



AATDF Surfactant/Foam Process for Aquifer Remediation

EXECUTIVE SUMMARY

The first surfactant/foam process field demonstration was successfully conducted during the spring of 1997 by Rice University and INTERA, Inc. at Operable Unit 2 (OU2) at Hill Air Force Base near Ogden, Utah. Funding was provided by the Advanced Applied Technology Demonstration Facility (AATDF) of the DOD. The University of Texas at Austin (UT) helped with some of the laboratory and simulation work and provided the basic surfactant formulation, although it was optimized by Rice University for use with foam. Hill AFB provided extensive logistical support, and Radian International (LLC) operated the effluent treatment facility.

Numerous military and industrial sites are contaminated with trichloroethylene (TCE) and other chlorinated solvents. Pump-and-treat processes have proved unsuccessful in remediating these sites because they are unable to remove much of the liquid contaminant which acts as a long-term source, slowly dissolving in ground water which flows by, thereby continuously regenerating the dissolved plume over a period of years or even decades.

No satisfactory method currently exists for removal of all, or nearly all of the liquid chlorinated solvent from a contaminated ground-water aquifer. Surfactants offer the possibility of such removal by solubilization and/or mobilization of the liquid source, as demonstrated by previous laboratory and field work. However, a significant limitation of surfactant processes and indeed of all processes involving injection of fluids to affect remediation is that the injected fluids flow preferentially in zones of higher hydraulic conductivity in a heterogeneous aquifer. In fact, most of the injected fluids continue to flow through these higher conductivity zones even after they have been cleaned and thus make a minimal contribution to remediation. Only a small portion of the injected fluids flow through the zones of lower hydraulic conductivity, which remain contaminated. As a result, the time and cost of remediation are much higher than in a homogeneous aquifer and the total quantity of surfactants or other materials introduced into the subsurface is greater.

The main objective of the surfactant/foam process is to improve process performance in a heterogeneous aquifer by providing a more uniform sweep of the formation. After an initial slug of an aqueous surfactant solution is introduced into the aquifer, entering mainly the high conductivity zones, some air is injected which forms a "foam" in these zones and significantly increases the resistance to



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liquid flow in the higher conductivity zones. Hence, when additional surfactant solution is injected, a larger portion of it enters the low conductivity zones, leading to more rapid remediation. The validity of this concept was confirmed during the present project by experiments conducted in a laboratory model containing two layers of sands with different hydraulic conductivities. For instance, in one case where conductivities differed by a factor of 20, nearly all TCE was removed by the surfactant/foam process after one pore volume of surfactant solution had been injected. In contrast, a third of the TCE originally present remained even after continuous injection of 26 pore volumes of the same surfactant solution without foam. In both cases interfacial tension was low enough that both solubilization and mobilization of contaminant occurred.

OU2 is underlain by an alluvial sand aquifer which forms a channel confined on its sides and below by thick clay deposits constituting a capillary barrier to contaminant migration. The deepest part of the sand in the test area is approximately 13.7 meters (45 feet) below the ground surface and 5.5 meters (18 feet) below the water table. The contaminant consisted of waste from past degreasing operations at the base and contained about 70% TCE with smaller amounts of perchloroethylene (PCE) and trichloroethane (TCA).

The test site spans the width of the channel and is 6.1 meters (20 feet) long. It does not contain a pool of extensive contaminant accumulation but instead encompasses a portion of the migration path of contaminant between the disposal trenches and two pools where tests of other remediation technologies have been carried out. Soil samples from about a year before the test and samples from the wells themselves revealed that the contaminant was confined to the bottom 1.2 meters (4 feet) of the channel and was present in relatively small quantities, viz., local saturations of 2%-14% pore volume. A partitioning interwell tracer test (PITT) conducted before the test indicated that about $0.079 \pm 0.026 \text{ m}^3$ (21 ± 7 gallons) of liquid contaminant was present, which is consistent with the estimates of 0.076 - 0.110 m^3 (20-28 gallons) based on data from the borings and wells. The tracer estimate corresponds to an initial average saturation of 0.26% or 668 mg/kg soil.

One hundred five soil samples were subjected to sieve analysis to obtain information on variation of hydraulic conductivity with lateral position and especially elevation, within the demonstration area. The contaminant was located in sands with conductivities of 1 - $3 \times 10^{-4} \text{ m/s}$ (permeabilities 10-30 darcy). However, more permeable sands containing no contaminant and having conductivities greater than 10^{-3} m/s (permeabilities greater than 100 darcy) were seen at elevations of 1.0-1.5 meters (3-5 feet) above the confining clay layer at the base of the channel. Since injection was planned over a 1.5-meter (5-foot) screened interval, these coarse sands, if continuous, would provide a preferential



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flow path or "thief zone" for the injected surfactant solution in the absence of foam.

Three injection and three extraction wells were completed in a 6.1 meter (20 foot) line drive pattern spanning the channel (the outermost wells were about 3.7 meters (12 feet) apart). Two monitoring wells were located near the center of the channel at positions about 1/3 and 2/3 of the distance between the injection and extraction wells. Each monitoring well was screened so that it could be sampled in three locations: the bottom 0.3 meter (1 foot) above the clay, 1.2-1.8 meters (4-6 feet) above the clay (corresponding to the thief zone mentioned above), and 3-4 meters (10-13 feet) above the clay. Two hydraulic control wells were located outside the pattern along the channel about 3 meters (10 feet) from the central injector and central extractor respectively.

Following the initial PITT, a surfactant-free solution containing about 1 wt% sodium chloride, the optimum value for mobilizing and solubilizing contaminant with the surfactant used, was injected for one day. The total volume of this solution was approximately equal to the swept volume of the pattern as determined by the PITT. Injection of a solution containing 3.5 wt% of the anionic surfactant sodium dihexyl sulfosuccinate at the same salinity commenced and continued at the same rate for slightly over three days. After 8 hours of surfactant injection, air injection began with each well in turn receiving air for approximately two hours. Air pressure was controlled to allow air to enter the upper part of the screened interval while surfactant solution continued to flow into the lower part. The total amount of surfactant solution with the above concentration was 3.2 times the swept volume of the pattern. Afterwards, a more dilute sodium chloride solution (0.8 wt%) was injected for 12 hours, followed by a waterflood to break the foam and remove most of the surfactant and finally a second PITT to determine the amount of contaminant remaining.

The foam performed as expected. No significant problems were encountered with air injection, and pressure rose at the injection wells, indicating an increase in the resistance to flow. Moreover, foam was observed in samples from the two upper screened intervals of both monitoring wells throughout much of the test. That is, foam formed in the upper intervals and diverted surfactant solution to the contaminated zone at the bottom of the aquifer. The response from injection of a nonpartitioning tracer with the surfactant indicated that foam reduced the swept volume by approximately 50%. Subsequent waterflooding broke the foam and restored the swept volume to its initial value, as shown by the final PITT.

A mass balance showed that virtually all (99%) of the surfactant that was injected during the test was recovered. The contaminant produced at the extraction wells (in addition to that which would have been present in dissolved

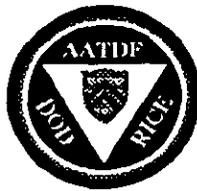


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form if no surfactant had been used) was approximately 0.13 m^3 (34 gallons) based on analysis of the effluent from each well as a function of time. An additional 0.009 m^3 (2.5 gallons) of contaminant was recovered in a dense microemulsion phase, which was pumped to the surface from the bottom foot of monitoring well MW-2. This well, located about 7 feet from the central extractor, was situated in a small, local depression and apparently continued to receive mobilized contaminant intermittently during the process. The total production of 0.14 m^3 (36.5 gallons) exceeds the initial estimate of 0.079 m^3 (21 gallons) given above. It thus appears that contaminant from outside the pattern was able to enter during the test, probably from the region beyond the injection wells which was known to be contaminated. Data from both monitoring wells support this conclusion. Probably owing to this effect, contaminant in the form of a free phase or a dense middle phase microemulsion continued to be present at the base of MW-2 for about three days after surfactant injection had ended. Also, contaminant continued to be produced at a relatively low concentration -- about 500 mg/L compared to a background of 100 mg/L -- in the central extraction well for about four days beyond the period of surfactant injection. However, 0.079 m^3 (21 gallons) of contaminant, the amount believed to be in the pattern initially, had been produced by the time that surfactant and air injection was complete.

In spite of the apparent influx of contaminant, both the final PITT and data from five borings taken at the end of the demonstration showed that very little liquid contaminant remained in the pattern. According to the PITT, only about $0.010 \pm 0.008 \text{ m}^3$ (2.6 ± 2.0 gallons) was present in the entire swept volume of 31.4 m^3 (8300 gallons). Two of the final borings showed no contamination. The others showed slight contamination just above the clay aquitard. Based on these results and the fact that only a small portion of the pattern is located at the depths where contaminant was found, total contamination was estimated to be 0.006 m^3 (1.6 gallons). In view of the uncertainty of both estimates, agreement is satisfactory. The average final contaminant saturation using the PITT results was 0.03% (77 mg/kg soil). This value is equal within experimental error to the lowest value (0.04%) achieved previously with surfactant remediation, which was during the INTERA/UT test in a nearby portion of OU2 in the summer of 1996. Although both that test (which used no mobility control) and the present one were conservatively designed, it is worth noting that the surfactant/foam process used only about 60% as much surfactant per unit of swept volume.

The PITT has been highly successful at several sites as a tool for estimating liquid contaminant content of an aquifer. When the aquifer is nearly clean, however, as at the end of the present test and the INTERA/UT test, the average saturation obtained depends on extrapolating asymptotic behavior which occurs near the end of the PITT when tracer concentrations are low. Under these conditions it is desirable to assure that analytical methods for the tracer are highly



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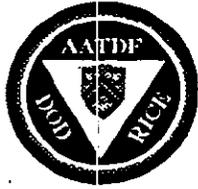
accurate and that the test is continued long enough to minimize uncertainty involved in the extrapolation.

As mentioned previously, one monitoring well was located at a local depression in the clay aquitard. This situation occurred by chance as it was not practical to determine fine details of aquitard contour before drilling the wells. It would have been better to locate an extraction well in the depression. Improved and cost effective techniques for determining the aquitard profile should be developed to avoid similar situations in future remediation processes.

Mobilized contaminant initially within the pattern and that entering from outside tended to migrate to this low spot. A surfactant or surfactant/foam remediation process should be designed to ensure that liquid contaminant or dense middle phase microemulsions can be recovered from such depressions even though their existence and locations are unknown, and even though flow from them to the extraction wells has an upward component which is opposed by gravity. It may be desirable, for example, to include a period during the last part of surfactant injection where salinity is low enough that contaminant remaining in such depressions can be solubilized into the aqueous surfactant solution.

The success of the surfactant/foam demonstration at Hill OU2 can be attributed to the extensive program of characterization, laboratory testing and numerical simulation used for the final field design. Analysis of the initial borings provided a good picture of variation of the hydraulic conductivity and contaminant saturation with elevation above the clay aquitard. Laboratory testing was critical in identifying surfactants with high contaminant solubilization, quick equilibration (coalescence) times, and minimal emulsion/gel/liquid crystal forming tendencies. All these characteristics enabled quicker remediation while preventing undesirable effects such as loss of surfactant due to gel/emulsion trapping and loss of hydraulic conductivity due to plugging. Laboratory column and two dimensional sand tank experiments provided extensive information on the ability of surfactants to remediate heterogeneous soils contaminated with DNAPL. In particular, they showed that gas should be injected at a constant pressure rather than at a constant flow rate.

In addition to laboratory testing, numerical modeling was an important factor in the interpretation of the field test. The results from the laboratory experiments were used as inputs into a compositional simulator (UTCHEM), modified to account for foam flow, and the field surfactant/foam flood was numerically simulated.



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Such numerical simulation of remediation processes such as surfactant/foam flooding is a powerful tool that may be used to gain insight into the application of similar remediation processes at other NAPL contaminated sites.

The ability of the surfactant/foam process to reduce a chlorinated solvent contaminant source to very low levels in a heterogeneous aquifer, as shown by this demonstration, suggests that this process should be considered as an option for remediation of similar sites in the future.