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Solar-Powered In Situ Soil Washing with Biodegradable Surfactant to Collect Residual LNAPL

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ABSTRACT: The goal of this study was to implement a unique, simple and sustainable LNAPL recovery process and evaluate site-specific volumes of LNAPL collected and rates of soil and groundwater cleanup that could be achieved. The recovery process was a combination of groundwater recirculation, soil washing via LNAPL mobilization, and collection of LNAPL via a hydrophobic LNAPL skimmer. A biodegradable surfactant, ECOSURF™ SA-15, was added to the recirculation line to lower the interfacial tension and facilitate movement of the LNAPL via mobilization. All equipment (submersible pump, LNAPL skimmer, surfactant feed pump, controls, and various other equipment) used was powered by a solar panel array. Approximately 62 gallons (235 liters) or 490 pounds (223 kg) of LNAPL were collected at the recirculation site during the PSS. Data suggest that surfactant amendments greatly enhanced free product collection. The maximum rate of free product collection was approximately 1 gallon (3.8 liters) per day.

INTRODUCTION

This paper presents the findings of a sustainable, surfactant-enhanced, product recovery Pilot-Scale Study (PSS) completed between January 2010 and May 2010 at the Hydrocarbon Burn Facility (HBF) located at John F. Kennedy Space Center (KSC), Florida. The HBF was operated between 1966 and 1994 as a fire-fighting training facility. Petroleum fuels mixed with volatile waste solvents and associated impurities were used during the training activities. These activities at HBF resulted in the accumulation up to 1.5 feet (46 cm) of light non-aqueous-phase liquid (LNAPL) on the surface of the groundwater at various locations within the HBF site. LNAPL at the site is in the C10 to C15 range, which corresponds to mostly diesel fuel. The viscosity of LNAPL at the site is within the range of 1.4 to 10.9 centipoise, and the density of the LNAPL varies from 0.8050 to 0.8593 grams per cubic centimeter. Interfacial tension between LNAPL and groundwater at the site ranged from 9.0 to 21.0 dynes per centimeter.

The overall goal of the recirculation pilot study was to determine if LNAPL recovery using an in situ soil flushing technology is an effective approach for removing the LNAPL layer within the study area.

MATERIALS AND METHODS

The PSS was implemented within an approximate 1,500-square-foot (140 m^2) area with one extraction well, one injection well, and six monitoring wells installed. The extraction, injection, monitoring wells, and groundwater particle tracking model is illustrated in Figure 1. The monitoring wells were 2-inch (5 cm) diameter wells and were installed to total depths of 14 feet (4.3 meters) and were screened from 9 to 14 feet (2.7 to 4.3 meters) bgs. The injection and extraction wells were 5-inch (12.7 cm) diameter and

were installed to 25 feet (7.6 meters) bgs and was screened from 5 to 25 feet (1.5 to 7.6 meters) bgs.

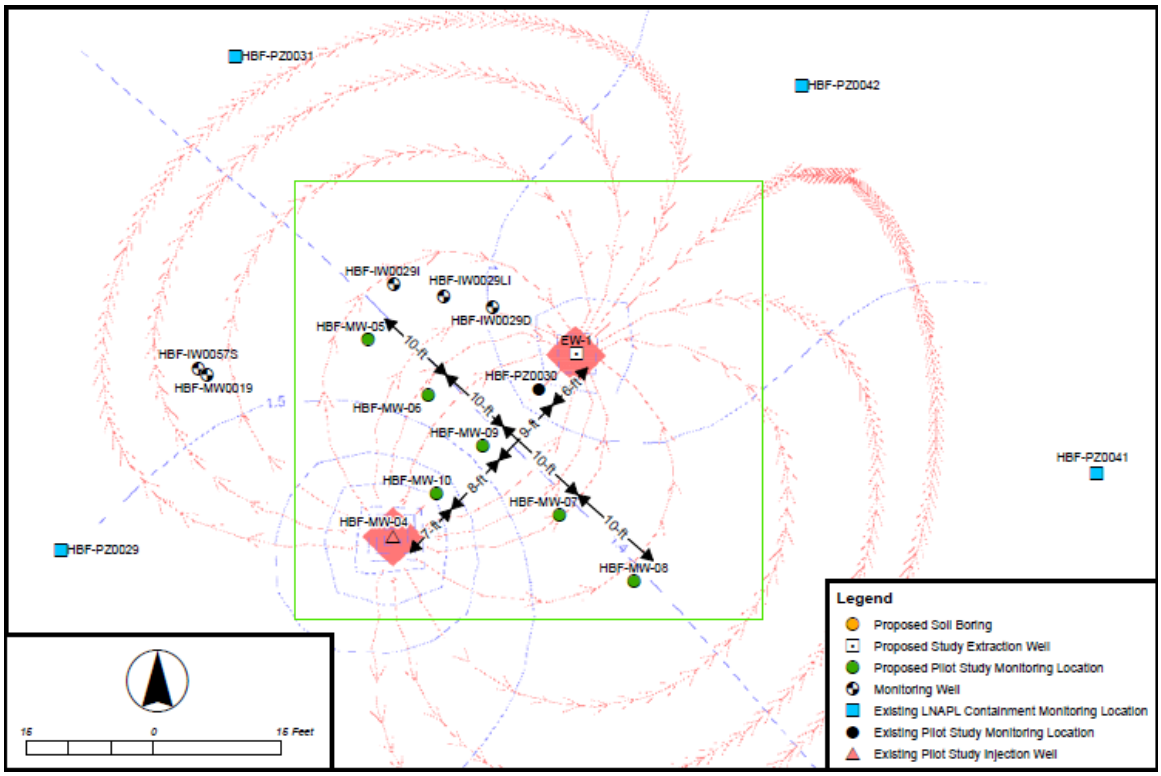

FIGURE 1. The extraction, injection, and monitoring well locations. Also illustrated is the particulate travel times used in the development of design criteria.

Recirculation Pumping Rate and Zone of Capture. Based on a groundwater flow model using MODFLOW and particle tracking using MODPATH, 3 gpm (11.3 Lpm) was selected as the optimal groundwater recirculation rate. An estimated minimum travel time of 7 days for the injected groundwater and additives to travel from the injection point to the extraction point was determined under steady-state water level conditions.

The footprint estimated to be influenced by the recirculation system was determined using the 3 gpm recirculation rate and the minimum travel time of 7 days. At this pumping rate and conditions predicted by MODFLOW, the subsurface pore space primarily influenced by the recirculation system was determined to be 32,240 gallons (122,000 liters).

Surfactant Addition. The amount of surfactant to be added to groundwater was determined based on the critical micelle concentration (CMC) of the surfactant chosen, which was ECOSURF^{TM} SA-15 with a CMC of 153 mg/L. By choosing the CMC as the target concentration at which to inject the surfactant the primary mechanism for removing LNAPL was mobilization. Contrary to solubilization, mobilization is achieved by dosing a surfactant so the interfacial tension between water and LNAPL is at its lowest value.

Another advantage to mobilization is that LNAPL is more easily recovered via specific gravity separation because surfactant and oil emulsions are not expected to occur.

The surfactant was added to the groundwater recirculation line to achieve a concentration of three times the CMC. Although the interfacial tension is the lowest at the CMC, the surfactant was dosed at three times this value to ensure that the point at which the interfacial tension is at its lowest is met or slightly exceeded. The dosage of surfactant was initially decreased during the pilot study to keep the concentration of surfactant within the range where interfacial tension between LNAPL and groundwater is at its lowest point.

Surfactant addition was performed by a continuous-feed pump that injected ECOSURF™ SA-15 at a concentration of 52 g/L into the groundwater injection line at 1.56 gph (5.9 Lph). Approximately 8.5 days after startup, the concentration of the feed was reduced to 32.3 g/L. This process of reducing the surfactant feed concentration was continued during the early period of the pilot study operation to avoid surfactant accumulation.

A dual pumping system was installed at extraction well HBF-EW-01 and a 12-volt direct current (DC) submersible groundwater pump manufactured by SunPumps™ was used to extract groundwater from the extraction well at approximately 3 gpm (11.4 Lpm) and provide groundwater to the recirculation system. The Magnum Spill Buster™, was installed and operated simultaneously within the extraction well to extract partitioned LNAPL.

The Magnum Spill Buster™ unit and submersible pump were powered by four deep-cycle batteries that provided 24 volts charged by a six-panel solar array. One deep-cycle battery providing 12 volts of power was charged by a two-panel solar array, which provided power for the surfactant feed pump, tank mixer, and control panel.

Phase I Operations. Phase I consisted of the operation of the recirculation system only with no surfactant addition. The recirculation system was initially operated with no surfactant addition for approximately 2 months from November 19, 2009, to January 26, 2010. During Phase I, a testing dose of surfactant was injected on December 16, 2009 to check operation of the injection system.

Baseline groundwater samples were also collected on December 16, 2009, and analyzed for total petroleum hydrocarbons (TPH). TPH samples were shipped to Gulf Coast Analytical Laboratories in Baton Rouge, Louisiana, for analysis of method Florida Petroleum-Range Organics (FL-PRO). System checks including water levels, free product levels, free product collection volume, and flow rate were recorded twice a week during this period.

Phase II Operations. Phase II of recirculation system operation was from January 26 to May 28, 2010. During Phase II of the study, continuous surfactant injection began on January 26, 2010 amending the groundwater returned to the injection well to contain 460 mg/L of surfactant. Dosage adjustments occurred on February 12, February 18, and March 9, 2010, with adjustments to 280, 160, and 280 mg/L, respectively. System checks including water levels, free product levels, free product collection volume, and flow rate were recorded twice a week during January 26 to May 6, 2010. From May 6 to May 28, 2010, only free product collection volumes and flow rate information were collected.

Groundwater samples were collected on February 11, February 25, March 15, and April 6 for TPH and surfactant analysis. Surfactant samples were shipped to Analytical Services, Inc., in Huntsville, Alabama, for analysis via Method SM 5540 B, D. TPH samples were shipped to Gulf Coast Analytical Laboratories in Baton Rouge, Louisiana, for analysis by method Florida Petroleum-Range Organics (FL-PRO).

RESULTS AND DISCUSSION

Free Product Collection. A summary of free product collected during the PSS during the recirculation study is illustrated on Figure 2. Approximately 62 gallons (235 liters) or 490 pounds (223 kg) of LNAPL were collected during the PSS. During Phase I of the recirculation-only portion of the study, approximately 1.5 gallons (5.7 liters) of free product were collected. However, it was thought that this volume may have been a result of the testing dose of surfactant that was injected on December 16, 2010 as the 1.5 gallons (5.7 liters) was collected shortly after this event.

During Phase II (surfactant addition portion of the study), approximately 60.5 gallons (229 liters) of free product were collected. After continuous injection of surfactant, which began on January 26, 2010, the rate of free product collection increased steadily until approximately March 5, 2010. Immediately after March 5, it was observed that the rate of free product collection began to decrease, so on March 9, the dosage of surfactant was increased back to 280 mg/L. After March 9, the rate of free product collection was steady at approximately 1 gallon per day until approximately April 8, eleven days after the surfactant addition ceased on March 27, 2010. After April 8, the rate of free product collection decreased suggesting that surfactant injection is directly related to the rate of free product collection. Considering the last three data points, on May 6, May 19, and May 28, 2010, the average rate of free product collection was significantly reduced to approximately 0.2 gallons (0.76 liters) per day.

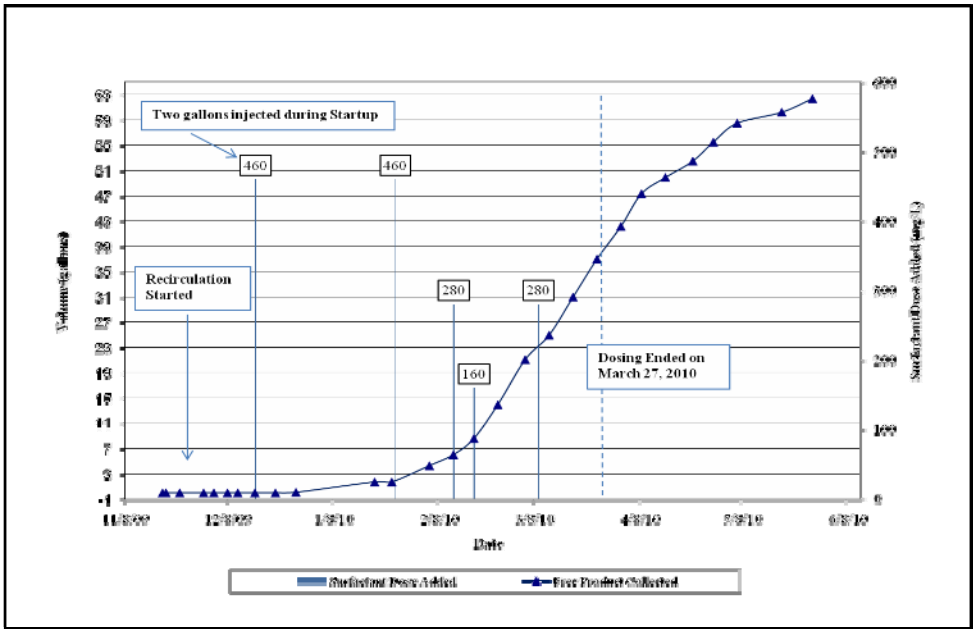

FIGURE 2. Free product collected and dosage of surfactant added.

Free Product Levels. Free product levels were measured in monitoring wells within the pilot study area. Free product levels in wells between the extraction well and injection well are illustrated on Figure 3. Also illustrated on Figure 3 is the recirculation flow rate, which is plotted on the secondary y-axis. Free product thickness in PZ0030, which is in the approximate center of PSS area and historically had high levels of free product, fluctuated throughout the study with a general trend of increasing thickness observed. However, one exception to the generally increasing trend was observed around February 5, 2010, and was associated with the reduced groundwater recirculation rate of the system. In the extraction well, free product accumulated up to approximately 3 feet (0.9 meters) in thickness on February 25, because of a skimmer malfunction. As shown of Figure 3, free product was observed in MW0010 starting on March 5 and continued to increase in thickness. On several occasions from November 19, 2009 to January 20, 2010, a thin layer of free product was observed at MW0009.

As described above, no product was observed at the injection well during the PSS, which indicates that emulsions were not forming due to surfactant addition or pump action and that LNAPL was separating by gravity from the extraction well as designed. Free product thickness in PZ0030 increased throughout the PSS, indicating that LNAPL movement and possibly desorption was occurring, and levels decreased when recirculation flow rates were reduced, as indicated by the decrease in flow rate around February 5, 2010.

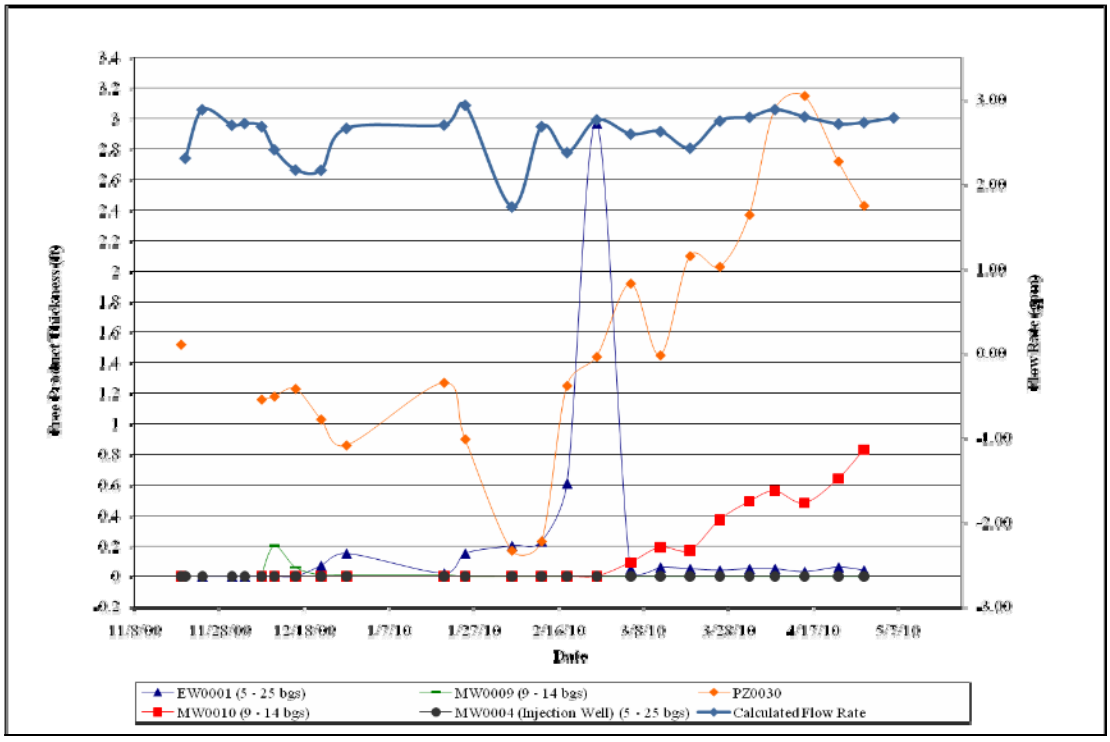

FIGURE 3. Free product thickness levels of the injection, MW-10, PZ0030, MW-09, and the extraction well.

ROI Determination. Groundwater samples were collected from monitoring wells within the pilot study area and analyzed for TPH. Results are presented in Table 1. Baseline samples were collected on December 16, 2009, and the 1st, 2nd, 3rd, and 4th, sampling rounds were conducted on February 11, February 25, March 15, and April 6, 2010, respectively. TPH concentrations from the first sampling round increased significantly in all wells from baseline concentrations. A greater increase in TPH concentrations was observed in the wells between the injection well and extraction well. During the second sampling round, on February 11, 2010, site-wide TPH concentrations decreased compared to the first sampling round. During subsequent sampling rounds, TPH concentrations were quite variable except for concentration differences in MW0005 and MW0006 (sidegradient wells to the north) compared to MW0007 and MW0008 (sidegradient wells to the south). The difference was most likely due to the location of the monitoring wells as installed in the field compared to the symmetrical installation plan or alternatively pockets of free product in the MW0007 and MW0008 area.

Based on the first round of data collected, increased site-wide TPH concentrations suggest that sorbed LNAPL desorbed and mobilized within the recirculating groundwater. Based on subsequent rounds of data collected, highly fluctuating TPH concentrations in the groundwater samples also suggests that free product was continuing to desorb throughout the pilot study area. Considering that TPH concentrations were changing throughout the PSS monitoring wells over time, suggests that the ROI of the system included the furthest sidegradient wells, which were located up to 20 feet (6.1 meters) from the center of the PSS area.

Surfactant Demand. Groundwater samples were collected from monitoring wells within the pilot study area and analyzed for surfactant. Results are presented in Table 1. Baseline sampling was conducted on December 16, 2009, and the first four sampling rounds were conducted on February 11, February 25, March 15, and April 6, 2010.

During the first sampling round, surfactant concentrations at the wells were less than the dosage concentration of 460 mg/L at the time of sampling. The surfactant concentration at the injection well was the greatest at 73.6 mg/L, with all other wells having surfactant concentrations in the very low (1.3 mg/L) to non-detect range. Subsequent sampling on February 25, March 15, and April 6, 2010, was conducted when the surfactant dosage injected was 160 mg/L, 280 mg/L, and when surfactant injection ceased, respectively. During these sampling rounds, surfactant concentrations were all in the very low to non-detect range, indicating that the surfactant demand in the groundwater and surrounding subsurface exceeded the dosage injected. During the final sampling rounds, only MW0009 and the extraction well were sampled because surfactant injection had ceased and because surfactant was not detected at many wells during previous rounds. However, during the final two sampling rounds a slight increasing trend in surfactant concentrations was observed at the extraction well, indicating that some residual surfactant was still in the pilot study area.

Based on the data collected, low site-wide surfactant concentrations suggest that surfactant demand during the pilot study was significant. The surfactant concentration of 73.6 mg/L observed at the injection well while 460 mg/L was dosed suggests that in the immediate area around the injection well the surfactant demand was greater than the assumed demand.

TABLE 1. Groundwater TPH and surfactant concentrations.

Location (HBF-)	Screen Interval (bgs)	TPH (µg/L)				
		16-Dec-2009	11-Feb-2010	25-Feb-2010	15-Mar-2010	6-Apr-2010
Total Petroleum Hydrocarbons (µg/L)						
EW0001	5-25	NA	**10400**	**9510**	**5090**	**5270**
MW0004	5-25	1110	**20400**	2850	3320	**5050**
MW0005	9-14	277	718	132	119	97.4
MW0006	9-14	1120	2020	949	737	578
MW0007	9-14	2720	7140	**8520**	**7350**	**13200**
MW0008	9-14	**9360**	**13300**	**11000**	**11600**	**32500**
MW0009	9-14	706	5260	2330	**6350**	4220
MW0010	9-14	1530	**6220**	3940	FP	FP
Surfactant (mg/L)						
EW0001	5-25	NA	ND	ND	0.4	1.3
MW0004	5-25	NA	73.6	ND	0.4	NA
MW0005	9-14	NA	ND	ND	ND	NA
MW0006	9-14	NA	ND	ND	ND	NA
MW0007	9-14	NA	ND	ND	ND	NA
MW0008	9-14	NA	ND	0.3	ND	NA
MW0009	9-14	NA	0.4	ND	ND	1.0
MW0010	9-14	NA	0.4	ND	NA	NA

NA = Not analyzed.
FP = Free product observed.
bgs = Below ground surface.
ND = Non-detect.
Bold value indicates TPH concentration is greater than FDEP Groundwater Cleanup Target Level (GCTL) of 5000 µg/L.

Equipment Performance. Overall, the recirculation system performed very well, with no system wide down time. In February, a skimmer malfunction occurred due to a faulty circuit board, which was replaced, but the recirculation system was still operational during that time. The 24-volt solar panel array and battery system maintained a supply voltage between 23.0 to 26.8 volts throughout the PSS to power the submersible pump and Spill Buster Unit. The groundwater recirculation rate varied from 2.1 to 3.0 gpm (7.9 to 11.4 Lpm) according to variations in the 24-volt supply, which coincidently provided insight to how free product collection rates correspondingly varied with flows.

CONCLUSIONS

The PSS at the recirculation site was conducted for approximately 5.5 months from November 19, 2009 to May 28, 2010. Approximately 62 gallons (235 liters) or 490 (223 kg) pounds of LNAPL was collected at the recirculation site during the PSS. Data suggest that after surfactant was added, collection of free product was greatly enhanced. The maximum rate of free product collection was approximately 1 gallon (3.8 liters) per day. Low surfactant concentrations in groundwater samples suggest that site-wide surfactant demand in the subsurface of the pilot study area is significant. The optimum site-wide CMC of 153 mg/L was not achieved, but if the optimum CMC was met free product collection rates in excess of 1 gallon per day could have been very likely.

Fluctuating site-wide TPH concentrations suggest that sorbed LNAPL desorbed and mobilized within the recirculating groundwater. Fluctuating TPH concentrations within the PSS monitoring wells over time, suggests that the ROI of the system included the furthest sidegradient wells, which were located up to 20 feet (6.1 meters) from the center of the PSS area.

Considering the data collected and the evaluation conducted, LNAPL present at the site was effectively mobilized to the extraction well and extracted with no emulsion issues observed indicating mobilization was the primary mechanism of removal and solubilization of LNAPL during the PSS was not likely. The groundwater recirculation system and associated equipment performed very well with no system wide down time, was low cost, and incorporated solar power and a biodegradable surfactant.

ACKNOWLEDGMENTS

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