologies were implemented. The first was enhanced reductive dechlorination to address TCE (and indirectly chromium via the change in redox). This was conducted at DP002, DP005, and the north and central section of DP003. The second method was enhanced aerobic cometabolism (EAC) to address TCE and dioxane. This technology was conducted at the southern section of DP003.

A grid of injection wells was emplaced in each source zone to create the treatment system. An example is shown in Figure 4 for site DP003. The PVC casings were securely grouted into the target formation. A high pressure water blaster pump capable of 10,000 psi and 28 gpm was used to cut through the pre-selected interval of the casing, creating a kerf into the surrounding formation and thus generating a fracture zone. A sand slurry was then injected to maintain fracture integrity. The fracture intervals were selected with the intent to deliver amendments to locations of persistent high residual COC concentrations.

The ERD-ISBR technology was implemented by first using high pressure water injection to induce fracturing of lower-permeability zones. A slurry composed of sand, EDS-ER, Nutrimens, and KB-1 was then immediately injected into the fissures. EDS-ER™ is an extended release, soy-based, water-mixable electron donor self-emulsifying oil with a neutral pH that has a lower viscosity than standard emulsified vegetable oil. Nutrimens® is a metabolic supplement designed to enhance the kinetics and efficiency of microbial systems specifically related to bioremediation. KB-1 is a commercial mixture of microbial cultures containing specific bacteria (Dhc and Dhb) that are known to biotransform TCE completely.

(III) change in COC concentration based on samples collected from extraction wells located downgradient of the treatment zone before and after the remedial action.

Metric I: monitoring the change in the COC concentrations determined for groundwater samples collected from 1-4 monitoring wells located within the treatment zone.

This metric is the standard one used for the vast majority of RA performance assessments. Data collected more than 3 years after RA completion are compared to the corresponding baseline data collected prior to RA implementation. This method is the official designated performance assessment approach implemented by the contractor. This metric will be used for all three RA sites.

Metric II: monitoring the change in the COC concentrations determined for groundwater samples collected from multiple monitoring wells located within the treatment zone.

Aggregate COC concentrations were tabulated based on sampling of 17 monitoring wells located within the treatment zone for site DP003. Data collected more than 3 years after RA completion are compared to the corresponding baseline data collected prior to RA implementation. An example is presented in Figure 1. This metric will be used only for site DP003 based on the availability of equivalent data collected in prior assessments of ISCO at the site.

Metric III: monitoring the change in COC concentration based on samples collected from extraction wells located downgradient of the treatment zone.

Concentrations were tabulated for samples collected from extraction wells located downgradient of the treatment zone. The change in concentrations for before and after the RA is equivalent to the change in CMD, assuming similar overall discharge rates. This metric will be used only for site DP003 based on the availability of equivalent data collected in prior assessments of ISCO at the site.

2.2 TECHNOLOGY DEVELOPMENT

The ISCO and ISBR remediation technologies are mature methods that have been used at numerous sites. A meta-analysis of ISCO performance was reported by Krembs et al. (2010). Meta-analyses of ISBR performance were reported by McGuire et al. (2016) and Tillotson and Borden (2017). These large-scale assessments of numerous applications provide excellent indices to which to compare the performance of the applications examined in the present study.

Fracturing to enhance delivery of amendments is recognized as a useful approach for sites wherein contaminant removal is limited by the presence of contaminant sequestered in low-permeability units (e.g., NAVFAC, 2014; Horst et al., 2019). An extensive literature review found no meta-analysis of the performance of RAs employing fracturing-enhanced amendment delivery.

Performance assessments of RAs are routinely conducted. However, most are conducted for relatively short monitoring periods. The use of longer monitoring periods is recognized to be important for increasing the robustness of performance assessments. The use of longer monitoring periods is becoming more common, but short-term assessments continue to represent the majority of efforts. For example, McGuire et al. (2016) collected performance data for 118 sites at which enhanced anaerobic bioremediation was used. Only 29% of the implementations had post-treatment monitoring periods of at least 3 years. Based on the meta-analysis, it was suggested that 3 years was a sufficient period of monitoring for effective performance assessment.

The contaminant mass flux or mass discharge for a source zone is now recognized as a key metric for assessing risk and remediation performance (e.g., Stroo et al., 2003; DiFilippo and Brusseau, 2008; Christ et al., 2010; ITRC, 2010). Mass discharge is a measure of both mass removal from the source zone (reflective of source longevity) and mass delivery to the plume (reflective of plume response). As such, mass discharge inter-relates source-zone dynamics and plume dynamics, and is a key determinant for evaluating the effectiveness of a source-zone remediation effort. Multiple projects have demonstrated that the change in CMD after implementation of a remediation technology serves as a robust, effective measure of performance (see Figure 2 for an example).

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

It is anticipated that the use of longer-term post-treatment monitoring periods will improve the robustness of performance assessments. The primary disadvantage is the additional costs accrued for extended monitoring. Another potential disadvantage is the possible delay in decision-making associated with the extended time for project completion.

Remediation performance assessment is typically based on analysis of changes in contaminant concentrations for groundwater samples collected from one or more monitoring wells within the treatment zone. The effectiveness of this point-sampling-based method may be limited in some cases for large, complex sites characterized by high degrees of heterogeneity. Alternative methods are available, such as the use of contaminant mass discharge as a more integrative measure of the performance of source-zone remediation efforts. The alternative methods come with additional cost requirements.

3.0 PERFORMANCE OBJECTIVES

The performance objectives are presented in Table 1.

Table 1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
1. Metric I	Groundwater COC concentrations collected before and after completion of remedial operation for designated performance-monitoring wells All three sites	Data collected for a minimum of 3 years post treatment
2. Metric II	Groundwater COC concentrations collected before and after completion of remedial operation for 17 monitoring wells located within the treatment zone Site DP003	Data collected for a minimum of 3 years post treatment
3. Metric III	Groundwater COC concentrations collected before and after completion of remedial operation for two extraction wells located downgradient of treatment zone Site DP003	Data collected for a minimum of 3 years post treatment
4. Rebound Analysis	COC data collected for an extended time period after completion of remedial operation	Data collected for a minimum of 3 years post treatment
Qualitative Performance Objectives		
5. Comparative performance I	Remedial performance data for other fracturing-enhanced RAs	Comparison attained
6. Comparative performance II	Remedial performance data for other ISBR RAs	Comparison attained

3.1 PERFORMANCE OBJECTIVE 1: METRIC I

The governing hypothesis for all three metrics is that implementation of the remedial actions will cause a reduction in resident COC concentrations of at least 30-50% from baseline. This is based on the range specified in the site remedial plan, which was determined to provide sufficient reduction to meet the site cleanup performance objectives. This is detailed in the final Optimized Exit Strategy Plan for the site, which was reviewed and approved by the Air Force Civil Engineer Center (URS, 2013). Thus, it is anticipated that implementation of the RAs will result in a decrease in COC concentrations in groundwater.

Metric I consists of collecting COC concentration data for 1-4 designated monitoring wells located within the treatment zone to monitor the anticipated decreases. The objective for Metric I is to obtain at least 3 years of post-treatment monitoring data for each RA conducted at the project site.

Three years is deemed sufficient to conduct a robust long-term performance assessment, based on the results of prior research (e.g., Brusseau et al., 2011; McGuire et al., 2016).

3.1.1 Data Requirements

The technology remedial effectiveness will be evaluated on the basis of contaminant concentration reductions in groundwater within the zone of treatment. Data required for the remedial effectiveness assessment include pre- and post-treatment contaminant concentrations in the treated media. Groundwater samples for contaminant concentration characterization are collected and analyzed both before and after the RA implementation. These data were collected by the site contractor per contract requirement (URS, 2015).

3.1.2 Success Criteria

The objective will be considered to be met if COC data are collected for a period of at least 3 years after completion of the RA.

3.2 PERFORMANCE OBJECTIVE 2: METRIC II

Metric II is based on collecting COC concentration data for 17 monitoring wells located within the treatment zone of site DP003. The objective for Metric II is to obtain at least 3 years of post-treatment monitoring data for the RA conducted at the project site.

3.2.1 Data Requirements

Groundwater samples for contaminant concentration characterization are collected and analyzed both before and after the RA implementation.

3.2.2 Success Criteria

The objective will be considered to be met if COC data are collected for a period of at least 3 years after completion of the RA.

3.3 PERFORMANCE OBJECTIVE 3: METRIC III

Metric III is based on collecting COC concentration data for two extraction wells located downgradient of the treatment zone of site DP003. The objective for Metric III is to obtain at least 3 years of post-treatment monitoring data for the RA conducted at the project site.

3.3.1 Data Requirements

Groundwater samples for contaminant concentration characterization are collected and analyzed both before and after the RA implementation.

3.3.2 Success Criteria

The objective will be considered to be met if COC data are collected for a period of at least 3 years after completion of the RA.

3.4 PERFORMANCE OBJECTIVE 4: REBOUND ANALYSIS

This objective is based on evaluating the occurrence of rebound after RA implementation.

3.4.1 Data Requirements

Groundwater samples for contaminant concentration characterization are collected and analyzed for an extended period after the RA implementation.

3.4.2 Success Criteria

The objective will be considered to be met if COC data are collected for a period of at least 3 years after completion of the RA.

3.5 PERFORMANCE OBJECTIVE 5: COMPARATIVE PERFORMANCE I

This objective will provide a comparison of remedial performance data for other fracturing-enhanced RAs.

3.5.1 Data Requirements

RA performance data for other projects using fracturing to enhance amendment delivery for ISBR or ISCR.

3.5.2 Success Criteria

The objective will be considered to be met if sufficient data sets are available for comparison.

3.6 PERFORMANCE OBJECTIVE 6: COMPARATIVE PERFORMANCE II

This objective will compare remedial performance data for other ISBR RAs.

3.6.1 Data Requirements

RA performance data for other projects using ISBR for chlorinated-solvent contaminated sites.

3.6.2 Success Criteria

The objective will be considered to be met if sufficient data sets are available for comparison.

4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND HISTORY

The project was conducted using data and information obtained for RAs conducted at the Air Force Plant 44 site, which is part of the Tucson International Airport Area federal Superfund site located in Tucson, AZ. The TIAA site was placed on the EPA National Priorities List in 1983. The TIAA site comprises several primary source zones and a large, several kilometer long, groundwater contaminant plume that resides in the regional aquifer (see Figure 5). Trichloroethene and 1,4-dioxane are the primary contaminants of concern (COC) for the regional groundwater plume. Chromium is also present in localized zones.

The AFP44 section of the TIAA site encompasses the southern part of the Superfund complex.

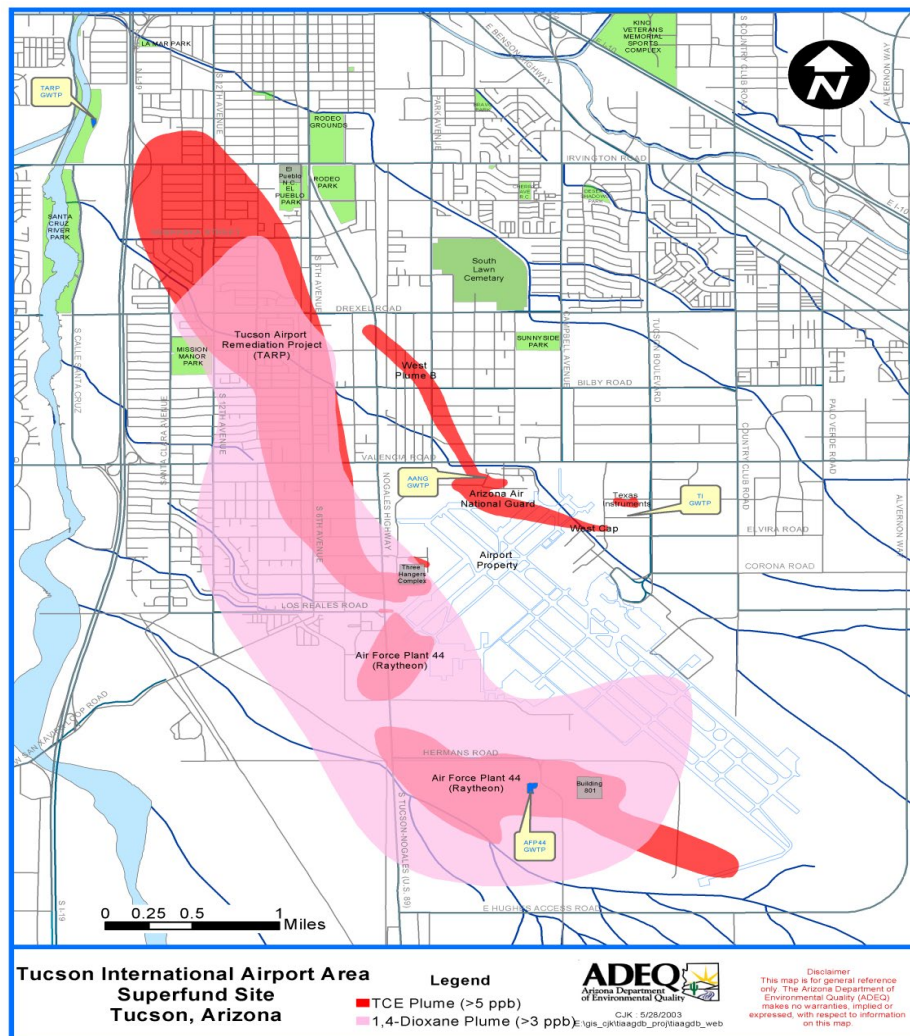


Figure 5. Map of TIAA Site.

Multiple remediation efforts have been conducted at the AFP44 site. A large-scale pump-and-treat system has been in operation since 1987. Soil vapor extraction has been conducted at all three DNAPL source zones. The SVE operations were completed prior to the initiation of additional remediation projects focused on the saturated zones of the source zones.

ISCO was conducted at DP003 and DP002. Full-scale implementation started in December 2002 at site 2 and October 2004 at site 3. The final injections occurred in December 2005 and August 2006 for sites 2 and 3, respectively. ISBR was conducted at DP003, DP002, and DP005 starting in late 2014 and completed in early to mid 2015.

4.2 SITE GEOLOGY/HYDROGEOLOGY

The TIAA Superfund site is located in the Tucson Basin, which is underlain by several thousand feet of alluvial sediments interbedded locally with volcanic flows, agglomerates, and tuffaceous sediments. The major hydrogeologic units in the area of the site have been designated as (in descending order with depth): the Unsaturated Zone, the Upper Aquifer, an Aquitard Unit, and the Lower Aquifer (GRC, 1991). The Unsaturated Zone extends from the land surface to the regional groundwater surface, which is located ~40-50 m below ground surface. Soil and groundwater contamination resides primarily in the Unsaturated Zone, the Upper Aquifer, and the Aquitard Unit.

The subsurface is highly heterogeneous, with hydraulic conductivities spanning many orders of magnitude. Laterally extensive low-permeability (clay) units reside both below and above the regional aquifer. Prior characterization and research projects indicate that the remaining high levels of contamination are associated primarily with these poorly-accessible low-permeability units (Brusseau et al., 2007, 2013; URS, 2013). This current site condition is representative of a great majority of DoD sites contaminated by chlorinated solvents.

4.3 CONTAMINANT DISTRIBUTION

Contaminants are believed to have entered the subsurface by seepage from unlined pits and ponds used during the late 1950s to mid 1970s for disposal of organic solvents. The site contains multiple primary source zones at which the presence of solvent liquid (DNAPL) has been confirmed. Due to past disposal practices, elevated concentrations of chromium are also present in the vicinity of the source zones. Three of these source zones, designated as DP002, DP003, and DP005, have been the focus of aggressive remediation projects.

5.0 TEST DESIGN

The project is designed to accomplish a robust, long-term assessment of the performance of ISCO and enhanced ISBR remediation technologies, and to compare performance to other RA projects. Specific technical questions to be addressed include:

- what is the long-term performance of fracturing-enhanced ISBR remediation for this specific application site.
- was rebound observed for the ISBR RA.
- how does the observed performance of the FE-ISBR project compare to the prior ISCO project conducted at the same site.
- how does the observed performance of the FE-ISBR project compare to other projects that have employed fracturing to enhance amendment delivery for ISBR or ISCR.
- how does the observed performance of the FE-ISBR project compare to other ISBR projects.
- do the alternative methods for assessing performance provide consistent results.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

Multiple technologies have been implemented at the site, which allows comparative analysis and evaluation of three high-profile, high-potential remediation technologies- ISCO, EDC-ISBR, and EAC-ISBR. These are generally three of the primary technologies that would most often be considered for source remediation at typical chlorinated-solvent sites. Multiple metrics will be used for the performance assessment, which will enhance the robustness of the analysis.

The remediation projects have been conducted at “full scale”, in an open aquifer environment. This is in contrast to many technology demonstrations that are conducted in a small subsection of a source zone, or are conducted within isolated test cells.

The primary COCs are TCE and dioxane, two of the most critical to DoD sites. In addition, site conditions (limited mass removal due to COC in lower-permeability units) are representative of a large majority of DoD sites with large groundwater contaminant plumes. Chromium is present at the site, which is another prominent COC at many DoD sites. Chromium is a primary co-contaminant of interest particularly for redox-based remediation technologies such as ISCO and ISBR. The presence of chromium provides an opportunity to evaluate the long-term impact of remediation on this critical co-contaminant.

SVE has been conducted at all of the source zones, and completed prior to the ISCO and ISBR operations. Thus, all source zones have been similarly subjected to SVE, producing a uniform initial condition for the tests. In addition, the fact that SVE operations have been conducted is beneficial in that it is representative of the status of most chlorinated-solvent sites (i.e., SVE is a standard remedy for most such sites).

5.2 BASELINE CHARACTERIZATION

The PI has conducted several prior projects at the AFP44/TIAA site funded by the Air Force, SERDP, and NIEHS. Thus, a wealth of data are available to support the analysis of the project data.

For example, an advanced site characterization project was conducted to determine the transport and fate of contaminants at the site, and to delineate the occurrence and magnitude of DNAPL contamination in the source zones. The project consisted of several components, including traditional site-characterization activities, integrated contaminant elution and tracer tests, laboratory experiments, and mathematical modeling. This information was used to enhance the site conceptual model and help optimize operation of the pump-and-treat system.

Several sets of laboratory experiments were conducted, using aquifer material collected from the site, to examine the influence of various mass-transfer processes on contaminant transport (Johnson et al., 2003a, 2003b, 2009). Several sets of tracer tests have been conducted at the study site. Standard non-reactive tracer tests were conducted to characterize vertical variability of mean pore-water velocities and to determine effective dispersivities (Brusseau et al., 1999). Multiple non-reactive tracers with different diffusion coefficients were used for the tests to characterize the contribution of diffusive mass transfer to solute transport (Nelson et al., 2003). A biodegradable-tracer test was conducted to evaluate general in-situ microbial activity (Sandrin et al., 2004). Partitioning tracer tests were conducted within the source zones to delineate the occurrence and magnitude of DNAPL (Nelson and Brusseau, 1996; Simon and Brusseau, 2006). Induced-gradient contaminant elution tests (also called contaminant mass discharge tests) were conducted within the source zones to characterize mass-transfer and mass-removal behavior under controlled conditions (Brusseau et al., 2007). Three-dimensional groundwater flow and contaminant transport modelling was conducted to evaluate extant and modified site conceptual models, and to evaluate the impact of potential source-zone remediation operations (Zhang and Brusseau, 1998, 1999; Brusseau et al., 2007).

As noted in section 3, baseline concentration data for COCs in groundwater were collected by the site contractor.

5.3 TREATABILITY OR LABORATORY STUDY RESULTS

The ISBR method has been widely used at other chlorinated-solvent contaminated sites.

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The goal and objectives of the project were accomplished through the following tasks.

Task 1: Conduct a long-term performance assessment for ERD-based ISBR for source zone DP003. A long-term performance assessment will be conducted approximately three years after completion.

Task 2: Conduct a long-term performance assessment for EAC-based ISBR for source zone DP003. A long-term performance assessment will be conducted approximately three years after completion.

Task 3: Conduct a long-term performance assessment for ERD-based ISBR for source zones DP002 and DP005. A long-term performance assessment will be conducted approximately three years after completion.

Task 4: Compare ISBR and ISCO performance. Compare performance of ISBR to the prior ISCO.

Task 5: Compare ISBR performance to other fracturing-enhanced RAs.

Task 6: Compare ISBR performance to other ISBR RAs.

5.5 FIELD TESTING

The metrics used for the present study were applied in a prior study conducted at the site (Brusseau et al., 2011). This provides confidence in the ability to effectively employ them for the present study.

5.6 SAMPLING AND DATA ANALYSIS METHODS

Groundwater samples were collected by the site consultant in accordance with EPA guidelines on groundwater sampling at superfund sites. All analyses followed standard methods that are used extensively in the industry; consequently, details are not provided herein.

Selected monitoring wells located within the respective treatment zones were used for sample collection. Samples were collected monthly for the short-term assessment period. Samples were collected semi-annually for the longer-term assessment period.

The designated performance monitoring wells set by the contractor for ERD-ISBR in site DP003 are M96, M98, and M100. The designated performance monitoring well for EAC-ISBR in site DP003 is M69. The designated performance monitoring wells for ERD-ISBR in site DP002 are M86, M87, M88, and M91. The designated performance monitoring wells for ERD-ISBR in site DP005 are E26, E27, and E29. Data collected from these wells are used for Metric I.

The monitoring wells used for Metric II are shown in Figure 6. Also shown in the figure are the two extraction wells used for Metric III.

The data were analyzed and reported using the %-Reduction index. This is the most common manner in which performance data are reported. It is calculated as: $(C_i - C_f)/C_i \times 100$, where C_i is the concentration for the pre-treatment period and C_f is the concentration for the post-treatment period. The geometric means of data reported over the years 2011-2014 are used to obtain a single representative C_i for the pre-treatment period for each monitoring well. The final concentrations collected for the monitoring period are used for C_f . The geometric means of concentrations for each well are used to obtain a single set of C_i and C_f values for each RA.

In addition, the order-of-magnitude reduction will be evaluated where appropriate, recognizing the effectiveness of log-scale assessments of changes in concentrations and masses (e.g., Brusseau, 2013; McGuire et al., 2016). The order-of-magnitude reduction is calculated as: $-\log(C_f/C_i)$.

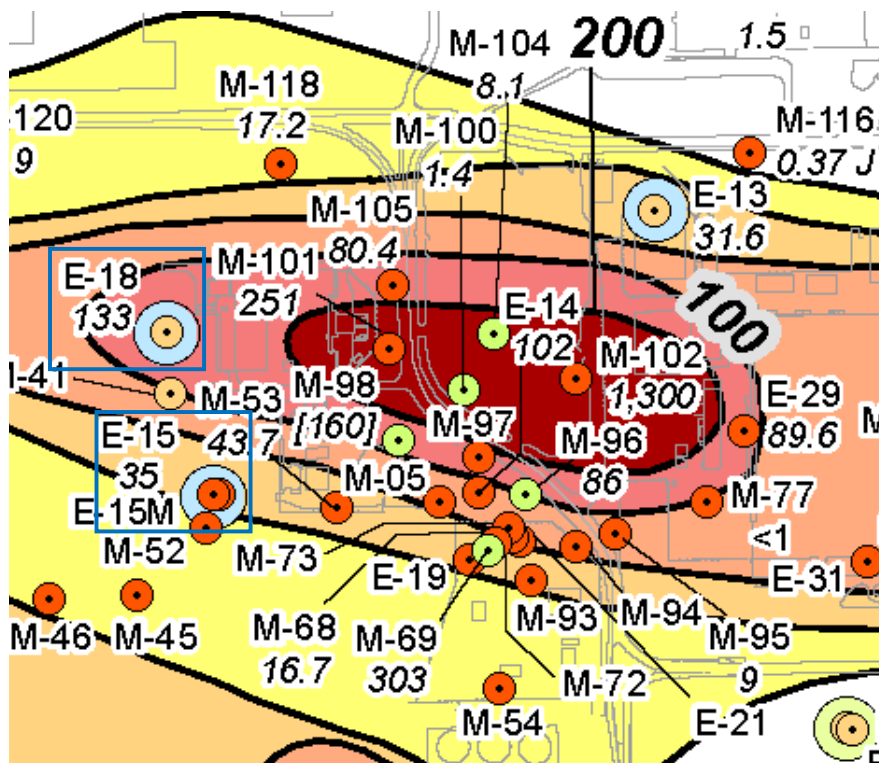


Figure 6. Map of Site DP003 with Monitoring Wells Identified.

The two blue squares denote the extraction wells located downgradient of the treatment zone. The blue shading around the two wells denotes groundwater extraction.

5.7 ASSESSMENT RESULTS

5.7.1 Performance of ISBR

A total of 9-10 sample sets were collected over the ~3-year monitoring period for TCE, dioxane, and chromium for the designated performance monitoring wells. The data are presented in Tables in Appendix B. The concentrations are rounded to the nearest decimal. It is observed that concentrations declined for most COCs for most wells. However, increases were observed for some sampling periods.

The %-reduction performances of the ISBR RAs based on assessment of the COC data collected for the contractor-designated performance-monitoring wells are presented in Table 2.

ERD-ISBR was observed to be very effective for TCE treatment in site DP003, with a 94% reduction, equivalent to a 1.2 order-of-magnitude reduction in concentration. It was also effective for chromium, with an 83% reduction. The %-reduction for dioxane was 36%. The %-reduction for TCE and chromium for sites DP002 and DP005 are lower than observed for site DP003.

The observation of cis-1,2-dichloroethene, vinyl chloride, ethene, and ethane in groundwater samples after the RA implementation supports that reductive dechlorination was initiated in the treatment zone (see Figure 7).

Table 2. Performance of ISBR at AFP44 Based on Designated Monitoring-well Data

	TCE	Dioxane	Chromium
Site 3 ERD-ISBR			
% Reduction	94	36	83
OOM Reduction	1.2	0.2	0.8
Site 3 EAC-ISBR			
% Reduction	60	92	0
OOM Reduction	0.4	1.1	0.0
Site 2 ERD-ISBR			
% Reduction	34	-	13
OOM Reduction	0.2	-	0.1
Site 5 ERD-ISBR			
% Reduction	20	-	38
OOM Reduction	0.1	-	0.2

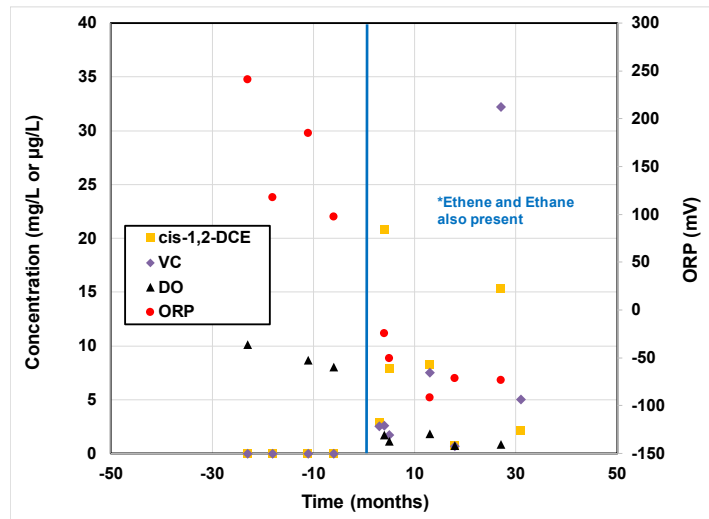


Figure 7. Concentrations of Various Analytes Before and After Implementation of ERD-ISBR at site DP003.

Dissolved oxygen (DO) is in mg/L units; cis-1,2-DCE and VC are in µg/L units.

EAC-ISBR was used in a localized section of site DP003 to address high concentrations of dioxane present. It was very effective for this purpose, with a reduction of 92% achieved. It was moderately effective for TCE, with a 60% reduction. It is noteworthy that the concentrations of chromium remained essentially unchanged over the course of the EAC-ISBR treatment. This indicates that the generation of aerobic conditions had no measurable impact of chromium levels in groundwater.

5.7.2 Performance Based on Alternative Metrics

The contractor for the ISCO RA project selected 17 monitoring wells in the treatment zone of site DP003 to use for performance assessment for TCE remediation. Data were collected for these same wells to conduct an equivalent performance assessment for ISBR at site DP003 (Metric II). These results are presented in Table 3.

Table 3. Performance of ISBR at Site DP003 Based on Data Reported for 17 Monitoring Wells

TCE [µg/L]	Before	After
MW	2011-2014	July 2018
E14	100	102
E15	110	35
E19	58	10
E21	27	20
M104	16	8
M102	374	1300
M101	345	251
M100	317	1
M98	451	160
M97	100	120
M96	218	86
M95	161	9
M94	330	15
M93	50	10
M92	47	-
M53	48	44
M05	7	40
Geomean	96	37
% Reduction	62	

A reduction of 62% is obtained for TCE for site DP003. This is lower than the 94% decrease observed for ERD-ISBR at site DP003 based on the three designated performance-monitoring wells. This disparity may reflect the specific locations of the performance-monitoring wells versus the broader coverage provided by the 17 wells distributed across the treatment zone. The use of a small number of monitoring wells is likely to cause greater uncertainty in the results due to spatial variability.

A reduction of 34% for TCE is obtained based on the extraction-well data (Metric III). This value is likely to be lower than the actual value because data were not collected until starting approximately 9 months after completion.

5.7.3 Performance Comparison to ISCO

ISCO was conducted at site DP003 and DP002 years prior to ISBR implementation. Aggregate reduction in TCE concentrations of 68% and 87% were reported by the contractor based on data collected from the selected 17 and 12 monitoring wells, respectively, in the treatment zones for the two sites. These values were calculated using arithmetic means of the individual monitoring-well concentrations.

The %-reduction was recalculated for the present study using geometric means to be consistent with the ISBR data analysis. The recalculated %-reductions are 75% and 64% for DP003 and DP002, respectively. It is noteworthy that the value for DP003 is identical to the reduction determined by Brusseau et al. (2011) using CMD tests conducted in the DP003 treatment zone. This provides confidence in the robustness of the %-reductions determined using concentration data obtained from a relatively large number of monitoring wells located within the treatment zone.

The %-reduction performances of ISCO and ISBR at site DP003 are in a similar range, 75% versus 62%.

It is noted that the %-reductions for the two RAs conducted at site DP003 and the one conducted at site DP002 are all greater than the %-reduction for DP005 (see Table 1). Recall that ISCO was conducted prior to the ISBR RAs at sites DP003 and DP002, but not at site DP005. These results may indicate that ISBR was more effective at the locations at which ISCO was conducted previously. However, it is also noted that the initial concentrations of TCE at sites DP003 (494 µg/L) and DP002 (227 µg/L) were significantly greater than at site DP005 (45 µg/L). Hence, the greater %-reductions observed for DP003 and DP002 may reflect the higher initial concentrations.

It is observed that the %-reduction for TCE reported for site DP002 is substantially lower than that reported for DP003, even though ISCO was previously conducted at both sites. One possible reason for this disparity is that site DP002 has a much greater proportion of lower permeability media present compared to DP003. However, it should be noted that the performance reported for site DP002 is based on a small number of monitoring wells.

5.7.4 Analysis of Concentration Rebound

Some evidence of concentration rebound was observed, as illustrated in Figure 8. Rebound appears to be complete after approximately 2-3 years. A rebound period of approximately 1 year was observed for the prior ISCO RA conducted at site DP003.

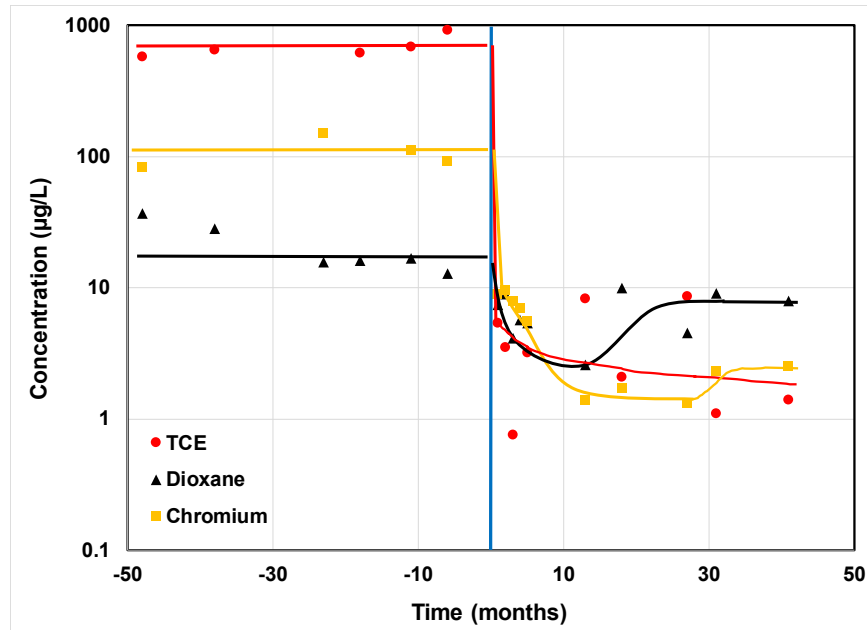


Figure 8. Concentrations of the COCs Before and After Implementation of ERD-ISBR at Site DP003.

5.7.5 Performance Comparison to other Fracturing-enhanced RAs

A literature search revealed only a few case studies of prior applications of fracturing for enhancing amendment delivery for ISBR or ISCR conducted in unconsolidated media. The performance comparison of the projects is presented in Table 3.

Table 4. Comparison of Remediation Performance for Fracturing-enhanced RAs

Site	COC	RA	Performance Period (yr)	% Reduction	Source
Site 3 AFP44	TCE	ISBR	3.4	62	This study
Site 2 AFP44	TCE	ISBR	3.2	34	This study
Site 5 AFP44	TCE	ISBR	3.4	20	This study
FEW AFB	TCE	ISBR	3	84	URS 2008, 2011
Hunters	CHL	ISCR	1	98	NAVFAC 2014
Danish	TCE	ISCR	0.5	>50	Wragg et al. 2016
MCC AFB	TCE	ISCR	0.25	28	Dyson et al. 2019

A range of %-reductions are observed. It is noted that the value reported for the MCC AFB site is likely to be smaller than the actual longer-term reduction.

5.7.6 Performance Comparison to other ISBR RAs

McGuire et al. (2016) conducted a meta-analysis of enhanced anaerobic bioremediation projects conducted for sites wherein the original COCs were either PCE or TCE. The median concentration reduction was 90% for 34 sites for which the performance monitoring period was at least 3 years.

Tillotson and Borden (2017) conducted a meta-analysis of enhanced reductive dechlorination bioremediation projects conducted for 37 sites with chlorinated ethene contamination. The post-treatment monitoring periods ranged from 4 months to 11 years. Only 4 sites overlapped with the analysis conducted by McGuire et al. (2016). The median reduction in PCE and TCE concentrations was ~90%, identical to that reported by McGuire et al.

The combined studies provide a data set of 67 sites for ISBR performance for PCE and TCE treatment. It is observed that the %-reductions reported for AFP44 in Table 1 range from below to similar to the median 90% literature value.

5.7.7 Performance Comparison of Assessment Timeframe

Concentrations of the COCs measured after >3 years of monitoring were approximately 50% lower than the values measured after 3 months for a majority of the sampling points. Therefore, an inaccurate assessment of performance would have been obtained based on the typical short-term assessment period. This demonstrates the advantage of conducting longer-term performance assessments.

The results of this project indicate that concentrations stabilized prior to the 3-year monitoring period. Thus, the 3-year timeframe appears to have been sufficient to obtain a robust assessment of performance. This is consistent with the results of the meta-analysis conducted by McGuire et al. (2016), which indicated that 3 years was a sufficient period of monitoring for effective performance assessment. Thus, it is suggested that future RA projects involving ISBR or ISCO/R employ a 3-year monitoring period to produce robust performance assessments.

6.0 PERFORMANCE ASSESSMENT

6.1 PERFORMANCE OBJECTIVE 1: METRIC I

Monitoring data were collected for more than three years after completion of the ISBR RAs, as discussed in section 5. Thus, the performance objective was successfully met. The data sets provide the ability to evaluate the long-term performance of ISBR at AFP44 based on Metric I, as discussed in Section 5.

6.2 PERFORMANCE OBJECTIVE 2: METRIC II

Monitoring data were collected for more than three years after completion of the ISBR RAs, as discussed in section 5. Thus, the performance objective was successfully met. The data sets provide the ability to evaluate the long-term performance of ISBR at AFP44 based on Metric II, as discussed in Section 5.

6.3 PERFORMANCE OBJECTIVE 3: METRIC III

Monitoring data were collected for approximately two years after completion of the ISBR RAs, as discussed in section 5. Thus, the performance objective was partially met. The data sets provide the ability to evaluate the long-term performance of ISBR at AFP44 based on Metric III, as discussed in Section 5.

6.4 PERFORMANCE OBJECTIVE 4: REBOUND ANALYSIS

Monitoring data were collected for more than three years after completion of the ISBR RAs, as discussed in section 5. Thus, the performance objective was successfully met. The data sets provide the ability to evaluate the occurrence of rebound after RA implementation.

6.5 PERFORMANCE OBJECTIVE 5: COMPARATIVE PERFORMANCE I

Remedial performance data for other fracturing-enhanced RAs were obtained from the literature. These data supported a comparison of the present-study RA performance to others, as discussed in Section 5. Thus, the performance objective was successfully met.

6.6 PERFORMANCE OBJECTIVE 6: COMPARATIVE PERFORMANCE II

Remedial performance data for a large number of ISBR projects conducted specifically for PCE and TCE were available from two recent meta analyses. These data provided an excellent index of performance for comparison of the ISBR RAs evaluated in the present study, as discussed in Section 5. Thus, the performance objective was successfully met.

7.0 COST ASSESSMENT

Extending the monitoring period from 3 months to 3 years will result in the collection and analysis of additional samples. The exact number of samples will depend upon the selected frequency of sampling and the number of wells sampled. For illustration, one can select a sampling period of every 4 months and 10 monitoring wells to be sampled. This would result in an additional 8 sample sets for each well, and a total of approximately 300 samples including trip/field blanks and some duplicates. Additional costs would be accrued from personnel and travel. Overall, the additional costs associated with the extended monitoring would be relatively minor in the general scheme of a typical RA project budget.

8.0 IMPLEMENTATION ISSUES

No implementation issues were encountered with the extended monitoring for this project. In general, a primary potential constraint to implementing performance assessments with longer time frames is the delayed delivery of performance results. This would cause delays in project completions and the attendant decision making. It would be necessary to plan for this before starting the project.

9.0 RESULTS OF ADDITIONAL ANALYSES

A question of interest for site characterization, including remedial performance assessment, is the effectiveness of different monitoring methods for systems influenced by significant heterogeneity. The influence of heterogeneity on monitoring-well sampling has been investigated in prior studies. The purpose of this analysis was to investigate the influence of well-field hydraulics and permeability heterogeneity on the effectiveness of the reduction in contaminant mass discharge metric for remediation efficiency.

A three-dimensional numerical model was used to simulate the impacts of different well-field configurations and magnitudes and types of permeability heterogeneity on pump-and-treat mass removal efficiency for large groundwater contaminant plumes. Four well-field configurations were tested, Longitudinal, Distributed, Downgradient, and enhanced natural gradient (with no extraction wells). See Figure 9 for a schematic of the configurations.

The results are presented in Figure 10. Systems whose CDMR-MR profiles are below the 1:1 relationship curve are associated with more efficient well-field configurations. For simulations conducted with the homogeneous domain, the CDMR-MR curves shift leftward, from convex-downward profiles for natural gradient and Longitudinal to first-order behavior for Distributed, and further leftward to a sigmoidal profile for the Downgradient well-field configuration. These results reveal the maximum potential impacts of well-field configuration on mass-removal behavior, which is attributed to mass-transfer constraints associated with regions of low flow.

In contrast, for the simulations conducted with the layered and 3-D distributed heterogeneities, the CDMR-MR relationships for the different well-field configurations exhibit convex-upward profiles. The nonideal mass-removal behavior in this case is influenced by both well-field configuration and back diffusion associated with low-permeability units.

Data collected from pump-and-treat operations conducted in a section of the TIAA federal Superfund site were used as a case study. The comparison between simulated and measured site data supports the general validity of the numerical model, and results from the case study are consistent with the conclusions of the theoretical study. These results illustrate that the CDMR-MR relationship can be an effective metric for assessing mass-removal efficiency.

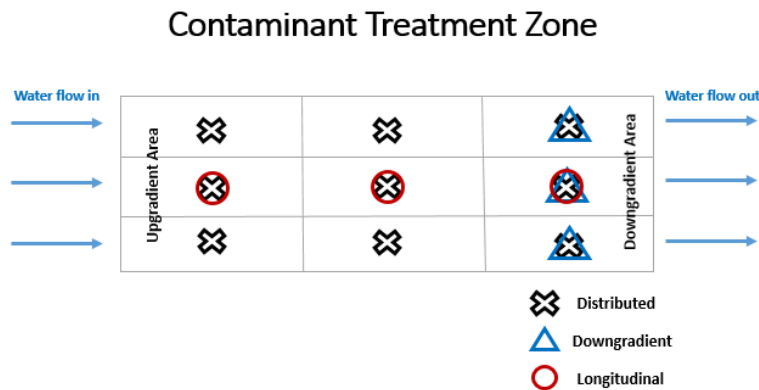


Figure 9. Schematic Presenting the Three Tested Well-field Configurations.

The fourth configuration tested was a natural-gradient system with no wells.

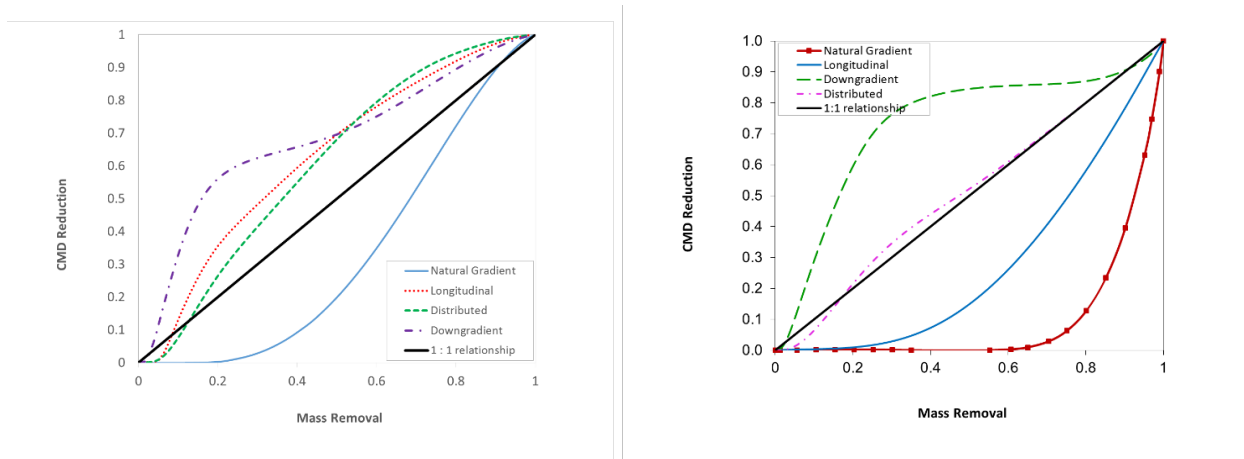


Figure 10. Impact of Well-field Configuration on Mass Removal Behavior in a Simulated 3D Domain.

Left: simulations conducted for a heterogeneous domain; right: simulations conducted for a homogeneous domain.

An integrated contaminant elution and tracer test toolkit, comprising a set of local-scale groundwater extraction-and injection tests, was developed to ameliorate the primary limitations associated with standard characterization methods. The test employs extended groundwater extraction to stress the system and induce hydraulic and concentration gradients. Clean water can be injected, which removes the resident aqueous contaminant mass present in the higher-permeability zones and isolates the test zone from the surrounding plume. This ensures that the concentrations and fluxes measured within the isolated area are directly and predominantly influenced by the local mass-transfer and transformation processes controlling mass removal. A suite of standard and novel tracers can be used to delineate specific mass-transfer and attenuation processes that are active at a given site, and to quantify the associated mass-transfer and transformation rates. The conceptual basis for the test was presented, followed by an illustrative application based on simulations produced with a 3-D mathematical model and a brief case study application.

Details of these analyses are presented in the following publications:

Guo, Z. and M.L. Brusseau, 2017. The impact of well-field configuration and permeability heterogeneity on contaminant mass removal and plume persistence, *J. Hazard. Mater.* 333, 109–115.

Guo, Z. and M.L. Brusseau, 2017. The impact of well-field configuration on contaminant mass removal and plume persistence for homogeneous versus layered systems. *Hydrol. Proc.* 31, 4748–4756.

Brusseau, M.L. and Z. Guo, 2018. The integrated contaminant elution and tracer test toolkit, ICET3, for improved characterization of mass transfer, attenuation, and mass removal. *J. Contam. Hydrol.* 208, 17–26.

10.0 CONCLUSION

This report summarizes the results of this ESTCP project designed to conduct a long-term assessment of the performance of fracturing-enhanced in-situ bioremediation (ISBR) at a site contaminated by trichloroethene, 1,4-dioxane, and chromium. The project was conducted at Air Force Plant 44, which is part of the Tucson International Airport Area federal Superfund site located in Tucson, AZ. The site comprises several primary source zones and a large, several kilometer long, groundwater contaminant plume that resides in the regional aquifer. The remedial action and performance monitoring were conducted by the Air Force contractor.

Performance monitoring data were obtained for a period of greater than 3 years after completion of ISBR. The project focused on treating the interface between the vadose zone and saturated zone. This interface region, which consists of primarily lower-permeability (clay) media, has been identified as a primary location for remaining COC. Slow release of COC from this domain is considered a primary cause of the observed delayed attainment of cleanup objectives.

The project produced the following outcomes:

Key Result 1: ISBR employing enhanced reductive dechlorination (ERD) was effective. TCE, chromium, and dioxane concentrations at site DP003 were reduced by 94, 83, and 36%, respectively. The observation of cis-1,2-dichloroethene, vinyl chloride, ethene, and ethane in groundwater samples after ISBR implementation (but not before) supports that reductive dechlorination of TCE was initiated in the treatment zone.

Key Result 2: ISBR employing enhanced aerobic cometabolism (EAC) was effective. Dioxane and TCE concentrations at site DP003 were reduced by 92 and 60%, respectively. The concentrations of chromium remained essentially unchanged over the course of the EAC-ISBR treatment, which indicates that the generation of aerobic conditions had no measurable impact on chromium levels in groundwater.

Key Result 3: The performance results are consistent with other field tests. A meta-analysis was recently reported of enhanced anaerobic bioremediation projects conducted for sites wherein the original COCs were either PCE or TCE. The median concentration reduction was 90% for 34 sites for which the performance-monitoring period was at least 3 years. The %-reductions observed for the present study are consistent with the meta-data.

Key Result 4: The longer-term performance assessment period provided a more robust assessment. Concentrations of the COCs measured after >3 years of monitoring were approximately 50% lower than the values measured after 3 months for a majority of the sampling points. This demonstrates the advantage of conducting longer-term performance assessments. The results of this project indicate that concentrations stabilized prior to the 3-year performance assessment. Thus, the 3 year timeframe appears to have been sufficient to obtain a robust assessment of performance. This is consistent with the results of the meta-analysis conducted by McGuire et al. (2016), which indicated that 3 years was a sufficient period of monitoring for effective performance assessment.

The primary potential constraints to implementing performance assessments with longer time frames are the additional costs and the delayed delivery of performance results. This latter factor would cause delays in project completions. The costs associated with the additional monitoring are likely to be relatively minor in the overall scheme of a typical project budget. Regarding the extended time to project completion, it would be necessary to plan for this before starting the project.

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APPENDIX A POINTS OF CONTACT

List all the important points of contact (POC) involved in the demonstration, such as co-investigators, sponsors, industry partners, and regulators. The list should include the following information: (1) full name; (2) complete mailing and/or FedEx addresses (if different); (3) telephone number, fax number, and e-mail address; and (4) the role of the individual in the project.

Use the tabular format below:

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Mark Brusseau	University of Arizona Dept of Environmental Science	520-621-1646 520-621-1647 brusseau@email.arizona.edu	PI

APPENDIX B SAMPLING DATA

Table B-1. Concentration data for site DP003.

M96				
Months after Completion	Sample Date	TCE ug/L	14Dioxane ug/L	Chromium ug/L
-	Before RA	267	14	18
1	March 2015	839	7	13
2	April 2015	79	7.1	119
3	May 2015	155	12	15
4	June 2015	141	11	14
6	August 2015	132	11	22
13	March 2016	92	9	13
18	August 2016	141	12	16
27	May 2017	139	9.7	12
31	Sept 2017	94	10	14
41	July 2018	86	11	12

Table B-2. Concentration data for site DP003.

M98				
Months after Completion	Sample Date	TCE ug/L	14Dioxane ug/L	Chromium ug/L
-	Before RA	436	70	61
1	March 2015	317	86	439
2	April 2015	201	54	329
3	May 2015	338	949	46
4	June 2015	258	62	397
6	August 2015	333	121	43
13	March 2016	284	103	459
18	August 2016	325	145	319
27	May 2017	198	48	31
31	Sept 2017	160	579	19
41	July 2018	-	-	-

Table B-3. Concentration data for site DP003.

M100				
Months after Completion	Sample Date	TCE ug/L	14Dioxane ug/L	Chromium ug/L
-	Before RA	678	20	106
1	March 2015	5.4	7.4	8.9
2	April 2015	3.5	8.9	9.6
3	May 2015	0.8	4.1	7.9
4	June 2015	-	5.7	6.9
6	August 2015	3.2	5.4	5.5
13	March 2016	8.2	2.6	1.4
18	August 2016	2.1	10	1.7
27	May 2017	8.6	4.5	1.3
31	Sept 2017	1.1	9.1	2.3
41	July 2018	1.4	7.9	2.5

Table B-4. Concentration data for site DP003.

M69				
Months after Completion	Sample Date	TCE ug/L	14Dioxane ug/L	Chromium ug/L
-	Before RA	754	3703	10
1	March 2015	784	1570	6.6
2	April 2015	964	1340	8.2
3	May 2015	639	1030	11
4	June 2015	851	1100	9.2
6	August 2015	604	961	9.9
13	March 2016	503	873	10
18	August 2016	436	851	9.1
27	May 2017	734	391	9
31	Sept 2017	408	192	11
41	July 2018	303	288	-

Table B-5. Concentration data for site DP002.

M86			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	232	31
2	July 2015	223	10
3	August 2015	247	8.8
4	Sept 2015	144	3.8
5	October 2015	123	7.9
9	Feb 24 2016	166	10
15	Aug 2016	188	3.5
24	May 2017	195	12
28	Sept 2017	194	12
38	July 2018	120	14

Table B-6. Concentration data for site DP002.

M87			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	571	27
2	July 2015	706	13
3	August 2015	534	13
4	Sept 2015	510	12
5	October 2015	527	13
9	Feb 24 2016	519	10
15	Aug 2016	884	9.9
24	May 2017	712	9.8
28	Sept 2017	936	10
38	July 2018	881	13

Table B-7. Concentration data for site DP002.

M88			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	312	49
2	July 2015	305	40
3	August 2015	288	37
4	Sept 2015	177	168
5	October 2015	171	41
9	Feb 24 2016	232	39
15	Aug 2016	239	33
24	May 2017	214	34
28	Sept 2017	162	50
38	July 2018	172	39

Table B-8. Concentration data for site DP002.

M91			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	65	88
2	July 2015	85	211
3	August 2015	72	562
4	Sept 2015	76	242
5	October 2015	81	85
9	Feb 24 2016	58	81
15	Aug 2016	66	213
24	May 2017	41	-
28	Sept 2017	32	339
38	July 2018	27	298

Table B-9. Concentration data for site DP005.

E26			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	6.1	14
2	April 2015	23	1.5
3	May 2015	20	0.5
4	June 2015	2.1	16
6	August 2015	8.8	11
13	March 2016	54	43
18	August 2016	19	1.9
27	May 2017	32	-
31	Sept 2017	36	3
41	July 2018	32	5

Table B-10. Concentration data for site DP005.

E27			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	97	306
2	April 2015	36	45
3	May 2015	43	29
4	June 2015	5.5	48
6	August 2015	19	74
13	March 2016	47	660
18	August 2016	91	1050
27	May 2017	89	1350
31	Sept 2017	66	688
41	July 2018	78	818

Table B-11. Concentration data for site DP005.

E29			
Months after Completion	Sample Date	TCE ug/L	Chromium ug/L
-	Before RA	155	130
2	April 2015	30	32
3	May 2015	180	108
4	June 2015	71	88
6	August 2015	69	45
13	March 2016	148	138
18	August 2016	33	80
27	May 2017	110	54
31	Sept 2017	115	53
41	July 2018	90	31

APPENDIX C INTEGRATED CONTAMINANT ELUTION & TRACER TEST TOOLKIT

1. The ICET³ Method

The integrated contaminant elution and tracer test toolkit (ICET³) method is an integration of aquifer-perturbation and tracer-test methods, coupled with the use of standard and novel tracers to target specific individual mass-transfer and attenuation processes (see Figure 11). It employs extended groundwater extraction to stress the system and induce and increase hydraulic and concentration gradients. In many cases, this serves to enhance the sensitivity of the method by perturbing extant magnitudes and rates of mass transfer and transformation. This also reduces the time required for obtaining quality measurements, and thus increases the ability to obtain measurements in reasonable timeframes. Injection wells can be employed for injection of clean water, which ensures that the concentrations and fluxes measured within the isolated area are directly and predominantly influenced by the local mass-transfer and transformation processes controlling mass removal. The suite of tracers is selected to allow characterization of specific processes, and quantification of associated rate coefficients.

The test interrogates a much larger volume compared to borehole-based methods, reducing uncertainty associated with spatial variability. The spatial domain interrogated by the test can be scaled according to site conditions and test objectives, which allows for cost-effective optimization of the test. The test can be conducted multiple times to characterize the impact of natural temporal variability or that of human-induced perturbations.

During the ICET³ test, groundwater samples are collected periodically from the extraction well (and monitoring wells if desired), and analyzed for the target constituents (contaminants of concern, tracers, nutrients, transformation products). The constituent concentrations are used to produce elution curves for the contaminants and breakthrough curves (comprising both arrival and elution waves) for the tracers. These curves provide the foundation data sets for the various applications of the method. It should be noted that groundwater levels can be monitored during the test to provide data for characterization of aquifer hydraulic properties.

2. Characterize mass removal and contaminant persistence

A primary application for the standard and integrated CET is its use for characterization of mass-removal behavior. Generally, it constitutes the most effective method for such characterization. The contaminant elution curves are inspected to determine the type of behavior exhibited. Specifically, the elution-curve profiles are examined for specific landmarks such as the presence and extent of steady-state (relatively uniform concentrations) and asymptotic (slow rate of decrease to low concentrations) stages, as well as distinct changes in slope. The observed behavior is interpreted in conjunction with the site conceptual model to evaluate mass-removal scenarios and help identify the one most likely representative of the extant system. This information is used to evaluate the potential impact of rate-limited mass-transfer or transformation processes on contaminant transport and fate.

When interpreting elution-curve data, it is critical to deconvolute the impact of the regional plume from the local processes influencing mass transfer and attenuation. In addition, it is important to recognize that the observed behavior is an aggregation of all factors and processes influencing mass removal. Data analysis and interpretation should always be reflective of this reality. This leads to the next application, delineation of specific processes.

3. Delineate specific mass-transfer and attenuation processes

As discussed in the preceding subsection, CET data can be used to evaluate the impact of mass-transfer and attenuation processes on mass removal. This analysis can be extended to identify specific operative processes. In this regard, interpretation of the test results is relatively straightforward for a system in which a single mass-transfer or attenuation process is predominant. However, for many systems, contaminant transport and mass removal is influenced by multiple processes. In such cases, a suite of tracers can be used to help delineate and characterize specific processes and their respective impact on mass removal.

Various types of tracers can be used, each to target a specific transport, mass-transfer, or transformation process:

1. Conservative tracer- a conservative tracer, one that is not subject to sorption, other retention processes, or transformation reactions (i.e., an analogue to water) is used to characterize advective-dispersive transport, residence times, and flow heterogeneity. This standard tracer approach has been widely employed for site characterization. Additionally, multiple conservative tracers, with different molecular weights (i.e., diffusion coefficients), can be used to characterize specifically the occurrence of diffusive mass transfer (back diffusion) and its impact on contaminant transport. Specifically, for a system influenced by a diffusive mass-transfer process, the rates of mass transfer will differ for solutes with different diffusion coefficients. Thus, tracers with different diffusion coefficients should exhibit dissimilar transport behavior (e.g., different amounts of spreading, different extents of tailing) for a given set of conditions.
2. Sorptive/retention tracers- tracers can be used to characterize the impact of retention on transport. One example are tracers that are sorbed by the sediment to evaluate the impact of sorption and retardation on transport and mass transfer. Other examples include tracers selected to probe other potential retention processes, such as partitioning to NAPL, to fluid-fluid interfaces, and to trapped air phases. Related tracer-test methods involve the use of partitioning tracers to characterize the presence and quantity of NAPL present in source zones, water content in vadose zones, and the magnitude of fluid-fluid interface.
3. Biotransformation tracer- susceptible to biotransformation, but is not affected by abiotic transformation. This type of tracer is used to characterize the specific impact of biotransformation processes. Tracer tests conducted with biodegradable tracers have been used successfully to characterize the impact of biotransformation processes. Products of biotransformation can be monitored along with the target tracer to provide additional data.

4. Abiotic transformation tracer- susceptible to abiotic transformation, but is not affected by biotransformation. This tracer type is used to characterize the specific impact of natural abiotic transformation processes, such as mineral-induced reduction. Products of abiotic transformation can be monitored along with the target tracer to provide additional data. Note that tracers can be selected to characterize speciation changes for inorganics due to abiotic (or biotic for biotransformation) processes.

It should be noted that the tracers discussed above generally refer to surrogates for contaminants of concern at a site. Of course, actual contaminants of interest can be used as tracers in these tests as well, which has often been done at research sites. However, such use at typical contaminated sites is often precluded.

The use of this integrated tracer suite provides a means to identify the contributions of individual processes to mass removal, including back diffusion, desorption, biotransformation, and abiotic transformation. The use of injected tracers allows accurate determination of mass recoveries and associated magnitudes and rates of mass-transfer and transformation. Thus, the test can provide improved, quantitative determination of the specific contributions of individual processes to overall mass removal and persistence.

4. Other Applications

Contaminant mass flux or discharge (CMD) has become an alternate or supplemental metric for use in characterizing risk and evaluating the performance of remedial operations. Multiple methods are available to measure CMD, with the CET one such approach. The CET method has been used for example to measure CMD before and after a large-scale in-situ chemical oxidation project conducted at the TIAA Superfund site in Tucson to evaluate remedial operation performance (Brusseau et al., 2011).

The mass of contaminant present at the time of characterization and remediation, referred to herein as resident contaminant mass, is a critical parameter for assessing risk and evaluating remediation efforts for contaminated sites. Unfortunately, accurate determination of resident mass is generally problematic at most sites, with the standard characterization method (high-resolution coring) being typically cost-prohibitive to employ. However, resident mass can be estimated by fitting simple mass-depletion functions to measured CET data. For example, mass-depletion functions have been applied to CMD data obtained from CETs conducted within NAPL source zones.

The CET is ideal for evaluating the potential effectiveness of hydraulic-based remediation methods. For example, solutions of reagent(s) (e.g., surfactants, oxidants, electron acceptors, electron donors) associated with a remediation technology under consideration can be injected to test effectiveness. Essentially, these are implemented as pilot tests of the proposed technology. The data can be analyzed as has been discussed for the CET applications to enhance knowledge gained from the pilot tests.

5. Implementation

The design of the test and the selection of components employed will depend upon the objectives of the test and site conditions. The specific configuration of the well field, the operational pumping rates, and the length of the test are primary design variables. Multiple additional factors need to be considered to ensure successful implementation. Mathematical modeling can be conducted to assist in the design of the tests, and is particularly recommended for more complex systems. Further details are provided in the related publication.

Figure 11. The ICET³ Method.

