EXECUTIVE SUMMARY

This Panel 1 and 5 Surfactant Enhanced Aquifer Remediation (SEAR) Report documents the design, implementation, and results of the SEAR applications conducted at Operable Unit 2 (OU 2), Hill Air Force Base (AFB), Utah in two of five well arrays (panels) constructed within a shallow alluvial aquifer contaminated with dense nonaqueous phase liquid (DNAPL). The SEAR applications utilized foam generated *in situ* for mobility control and represent the first full-scale application of the surfactant/foam flooding process for DNAPL remediation. The design and implementation of these SEAR applications were based on the results obtained during the first full-scale application of micellar surfactant flooding conducted in Panel 2 during the fall of 1999.

The OU 2 site, located on the northeastern boundary of Hill Air Force Base in Utah, was used from 1967 to 1975 to dispose of chlorinated organic solvents from degreasing operations. These dense non-aqueous phase liquids (DNAPLs), primarily trichloroethene (TCE), were placed into unlined disposal trenches underlain by an alluvial sand aquifer. This shallow unconfined aquifer is composed of a heterogeneous mixture of sand and gravel, and is contained in a buried paleochannel eroded into thick clay deposits. The disposal of the spent solvents resulted in DNAPL contamination of the aquifer, predominately as a mobile phase pooled in topographic lows in the surface of the thick clay deposits and as an immobile or "residual" phase retained as ganglia by capillary forces in the alluvium's pore space.

A rigorous SEAR design program using both laboratory studies and predictive modeling was conducted to maximize DNAPL removal from the target zone while achieving the most efficient use of surfactant through the use of foam for mobility control. Due to the similarities of the Panels 1 and 5 SEAR to the Panel 2 surfactant flood, much of the laboratory work required for the design process had already been completed. However, additional experiments were conducted to provide data on the use of foam as a form of mobility control. The generation and propagation of foam *in situ* was intended to divert surfactant from the upper, uncontaminated portion of the paleochannel to the lower DNAPL-contaminated zone in each panel. It was anticipated that the use of foam would enhance the surfactant sweep efficiency through lower permeability zones resulting in a substantially higher DNAPL recovery.

The laboratory studies specifically investigated the feasibility of reducing or eliminating isopropyl alcohol (IPA) as a co-solvent from the surfactant formulation since IPA suppresses and destabilizes foam. IPA was used in previous surfactant floods, not only to eliminate the potential for forming liquid crystals and gels, but also to decrease equilibration or microemulsion coalescence times. Both the coalescence times as well as the viscosity of the contaminant-rich microemulsion required quantification to ensure that the selected surfactant formulation had acceptable phase behavior properties. In addition, it was necessary to investigate the characteristics of foam generation for the surfactant formulations being investigated. These laboratory study results were used as model parameters for numerical simulations conducted for each SEAR application using the University of Texas Chemical Flooding Simulator (UTCHEM) and the geosystem model (a comprehensive description comprised of the hydrostratigraphy, hydrogeology, and geochemistry of the aquifer, as well as the distribution and physicochemical properties of the DNAPL present in the system) developed for each panel.

An investigation also was conducted to evaluate treatment alternatives and process design parameters to mitigate down stream foam generation due to the SEAR well field effluent. During the Panel 2 SEAR conducted in 1999, the wastewater stream was not actively treated to mitigate foam generation following discharge from the SRS treatment facility. The SEAR well field effluent stream was subjected to gravity separation and steam stripping for VOC removal, and a defoaming agent was added to the wastewater stream prior to contaminant treatment to reduce foam generation during the stripping process. Although the defoaming agent was successful in mitigating foam generation at the SRS treatment facility, the surfactant-ladened wastewater discharged from OU 2 created foaming in the process units at the Hill AFB Industrial Wastewater Treatment Plant (IWTP) and a Publicly Owned Treatment Works (POTW) located in North Davis, Utah.

A preliminary identification of potential surfactant treatment technologies was conducted using a literature search and detailed discussions with several technical experts in the surfactant manufacturing and research field. Following the identification of potential technologies, site-specific treatment parameters were used to screen technologies for technical implementability. Bench-scale treatability studies were conducted on applicable technologies and the results were used both for selecting the proper treatment and associated design parameters, and for understanding the complex behavior of the treated SEAR wastewater stream. An understanding of the treated wastewater stream was necessary to ensure that the treatment process would not result in intermediate compounds and/or byproducts toxic to microorganisms used in wastewater treatment systems. Toxicological assessment of the treated wastewater was conducted to reduce the potential for an upset of the activated sludge unit and/or trickling filter of the off-Base POTW.

Based on the results of the treatability studies, base-promoted hydrolytic decomposition of the surfactant was selected to mitigate downstream foam generation/stability during SEAR applications at the OU 2 site. The hydrolysis was conducted using a heated 1,000-gallon fiberglass-reinforced plastic (FRP) process tank at a pH of approximately 13 with NaOH addition. The addition of NaOH was based on a 4 to 1 molar ratio of OH^- to MA-80I and was adjusted according to the surfactant concentration of the SEAR well field effluent. The temperature of reaction was maintained between 80 °C and 85 °C with a residence time of approximately 60 minutes.

The Panel 1 SEAR was conducted for approximately 41 days from 21 September 2001 to 1 November 2001. This SEAR consisted of 11 days of pre-surfactant brine flooding using a 0.90 wt% NaCl solution, 13 days of surfactant flooding with 4 wt% sodium dihexyl sulfosuccinate (MA-80I) and 0.90 wt% NaCl, and 17 days of post-surfactant brine/water flooding. Air was simultaneously injected with surfactant in a two-hour alternating mode to generate foam. The average total injection and extraction rates for the Panel 1 SEAR were 11.3 and 11.2 gallons per minute (gpm), respectively. Effluent DNAPL concentrations reached 30,000 mg/L during the surfactant flood and decreased to between 100 mg/L and 300 mg/L following the post-surfactant water flood.

The initial estimate of DNAPL contained in the Panel 1 aquifer, including the shadow zone located between the northern extraction wells and the OU 2 containment wall, was approximately 400 gallons.

Based on the effluent concentration data from the extraction wells and the estimate of free-phase DNAPL recovered from the monitoring wells, the Panel 1 SEAR recovered approximately 1,179 ±212 gallons of DNAPL. Quantification of DNAPL recovery at the SRS during the Panel 1 SEAR was estimated to be 1,139 ±72 gallons.

It is estimated that a substantial volume of the recovered DNAPL was forced from low permeability zones via *in situ* foam generation and propagation. The use of foam for mobility control also reduced the overall pore volume swept during the flood and forced surfactant along the bottom of the channel. This resulted in the recovery of approximately 478 gallons of DNAPL mobilized to the monitoring wells located within the Panel 1 well field. Approximately 80% of the DNAPL was recovered from the southern portion of Panel 1, consistent with the DNAPL distribution obtained from a pre-SEAR partitioning interwell tracer test (PITT) conducted previously. Effluent concentrations of contaminant in the shadow zone extraction wells located in the northern-most portion of Panel 1 were low and the wells were subsequently taken off line during the SEAR as designed.

Two primary factors were attributed to the improved recovery of DNAPL during the flood. The first was the installation of additional wells in the Panel 1 aquifer that resulted in an improved surfactant distribution during injection/extraction operations. The second factor was the use of foam for mobility control. The use of foam forced surfactant through the deepest portions of the aquifer and through lower permeability zones that were not swept during the pre-SEAR PITT. Both of these factors increased the volume of surfactant flushed through the contaminated zones and resulted in a substantially larger volume of DNAPL recovered than was detected by the pre-SEAR PITT.

The total recovery of surfactant during the Panel 1 SEAR was expected to be lower than during previous surfactant floods completed at OU 2 because of surfactant injection into the Panel 2 well U2-077. This well was designed to generate a hydraulic barrier between Panels 1 and 2 during the surfactant/foam flood. Although the design simulations predicted a loss of approximately 7,800 pounds of surfactant (11% of the total injected mass) over the course of the flood, the IPA data show that the total surfactant recovery was approximately 81% ± 16%. This recovery was somewhat lower than expected and is attributed to heterogeniety (lower permeabilities) in the northern portion of Panel 2.

The data obtained at the end of the Panel 1 SEAR indicated that although it appeared that the DNAPL in the northern half of the panel had been successfully removed, the southern end of the panel still contained some DNAPL. This was evident as the contaminant concentrations in the effluent for the southern extraction wells declined at the same rate as the surfactant concentration. Therefore, a small-scale surfactant/foam flood (hot spot treatment) was proposed to recover the remaining DNAPL from the southern half of the panel.

The hot spot treatment was conducted from 5 June 2002 to 13 June 2002 in the southern portion of the Panel 1 aquifer. Based on the effluent concentration data from the extraction and monitoring wells, the hot spot treatment recovered approximately 17 ±3 gallons of DNAPL. Quantification of DNAPL recovery at the SRS during the Panel 1 hot spot treatment was estimated to be 11 ±38 gallons. A majority of the DNAPL recovered during the hot spot treatment was produced by the monitoring well U2-147 located in a depression in the Alpine Clay surface.

At the conclusion of the Panel 1 SEAR, a design review meeting was conducted to assess the performance of the flood and suggest improvements to the Panel 5 SEAR design. The majority of improvements concerned the foam injection system and forcing the water level to the bottom of each screened interval more aggressively during surfactant flooding. Changes to the wellhead design were made to better monitor down-hole conditions. A second concern was the difference in the expected versus the actual DNAPL volume recovered during the Panel 1 SEAR. This issue was addressed by incorporating a more robust, worst-case scenario into the Panel 5 SEAR design. In addition to these issues, several improvements to the flow system were incorporated, including the addition of pre-treatment system effluent staging tanks and pulse flow dampeners to alleviate problems incurred by the pneumatic pump flow pulses.

The Panel 5 SEAR was conducted for approximately 21 days from 21 June 2002 to 12 July 2002. The SEAR consisted of 3 days of pre-surfactant brine flooding using a 1.0 wt% NaCl solution, 7 days of surfactant flooding with 4 wt% sodium dihexyl sulfosuccinate (MA-80I) and 1.0 wt% NaCl, and 11 days of post-surfactant brine/water flooding. Air was simultaneously injected with surfactant in a two-hour alternating mode to generate foam. The average total injection and extraction rates for the Panel 5 SEAR were 8.5 and 11.2 gpm, respectively.

Effluent DNAPL concentrations reached 33,000 mg/L during the surfactant flood and decreased to between 10 mg/L and 300 mg/L following the post-surfactant water flood. The correlation between foam generation/propagation and increased contaminant concentrations observed during the Panel 1 SEAR was not as evident in the contaminant concentration trends obtained during the Panel 5 SEAR. However, an increase in contaminant concentration was observed in well U2-207 at the peak of air injection into well U2-115 thus, indicating foam generation/propagation was successful in pushing contaminant into well U2-207. As the air injection rates were increased from 0.5 standard cubic feet per minute (scfm) to 1.5 scfm, contaminant concentrations increased from 1,600 mg/L to greater than 20,000 mg/L. The contaminant concentrations in well U2-207 rapidly declined to less than 30 mg/L during the post-surfactant water flood.

The initial estimate of DNAPL contained in the Panel 5 aquifer was approximately 360 gallons. Based on effluent concentration data from the extraction wells and the estimate of free-phase DNAPL recovered from the monitoring wells, the Panel 5 SEAR recovered approximately 371 ±52 gallons of DNAPL. Quantification of DNAPL recovery at the SRS during the Panel 5 SEAR was estimated to be 221 ±41 gallons. Approximately 78% of the DNAPL recovered during the Panel 5 SEAR was produced from extraction wells U2-211 and U2-207, consistent with the pre-SEAR PITT results indicating that the majority of the DNAPL was located in the deepest portion of the Panel 5 aquifer located between wells U2-207 and U2-204. The high contaminant concentrations (as high as 33,000 mg/L) at extraction well U2-211 accounted for 56% of the DNAPL recovered while an additional 21% was recovered at extraction well U2-207. Based on the IPA production curves, the total recovery of surfactant during the SEAR was estimated as approximately 98% ± 9%.

Surfactant treatment operations were successfully conducted at the SRS treatment facility during the Panel 1 SEAR and hot spot treatment, and during the Panel 5 SEAR. The SRS was manually operated 24 hours a day during surfactant injection and for several days during the post-surfactant water flood to mitigate the downstream foaming potential of the SEAR well field effluent. Approximately 4,000 gallons of 50 wt% sodium hydroxide were used to decompose the surfactant during the Panel 1 SEAR and 1,700 gallons were used during the Panel 1 hot spot treatment. During the Panel 5 SEAR, approximately 3,400 gallons of sodium hydroxide were used. Shake tests conducted on the treated SEAR effluent indicated minimal foam generation and a foam breakage time of a few seconds. This is compared with the significant foaming exhibited by the untreated SEAR effluent and a foam breakage time of greater than 2 minutes. Additionally, foaming was not observed at the Hill AFB IWTP or the North Davis POTW during the SEAR applications.

Although implementation of a post-SEAR PITT was included in the design of each SEAR application, PITTs were not conducted due the uncertainty associated with PITT technology in highly heterogeneous aquifer systems and the suspected remaining contaminant mass in isolated areas of each panel following each SEAR application. Thus, the performance assessment was comprised of the following components:

- DNAPL mass recovered based on the SEAR effluent concentration data from the extraction wells and estimated DNAPL recovered from the monitoring wells.
- DNAPL mass recovered during the flood independently measured by the SRS treatment system.
- DNAPL mass estimated from the analyses of soil samples collected from confirmation borings drilled at the conclusion of each SEAR.
- Qualitative assessment of potential DNAPL mass remaining in the Panel 5 well field by characterizing contaminant concentration histories during integral pump tests.

Each component was independently evaluated and the results used in combination to assess DNAPL recovery and the overall effectiveness of each SEAR application.

A summary of DNAPL recovery during each surfactant/foam flood, including the Panel 1 hot spot treatment is show in Table ES-1. The DNAPL recoveries are based on two different estimation methods: (1) DNAPL recovery based on the SEAR effluent concentration data from the extraction wells and the estimate of free-phase DNAPL recovered from the monitoring wells, and (2) DNAPL recovery at the SRS treatment facility measured during transfer from the phase separators to the solvent storage tank. Also shown in the table is the uncertainty associated with each method of estimation, the corresponding range of DNAPL volume recovered, and the initial estimate of DNAPL thought to be contained in each panel prior to implementation of SEAR technology.

Table ES-1. Summary of DNAPL Recovered during the Panel 1 and 5 SEAR Applications

Estimation Method[a]	Estimated Vol. Recovered (gals)	Uncertainty (%)	Estimated Vol. Range (gals)	Pre-SEAR PITT Estimate (gals)
Panel 1 SEAR				
- SEAR Effluent	1,179	18.0	967 – 1,391	402 ± 78
- SRS Recovery	1,139	6.3	1,067 – 1,211	
Panel 1 Hot Spot				
- SEAR Effluent	17	17.6	14 – 20	21 ± 14[b]
- SRS Recovery	11	345	0 – 49	
Panel 5 SEAR				
- SEAR Effluent	371	14.0	319 – 423	360 ± 74
- SRS Recovery	221	18.6	180 – 262	

[a] SEAR effluent recovery based on integration of the DNAPL concentration histories and subject to uncertainty associated with relative errors in flow rate and concentration measurements. SRS recovery based on flow measurements of DNAPL transfer from phase separators to solvent storage tank and subject to uncertainty associated with relative errors in flow measurements and DNAPL transfer float assembly.
[b] A pre-SEAR PITT was not conducted prior to the Panel 1 hot spot treatment but DNAPL volume was estimated based on contaminant concentration histories measured at the completion of the Panel 1 SEAR.

The reported volumes of DNAPL recovered during the Panel 1 SEAR and hot spot treatment are in good agreement between the two estimation methods, ranging from 1,139 to 1,179 gallons for the Panel 1 SEAR and from 11 to 17 gallons for the hot spot treatment conducted in the southern portion of Panel 1. However, significant differences exist in the volume estimates obtained during the Panel 5 SEAR. Based on the integration of the SEAR effluent concentration data from the extraction wells and the estimate of DNAPL recovered at the monitoring wells, approximately 371 gallons of DNAPL were recovered during the Panel 5 SEAR. This is 150 gallons greater than the 221 gallons measured at the SRS treatment facility. Although uncertainties exist in each estimation method, these do not account for the large difference in the reported recoveries. Currently, it is unclear which value is more representative of the DNAPL recovery obtained during the Panel 5 SEAR. However, it is evident that approximately 1,150 gallons of DNAPL were removed from the Panel 1 aquifer and that at a minimum, 220 gallons of DNAPL were removed from the Panel 5 aquifer during the two surfactant/foam floods.

Three integral pump tests were conducted at the end of the Panel 5 SEAR. While the results of the integral pump tests do not provide definitive answers concerning the remaining DNAPL volume in the Panel 5 aquifer, they do provide qualitative information about the potential for remaining DNAPL and some inferences about its spatial distribution. These pumping tests indicate that remaining DNAPL is most likely located on the Alpine Clay contact in the vicinity of well U2-211. The comparison of data for wells U2-204, U2-206, and U2-207 indicate a continuous decrease in TCE concentrations as measured during the conservative interwell tracer test (CITT), PITT, and integral pump tests conducted at the completion of the Panel 5 SEAR. The contaminant concentrations measured during the Panel 5 CITT are indicative of DNAPL dissolution prior to any mass removal. The pre-SEAR PITT was conducted after a water flood to mobilize the free-phase DNAPL and hence a small contaminant concentration decrease is observed. The low concentrations observed after surfactant/foam flooding indicate that a significant mass of DNAPL has been recovered from the aquifer, and that the distribution of DNAPL has markedly changed. For instance, the TCE concentrations observed during the post-SEAR pump tests were approximately 90% to 95% less than those observed during the CITT.

Following the surfactant/foam floods, five confirmation borings were drilled in each panel. The boring locations were chosen to obtain soil samples where DNAPL was most likely to remain, including locations near wells that exhibited high or persistent contaminant concentrations during the floods, and locations where depressions or deep areas in the Alpine Clay surface were known or suspected to exist. Of the 20 soil samples collected from the Panel 1 aquifer and the 22 samples collected from the Panel 5 aquifer, only two samples were estimated to contain DNAPL. Sample U2-807-45.75 collected from boring U2-807 in Panel 1 contained 407 mg/kg TCE and was estimated to have a DNAPL saturation of 0.07%. Sample U2-814-40.5 collected from boring U2-814 in Panel 5 contained over 4,000 mg/kg TCE and was estimated to have a DNAPL saturation of 2.0%. Both samples were collected from the OU 2 alluvium located just above the Alpine Clay contact.

Comparisons of the post-SEAR confirmation boring data with soil data obtained from nearby borings prior to the SEAR applications indicate that the TCE concentrations within the soil in both panels have significantly decreased. With the exception of the two soil samples still containing DNAPL, the TCE concentrations in the post-SEAR soil samples were all less than 50 mg/kg. In addition, comparison of TCE concentrations in the two confirmation boring still containing DNAPL samples with data from nearby boreholes suggests a decrease in the concentration of TCE by an order of magnitude. The confirmation boring results indicate that the surfactant/foam floods were very effective in reducing the concentrations of TCE in the soil.

Using the predicted DNAPL saturations for samples U2-807-45.75 and U2-814-40.5 and an average porosity of 27% for the alluvium, it is estimated that less than 1 gallon of DNAPL is remaining in the contaminated pore volume surrounding sample 807-45.75 in Panel 1. The volume of DNAPL remaining in the contaminated pore volume surrounding sample U2-814-40.5 located in Panel 5 is estimated to be between 2 and 4 gallons.

Soil concentrations of TCE in the alluvium at OU 2 for elevations of 4,647 and 4,653 feet amsl in both Panels 1 and 5 are shown in Figures ES-1 and ES-2, respectively. These figures are included to illustrate the localized concentrations of TCE in the treated zone of the OU 2 alluvium as determined from the confirmation soil sampling conducted at the completion of the Panels 1 and 5 SEAR applications. It should be noted that these data were collected as part of the performance assessment for each SEAR and thus, the samples were collected in areas of the treated aquifer where DNAPL was most likely exist. Therefore, the data are not adequately distributed spatially to infer contaminant concentrations distant from the actual sample location. However, these figures do provide an indication of areas within the treated zone exhibiting elevation concentrations of contaminants.

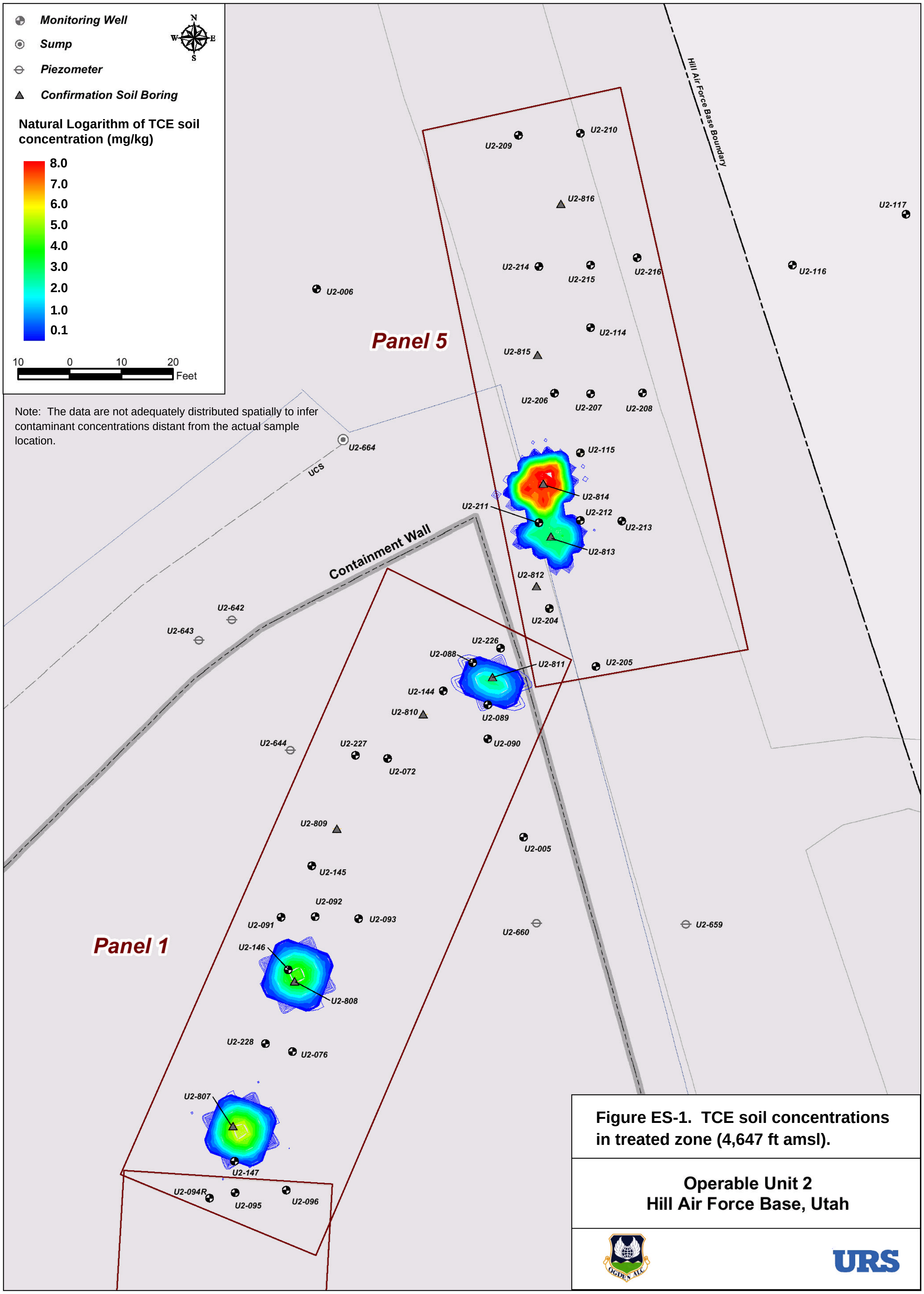

Figure ES-1. TCE soil concentrations in treated zone (4,647 ft amsl).

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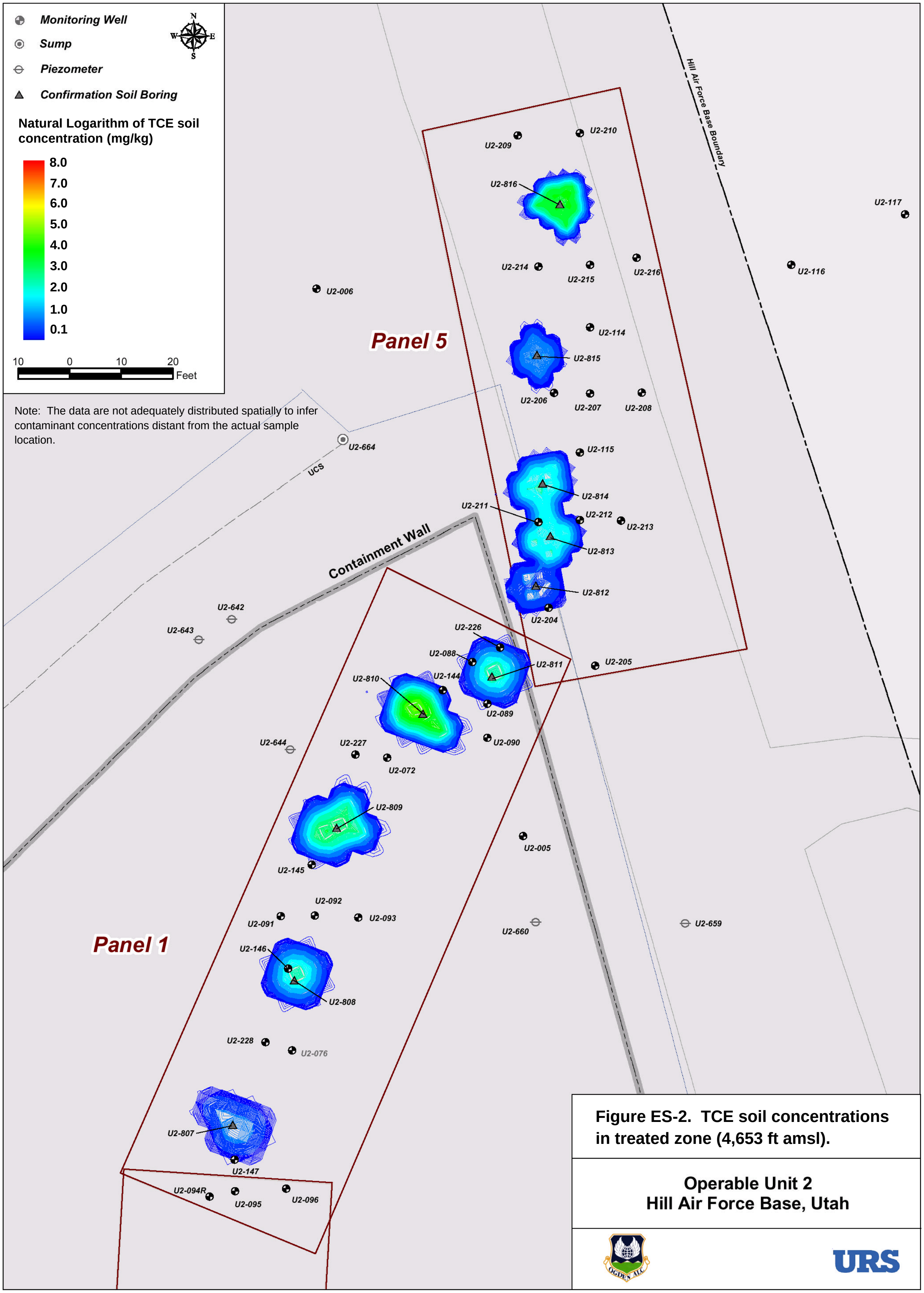

Figure ES-2. TCE soil concentrations in treated zone (4,653 ft amsl).

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Based on contaminant concentration histories obtained from the extraction wells during the Panel 5 SEAR and the confirmation soil sampling conducted in Panel 5, it appears that a small pool of dense microemulsion or DNAPL remains in a depression to the north of well U2-211. Thus, it is recommended that a water flood be conducted in this region to remove any remaining surfactant and easily extractable contaminant mass. Construction of the water flood was performed during the demobilization of the SEAR process equipment from the OU 2 site that occurred from 28 October 2002 to 12 November 2002. Prior to the implementation of the water flood, it is recommended that the water level in Panel 5 be pumped down to the SEAR design elevation of 4,662 feet amsl. Additionally, a monitoring program will be required to assess contaminant mass removal and the efficacy of the water flood.

Although the SEAR applications have removed a significant portion of the DNAPL mass from the Panel 1 and 5 source zones, residual levels of contamination (e.g., desorption from aquifer materials, DNAPL remaining in low-permeability zones, and dissolution of residual droplets and ganglia missed by the SEAR) may still create a relatively high concentration of chlorinated contaminants in the groundwater. Obtaining updated contaminant concentrations in the groundwater from strategically located wells along the centerline of the paleochannel aquifer will help optimize pump-and-treat operations. Whereas optimizing OU 2 pumping strategy represents a short-term goal, the characterization of the distribution of remaining contaminant mass in the OU 2 source zone represents a long-term goal that is required to select, design and implement long-term site management operations that will ultimately lead to site closure. The characterization of remaining contaminant mass within the OU 2 source zone will be completed during the refinement of the conceptual site model of the OU 2 source zone (*AFCEE Delivery Order 0052*).

A comparison of the performance of the Panel 1 and 5 surfactant/foam floods to the Panel 2 SEAR conducted without mobility control, strongly indicates that mobility control should be an integral part of all future SEAR technology applications in heterogeneous geosystems. Recommendations for future applications of the surfactant/foam process for DNAPL remediation include not exceeding an air injection pressure gradient of 0.7 pounds per square inch per foot of depth from ground surface to the top of the screened interval. A higher injection pressure may cause formation or well failure and backflow in the injection system. Careful monitoring of airflow rates, air pressure, and water levels in the injection wells is critical for controlling foam generation and propagation. Additionally, the airflow rates should gradually be increased throughout surfactant injection to increase foam generation in the more permeable zones. Finally, the use of direct-push installed monitoring points should be considered to help monitor the progress of the foam fronts.