EXECUTIVE SUMMARY

There is a consensus within the technical community that the pump-and-treat remediation of trichloroethene (TCE) and other chlorinated solvents fails to remove the source of the dissolved-phase plumes that are evident at many industrial sites and USAF bases. As Mackay and Cherry (1989) wrote: "...very little success has been achieved in even locating the subsurface sources (of the solvents), let alone removing them." It is now understood that dissolved-phase TCE plumes and those of other chlorinated solvents are due to the dissolution in ground water of these solvents, present, but not necessarily observed, in the subsurface as dense, non-aqueous phase liquids or DNAPLs. Dissolution of the trapped DNAPL occurs by ground water either percolating through DNAPL zones in the unsaturated zone of the aquifer above the water table or flowing through DNAPL zones in the saturated zone of the aquifer.

Within the USAF the problem is perceived more in terms of a budgetary crisis arising from the failure of pump-and-treat remediation to remove the DNAPL source zones within a short period of time. This position is most clearly stated in the draft position paper (October 1996) of the Defense Department's DNAPL Integrated Product Team (IPT). The IPT reported that a typical pump-and-treat system costs $400,000 to $500,000 per year to operate and is usually planned to operate for 30 or more years. Furthermore, USAF installation cleanup budgets are being increasingly used for the operation and maintenance (O&M) of pump-and-treat and soil-vapor extraction systems such that "*O&M costs will soon make new cleanup efforts impossible due to budgetary constraints.*" Consequently, the IPT concluded that "*more cost-effective technologies for solvent detection and remediation are needed now.*"

During the summer of 1996, INTERA conducted a successful demonstration of surfactant-enhanced aquifer remediation (SEAR) in collaboration with the Center for Petroleum and Geosystems Engineering at the University of Texas at Austin (UT) and with Radian International. The US Air Force Center for Environmental Excellence (AFCEE) funded the necessary DNAPL-zone characterization and surfactant-flood demonstration. The Center for Petroleum and Geosystems Engineering at UT funded the design of the surfactant floods, and Hill AFB near Ogden, Utah provided extensive logistical support. As is documented in this report, SEAR meets the requirements set down by the IPT for cost-effective detection and remediation of chlorinated-solvent DNAPL zones.

The demonstration was conducted at Operable Unit 2 (OU2) at Hill AFB, which had received large volumes of chlorinated solvents from degreasing operations conducted at the base. OU2 is underlain by an alluvial sand aquifer confined on its sides and below by thick clay deposits that form a capillary barrier to DNAPL migration. The hydraulic conductivity of this alluvium is in the range of 10^{-5} to 10^{-4} m/s. This aquifer contains tens of thousands of gallons of DNAPL, seventy percent of which is TCE.

A demonstration area was developed during the Spring of 1996 by installing a set of three injection wells and three extraction wells in a 3 x 3 line-drive geometry. This well field also contained one hydraulic control (injection) well to prevent the upgradient flow of tracers and surfactant, and one interwell monitor well. The distance between injectors and extractors was 20 ft; the distance between individual injectors and individual extractors was 10 ft; the water table depth was approximately 25 ft below ground surface; and there was a 4-ft thick zone of free-phase and residual DNAPL approximately 45 ft below ground surface. The screened intervals of the injectors and extractors were completed in this DNAPL zone and extended some distance above it. Prior to the demonstration, about 500 gallons of free-phase DNAPL were pumped from the recently-installed well field and sent for incineration.

The demonstration was conducted in two phases. The first of these phases comprised a partitioning interwell tracer test (PITT) followed by a DNAPL solubilization test, both of which were conducted in May and early June 1996. The PITT determined the spatial distribution and volume of DNAPL in the test zone of the alluvial aquifer. The solubilization test verified the efficiency of the selected surfactant, determined if the surfactant would cause the deflocculation and mobilization of fine-grained particles resulting in a reduction in permeability of the aquifer, and also addressed the issue of the effect of the surfactant-rich effluent on the efficiency of the steam stripping system at the site. This test involved the injection of an 8% surfactant solution into one injection well at 2 gpm for 0.6 days, producing an interfacial tension of 0.1 dynes/cm between the surfactant solution and the OU2 DNAPL.

The PITT indicated that there was a total of 346 gallons of DNAPL in the 4-ft thick test zone with an average residual DNAPL saturation of 20% (i.e., $S_r = 0.20$) or approximately 4% when measured over the whole, 20-ft thick, swept volume of the aquifer (i.e., $S_r = 0.036$). The solubilization test showed the selected surfactant to be extremely effective, and that there was no significant head loss due to mobilization of fines across the line-drive test zone. Furthermore, the steam stripper at OU2 readily treated the surfactant-rich waste waters.

The results of the Phase I field operations were used to finalize the design of the Phase II surfactant flood. The Phase II flood, the purpose of which was to remove all remaining DNAPL from the test zone in the alluvium, was preceded and followed by PITTs so that the performance of the flood could be assessed. The surfactant flood consisted of the injection of a solution of 8% surfactant, 4% isopropyl alcohol and 0.7%

NaCl, producing an interfacial tension of 0.02 dynes/cm. The Phase II field operations lasted for 30 days, of which surfactant injection at 7.5 gpm accounted for 3 days (i.e., 2.4 pore volumes), the follow-up water flood took 5.5 days and the final PITT took 6 days. This final PITT indicated that the average residual DNAPL saturation over the 20-ft thick swept zone of the aquifer had been reduced from 0.036 in early May to 0.0004 in late August in a swept volume of approximately 15,000 gallons. Therefore, the PITTs had shown that the two surfactant floods had recovered 341 of the 346 gallons of DNAPL within the test zone of the OU2 alluvial aquifer. This represents a total recovery of 99% of the DNAPL determined by the Phase I PITT to be present in the test zone of the OU2 aquifer.

Following completion of the field work, it was estimated from analysis of the final PITT that approximately five gallons of DNAPL was left in place at the end of the demonstration. The remediation time for these last five gallons has been calculated for various scenarios - as a pool and as vertical fingers with DNAPL blobs or ganglia of differing lengths trapped within the alluvium. Collectively, these scenarios reveal the relative efficiencies of SEAR versus waterflooding versus traditional pump-and-treat.

For the less probable case of a five-gallon pool of DNAPL remaining at the base of the aquifer (less probable, because such a pool would have been observable in monitoring well SB-6), the injection of 3, rather than 2.4, pore volumes of the surfactant/alcohol solution would have dissolved the pool during the demonstration by extending it a few days to a week at most. If instead, the injection of clean water at 7.5 gpm had been continued at the end of the surfactant flood, the five gallons of pooled DNAPL would have been removed by dissolution over a period of ten years. However, if the site reverted to pump-and-treat remediation with only groundwater extraction, then it would take 50 years to dissolve a five gallon pool of DNAPL.

The second case, the more probable one, is that of five gallons of residual DNAPL distributed throughout the aquifer as blobs or "ganglia" of different geometries and surface area. For this case, the injection of 3, rather than 2.4, pore volumes of the surfactant/alcohol solution would have dissolved the ganglia during the demonstration by extending it a day or two at most. If instead, the injection of clean water at 7.5 gpm were continued, the five gallons of DNAPL would have been removed by dissolution over a period of a few months, but less than one year in total. However, if the site had reverted to pump-and-treat remediation with only groundwater extraction and no injection of clean water, then it would take a few months to up to four years to dissolve the DNAPL.

Thus, over the course of a few months, at a cost of about $3000/gallon, 98.5% of the residual DNAPL was removed. This can be compared with the original USAF estimate for cleanup of the DNAPL that used the traditional time frame of 30 years with a cost of recovery now running at $32,000/gallon. The estimate of 30 years was based on a purely speculative estimate of the efficiency of pump-and-treat remediation and has no basis in fact. However, the cost of $32,000 per gallon of DNAPL recovered is similar to other pump-and-treat systems (e.g., McClellan AFB, CA and DOE Portsmouth, OH) that use ground-extraction wells and an air-stripping system to capture and treat TCE plumes. Furthermore, the recovery of some 500 gallons of free-phase DNAPL before the surfactant flood, and therefore prior to its dissolution and subsequent downgradient extraction and treatment, resulted in a cost savings of approximately $15 million to the USAF.

The two surfactant floods conducted at OU2, Hill AFB during the period May through August 1996 demonstrated the technical practicability of removing ~99% of residual DNAPL from alluvium, provided the site in question is well characterized and an exhaustive design protocol is followed. This level of DNAPL-zone remediation has significant implications for the regulatory issues of technical impracticability and natural attenuation.