Appendix F

Solar-Powered Air Stripping at the Rocky Flats Site, Colorado

Solar-Powered Air Stripping at the Rocky Flats Site, Colorado - 12361

John A. Boylan*
*S.M. Stoller Corporation, Rocky Flats Site, 11025 Dover Street, Suite 1000, Westminster, Colorado 80021

ABSTRACT

The U.S. Department of Energy's Rocky Flats Site (the Site), near Denver, Colorado, is a former nuclear weapons facility that was constructed beginning in 1951. With the end of the Cold War, the Site was cleaned up and closed in 2005. Four gravity-driven groundwater treatment systems were installed during cleanup, and their continued operation was incorporated into the final remedy for the Site. All utilities, including electrical power, were removed as part of this closure, so all Site electrical power needs are now met with small solar-powered systems.

The Mound Site Plume Treatment System (MSPTS) was installed in 1998 as an innovative system based on zero-valent iron (ZVI). Groundwater flow from the Mound source area containing elevated concentrations of volatile organic compounds (VOCs), primarily in the tetrachloroethene (PCE)-trichloroethene (TCE) family of chlorinated solvents, is intercepted by a collection trench and routed to twin ZVI treatment cells. Later, in 2005, remediation of VOC-contaminated soils at a second upgradient source area included adding an electron donor to the backfill to help stimulate biodegradation. This reduced concentrations of primary constituents but caused downgradient groundwater to contain elevated levels of recalcitrant degradation byproducts, particularly *cis*-1,2-dichloroethene and vinyl chloride. A gravel drain installed as part of the 2005 remediation directs contaminated groundwater from this second source area to the MSPTS for treatment. This additional contaminant load, coupled with correspondingly reduced residence time within the ZVI media due to the increased flow rate, resulted in reduced treatment effectiveness. Elevated concentrations of VOCs were then detected in MSPTS effluent, as well as in surface water at the downstream performance monitoring location for the MSPTS. Subsequent consultations with the Site regulators led to the decision to add a polishing component to reduce residual VOCs in MSPTS effluent.

Initially, several alternatives such as commercial air strippers and cascade aerators were evaluated; resulting cost estimates exceeded $100,000. After several simpler alternatives were considered and prototype testing was conducted, the existing effluent metering manhole was converted to house a spray-nozzle based, solar-powered air stripper, at a cost of approximately $20,000. About two-thirds of this cost was for the solar power system, which was initially designed to only provide power for 12 hours per day. Performance data are being collected and adjustments made to optimize the design, determine maintenance requirements, and establish power needs for continuous operation. Analytical data confirm the air stripper is sharply reducing concentrations of residual contaminants.

INTRODUCTION AND BACKGROUND

The Rocky Flats Site (the Site) is a former nuclear weapons production facility near Denver, Colorado. Its construction began in 1951, and production started in 1952. Its mission focused on the production of nuclear triggers for the nation's nuclear arsenal, and research and development work. As a result of releases of hazardous substances to the environment, the Site was listed on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as Superfund) National Priorities List in 1989.

In 1994, the site mission was changed to cleanup and closure. Final closure was completed in October 2005. The final CERCLA remedy and RCRA corrective action decision was approved in September 2006 [1]. The U.S. Department of Energy (DOE) Office of Legacy Management is responsible for implementing the remedy, which is regulated under the *Rocky Flats Legacy Management Agreement* [3] (RFLMA) between the Colorado Department of Public Health and Environment, the U.S. Environmental Protection Agency (EPA), and DOE.

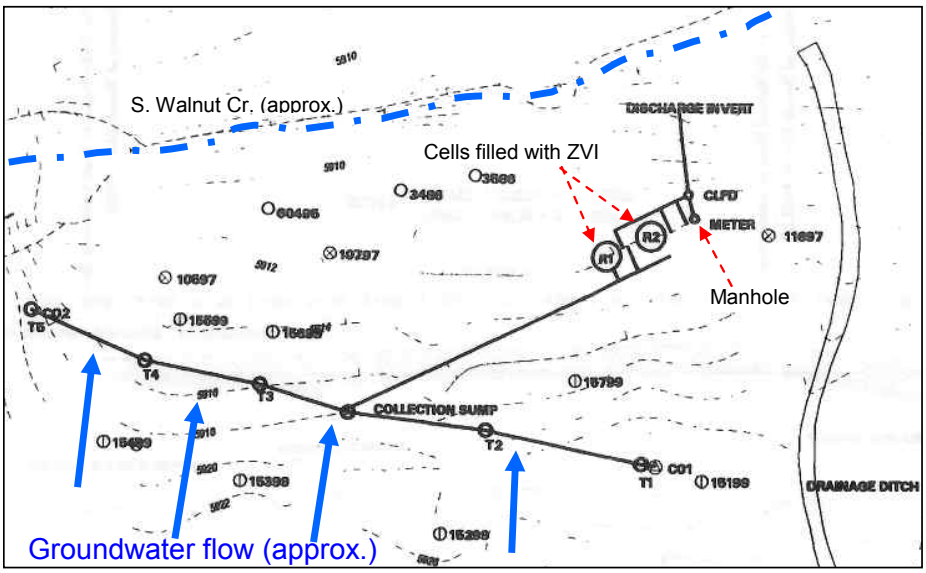
Contaminated groundwater is present in some areas of the Site. The most common contaminants are volatile organic compounds (VOCs) in the form of chlorinated solvents above EPA's maximum contaminant levels for drinking water. Contaminated groundwater discharges to surface water within the Site boundaries. To protect surface water and support closure of the Site, four groundwater treatment systems were installed to reduce contaminant plumes' impacts on surface water. Three of the systems address VOCs, and the fourth addresses nitrate and uranium groundwater contamination.

A primary design requirement for each groundwater treatment system was to operate passively—that is, by gravity. This requirement was imposed because the planned configuration of the Site upon closure included removal of all utilities such as electrical power. In 2002, a small, solar-powered pump was added to the nitrate/uranium treatment system to assist water delivery to the treatment cells; however, the other systems remained passive.

THE MOUND SITE PLUME TREATMENT SYSTEM

The Mound Site Plume resulted from leaking drums in an area referred to as the Mound. The source area was cleaned up in the 1990s, but groundwater impacts remained. The contaminant plume flows generally north toward nearby South Walnut Creek. The Mound Site Plume Treatment System (MSPTS) was installed in 1998 to intercept and treat this plume, and it represented a cooperative effort among the Site, the DOE Subsurface Contaminant Focus Area, and the EPA Superfund Innovative Technology Evaluation Program. The MSPTS includes a groundwater collection trench (which is essentially a French drain) that extends 67 meters (m) approximately perpendicular to groundwater flow to collect contaminated groundwater, and two cylindrical treatment cells (each approximately 3 m in diameter and 3.7 m tall) filled with zero-valent iron (ZVI), through which the collected groundwater is routed. The primary contaminants in the Mound Site Plume, tetrachloroethene (PCE) and trichloroethene (TCE), are reductively dechlorinated through contact with the ZVI. Treated water is routed to a small manhole for monitoring, and subsequently to a subsurface discharge gallery. Figure 1 illustrates the layout of the MSPTS in 1998.

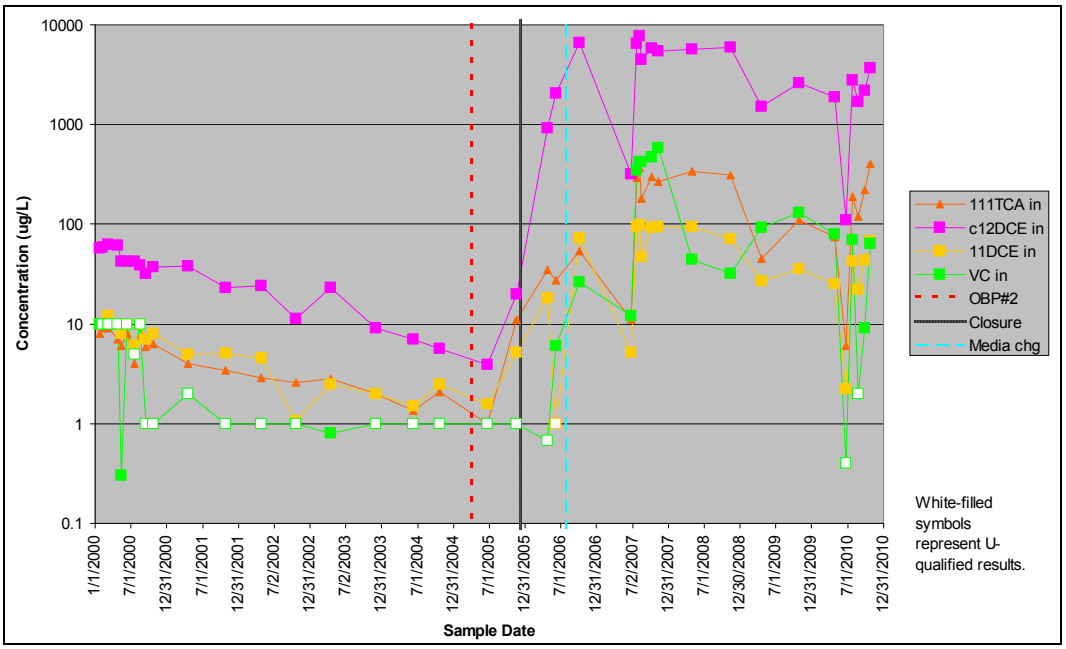
Another contaminant source area adjacent to the Mound, the Oil Burn Pit No. 2, was remediated in early 2005. Following source removal, the excavation was backfilled and electron-donor material was added to the backfill to stimulate biodegradation of residual VOCs. Because groundwater from this source area also threatened surface water quality in South Walnut Creek and was so close to the MSPTS, a gravel drain was installed to intercept and direct groundwater impacted by Oil Burn Pit No. 2 to the MSPTS for treatment.



NOTES: North is to top of illustration. Line from “T5” on left to “T1” on right represents the 67 m groundwater intercept trench; water flows from the collection sump to the ZVI-filled cells through the line shown. T1 through T5 are piezometers installed in the trench; also shown are numerous historic monitoring wells (e.g., 3486; 10297), most of which no longer exist. Drawing reflects April 1999 as-built configuration of MSPTS.

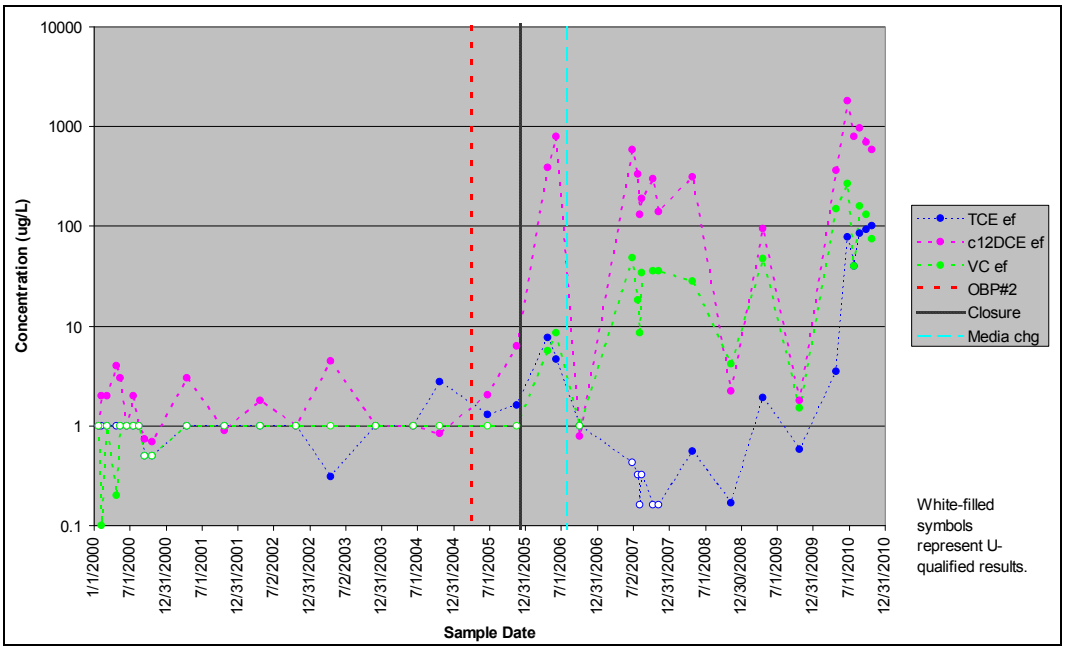
Figure 1. Schematic drawing of MSPTS features.

The full effect of the Oil Burn Pit No. 2 remedial action on the MSPTS was not clear until the year following Site closure. In mid-2005, influent flows increased sharply. From 2000 through 2004, the average flow rate was approximately 0.2 gallons per minute (gpm); however, in 2006, it was approximately 0.8 gpm. In mid-2006, concentrations of certain VOCs—particularly 1,1,1-trichloroethane and the degradation byproducts cis-1,2-dichloroethene (DCE), 1,1-DCE, and vinyl chloride—followed suit (Figure 2). Because these byproducts represent more recalcitrant compounds [2] for which the MSPTS was not designed, and the higher flow rate correlates to a shorter residence time within the treatment media, low concentrations of VOCs began to be detected in treated effluent from the MSPTS (Figure 3). A summary of averaged results is provided in Table 1 and clearly illustrates the changing water quality.



NOTES: Analytical data represent influent concentrations (as indicated by “in”). Units “ug/L” = micrograms per liter. 111TCA = 1,1,1-trichloroethane; c12DCE = cis-1,2-DCE; 11DCE = 1,1-DCE; VC = vinyl chloride. The “OBP#2” line refers to the date when the Oil Burn Pit No. 2 source area was remediated and the associated groundwater began to be directed to the MSPTS for treatment. The “Closure” line refers to Site closure in December 2005. The “Media chg” line refers to the date when the ZVI media in the MSPTS treatment cells was first replaced. “U-qualified results” represent nondetects.

Figure 2. Effects of Oil Burn Pit No. 2 remediation on MSPTS influent.



NOTES: All data represent effluent concentrations (as indicated by "ef"). Units "ug/L" = micrograms per liter. c12DCE = cis-1,2-DCE; VC = vinyl chloride. The "OBP#2" line refers to the date when the Oil Burn Pit No. 2 source area was remediated and the associated groundwater began to be directed to the MSPTS for treatment. The "Closure" line refers to Site closure in December 2005. The "Media chg" line refers to the date when the ZVI media in the MSPTS treatment cells was first replaced. "U-qualified results" represent nondetects.

Figure 3. Effects of Oil Burn Pit No. 2 remediation and media replacement on MSPTS effluent.

Table 1. Summary of Averaged Results for MSPTS Influent and Effluent, Before and After Site Closure.

Time period	1,1,1-TCA		1,1-DCE		cis-1,2-DCE		PCE		TCE		VC	
	In	Ef	In	Ef	In	Ef	In	Ef	In	Ef	In	Ef
2000 through 2005	5	1	6	1	32	2	65	1	89	1	4	1
2006 through 2010	176	4	50	4	3572	445	79	5	146	22	148	58

NOTES: Concentrations in micrograms per liter, and taken at face value regardless of qualifier. Detection limits varied (for example, for VC were occasionally as high as 10 ug/L). "In" = influent, "Ef" = effluent. 1,1,1-TCA = 1,1,1-trichloroethane; VC = vinyl chloride. Averages calculated from analytical results of 20 samples collected from 1/27/2000 through 11/18/2005 and 19 samples collected from 4/25/2006 through 10/28/2010.

The ZVI treatment media was replaced in the summer of 2006, both because of the consistent detection of residual VOCs in MSPTS effluent at concentrations exceeding applicable standards, and because the media had become increasingly clogged with naturally forming precipitates. Although the first samples collected from the MSPTS following the media replacement showed improved treatment of VOCs, subsequent samples consistently contained VOCs at undesirable levels (Figure 3). However, concentrations of VOCs in samples from the downstream performance monitoring location in South Walnut Creek remained below the applicable standards.

Regular communication and periodic consultation with the RFLMA regulators were maintained regarding treatment conditions and the path forward to reduce VOCs in MSPTS effluent. A wet spring in 2010 led to increased MSPTS flows, thereby decreasing residence time within the ZVI media and increasing effluent VOC concentrations. Applicable standards for TCE and vinyl chloride were subsequently exceeded in samples from the surface water performance monitoring location on South Walnut Creek, leading to more aggressive evaluation and treatment considerations.

EVALUATION OF POLISHING TECHNOLOGIES

Several approaches to addressing the residual VOCs in MSPTS effluent were considered. One approach that was not developed in detail was to add a third ZVI-filled treatment cell. While this option was feasible, the cost and level of effort required to install and maintain another cell—that is, the need to replace the media every few years, with spent media potentially requiring management and disposal as low-level radioactive waste—made it less attractive.

The initial design criteria were assembled from observed flows and VOC concentrations in MSPTS effluent, and the treatment targets represented by applicable water quality standards. A design flow of 3 gpm was selected as representative of a high that could be expected to occur during wet periods. Lengthy periods of flows exceeding 3 gpm are not expected. The desire was not to design the polishing component around short-term high flow conditions, but rather around the expected range of typical operating conditions based on past observations.

The VOC concentrations used in the design process were selected from previously observed concentrations in MSPTS effluent. These data were selected to more closely represent worst-case conditions, which in this case is appropriate: higher concentrations of VOCs are present in MSPTS effluent not only under higher-flow conditions but also under conditions in which the ZVI media is becoming coated and clogged with precipitates, a condition that develops within a few years after fresh media is installed. These data are summarized in Table 2.

Table 2. Concentrations of VOCs Used in Designing Polishing Alternatives.

Contaminant	Design Concentration (ug/L)	RFLMA Standard (ug/L)	Comments
Chloroform	9.9	3.4	
cis-1,2-DCE	1800	70	
PCE	29	1	Practical quantitation limit; underlying standard = 0.69 ug/L
TCE	77	2.5	
Methylene chloride	31	4.6	

Vinyl chloride	270	0.2	Practical quantitation limit; underlying standard = 0.023 ug/L
1,1-DCE	24	7	
1,2-Dichloroethane	3.6	1	Practical quantitation limit; underlying standard = 0.38 ug/L

NOTES: Units “ug/L” = micrograms per liter. The RFLMA standards referred to are promulgated in the post-closure regulatory agreement for the Site [3].

Engineered Riffles

The first approach to designing a polishing component focused on passive aeration. Another of the four treatment systems at the Site currently treats low concentrations of VOCs via engineered riffles (cascading aeration). Water enters this component and flows down a series of concrete steps that increases the turbulence and spread the water into a thin film to promote aeration of the water, thereby volatilizing VOCs. The low concentrations in MSPTS effluent suggested a similar approach might be appropriate.

A technical firm with expertise in applying air-stripping concepts to remediating VOCs in groundwater was contracted to help design a riffle component that would fit the criteria outlined above. The resulting design that was best suited to the location, based on overall slope and construction feasibility, was a concrete stepped spillway with estimated construction costs of $100,000. Optimal effectiveness would be maintained if flows were evenly spread across the width of the steps, there was a breeze of at least 16 km per hour across the flowing water, and the surface of the concrete—particularly the drip edges on each step—was clean. This indicated a need for a routine maintenance effort that was more robust than originally anticipated, including brushing off accumulated dust, plant debris, biofilm, and so forth. Installing a heavy-duty, vented grating over the entire length of the component was under consideration for safety concerns. However, the price of such a grating was not included in the cost estimate above. In addition, the grating would reduce air flow (which would reduce the effective aeration) and it would need to be removed for maintenance activities. Furthermore, a solar-powered pump would be required to deliver the ZVI-treated water to the entry of the riffle component, since it would be positioned at a higher elevation than the existing subsurface outfall from the MSPTS, and during the winter the water would periodically coat the riffle structure with ice. These undesirable factors led to an evaluation of other options.

Commercially Available Air Strippers

Applying air-stripping concepts to remediating water contaminated with VOCs is not a new approach. Commercially available strippers of various designs are readily available. Therefore, a manufacturer of small-scale air strippers was consulted to assess whether an appropriate unit might be available off the shelf.

The same design criteria summarized above were provided to the manufacturer. Understandably, rather than design and manufacture each individual air stripper around the specific conditions of its application, manufacturers have made available a smaller number of air stripper models designed and built to address a range of conditions. The unit deemed most appropriate for the Site’s effluent-polishing application was oversized but the most suitable overall because a smaller unit would have had to be specially designed and manufactured.

The cost of the air stripper itself was estimated at approximately $7,500 to $14,000, depending on whether the unit would be equipped to handle flows higher than the 3 gpm criterion. However, the power required to operate the blower motor supplying ventilation to the stripper—ranging from a 2-horsepower to 5-horsepower motor—would require a substantial solar installation. The solar array and associated batteries and control components, not including the construction of a suitable foundation and housing, were estimated to cost between $165,000 and $375,000. This cost did not include freeze-protection measures that might be required to minimize the potential for the aboveground air stripper to fail due to subfreezing temperatures in winter. Routine maintenance and cleaning of the air exchange components was also required.

As with the riffle approach, this alternative was shelved in favor of considering other alternatives.

Prototype Solar Air Stripper

Given the high costs estimated to polish such a small flow of water with relatively low concentrations of VOCs, the next alternative was based on a different approach: empirical testing.

The MSPTS is equipped with a manhole that provides access to the effluent for monitoring. Though small, this manhole could afford a potentially useful enclosure in which a small air stripper could be installed.

Proof-of-Principle Testing

A basic “proof-of-principle” test was first run, using untreated MSPTS influent water. Drip-irrigation spray nozzles were connected to a small fountain pump that was submerged in a closed tub containing the test water. A handheld photoionization detector (PID) was used to check baseline conditions in the headspace within the tub. (Raw influent water was used because the PID would more easily detect the corresponding higher VOC concentrations.) The pump/sprayer was operated for 5 minutes (which was the approximate time required to spray the volume of water contained within the tub) and the headspace was again sampled using the PID via a small hole in the tub lid. The lid was then removed to allow air within the tub to be exchanged with ambient outdoor air. The lid was replaced and the 5-minute cycle repeated. This was repeated 5 times for a total spraying time of 25 minutes. As expected, the PID confirmed VOCs were being liberated through this simple spraying process.

Testing of First Prototype

The next test evaluated a prototype that incorporated more representative components. A brass, full-cone spiral deflection nozzle (model TF10FCN by BETE) was attached to a hose fed by a small sump pump that was powered by a portable generator. Spiral nozzles were selected because theey resist clogs, produce a fine spray pattern, are easy to clean and inexpensive, and have no internal parts.

The pump was placed in the bottom of the effluent manhole. The manhole was temporarily modified to hold approximately 120 gallons by installing an extension that elevated the opening of the outlet, causing effluent from the ZVI cells to back up within the manhole. At a flow rate of 1 gpm, therefore, the manhole volume would represent an accumulation of 2 hours of flow and, by extension, a residence time within the manhole of 2 hours (ignoring preferential flow). Figure 4 shows the setup.

NOTES: The left photo shows the nozzle and hose affixed to the mounting bracket, designed and installed to allow the manhole door to be closed without affecting pumping operation. The right photo shows the nozzle spraying water into the manhole.

Figure 4. Photographs of first prototype.

A sampling tube was installed next to the manhole outlet and extended through a sealed port at the ground surface to allow water samples to be collected, without opening the manhole, using a peristaltic pump. In addition, a second tube was run from the headspace inside the manhole through a port to a PID to allow rough, qualitative monitoring of the air quality within the manhole as the air-stripper test proceeded.

Two tests were run. For each test, a new volume of ZVI-treated water was placed in the manhole. The manhole lid was closed throughout the first test, which was performed on January 13, 2011, and remained open throughout the second test on January 14, 2011. During the performance of each test, the manhole was isolated from receiving additional flow from the ZVI cells (i.e., no additional water was added to the manhole during the test).

Prior to assembling the air-stripper apparatus, the anticipated flow rate through the test nozzle using the sump pump was measured at 1.75 gpm. This correlates to approximately 69 minutes for one complete turnover of the water in the manhole, based on the 120 gallons of water held in the manhole. For convenience, during the tests this time period was rounded to 70 minutes.

Each of the two tests was operated long enough to allow four complete (70-minute) turnovers of the water within the manhole. Samples were collected from the water within the manhole before the air-stripper pump was energized, and additional samples were collected every 70 minutes thereafter as PID readings were recorded and variables such as weather conditions were described. Other than keeping the manhole lid closed for the first test and open for the second, no efforts were made to isolate or control airflow to or from the interior of the manhole. Therefore, differences in breezes and temperatures over the course of each test and between tests represented variables that were neither controlled nor quantified. In addition, after all tests using this apparatus had been completed, the flow rate was re-measured at approximately 1.5 gpm. This indicates that the expected number of turnovers was not completed. However, the value of the results obtained through these tests was not affected: the data still confirmed air

stripping of VOCs was occurring, and the concept of a small, solar-powered air stripper remained valid.

Analytical results for selected contaminants from the two tests using this more-representative prototype air stripper are presented as Table 3. Other contaminants were also evaluated, but those shown—PCE, TCE, cis-1,2-DCE, and vinyl chloride—represent the more common VOCs of interest in the effluent from the ZVI cells at the MSPTS. (Note that the ZVI media was clogged and scheduled to be replaced shortly after this test was conducted. Therefore, the test evaluated water that was not as fully treated as would be the case if the ZVI was fresh.)

Exchanges completed	Test	VOC	Result	Test	VOC	Result
0 (initial water)	Open Lid	PCE, ug/L	63	Closed Lid	PCE, ug/L	50
1			26			22
2			9.7			6.8
3			3.6			2.4
4			1.6			0.77 (J)
0 (initial water)		TCE, ug/L	390		TCE, ug/L	300
1			150			130
2			52			37
3			20			14
4			9.6			4
0 (initial water)		cis-1,2-DCE, ug/L	1500		cis-1,2-DCE, ug/L	1200
1			570			500
2			210			130
3			91			51
4			43			15
0 (initial water)		Vinyl chloride, ug/L	91		Vinyl chloride, ug/L	61
1			24			23
2			8			6.1
3			2.6			2
4			1.2			0.54 (J)

NOTES: Units “ug/L” = micrograms per liter. Lab qualifiers in parentheses; “J” indicates concentration is estimated.

Table 3. Selected Results from First Prototype.

The results from the first prototype (Table 3) show that the ventilation provided by the open lid improved air-stripper performance, indicating additional ventilation would be needed for optimal effectiveness. More importantly, these results suggest that the small-scale, empirically based approach has merit. This conclusion led to a more representative prototype design, discussed in the next section.

Construction and Optimization of Second Prototype

The tests described above were performed with the intent to determine whether a smaller, less expensive air stripper could be used to polish the effluent from the two ZVI cells. Results from tests of the first prototype indicated such an air stripper had sufficient potential to warrant installation and optimization.

The second prototype air stripper was installed in the effluent manhole as part of the media replacement activity conducted in February and March 2011. While the MSPTS was off-line for

this maintenance, components of the second prototype air stripper were selected and procured. This prototype was installed in late March 2011.

The manhole was thoroughly cleaned and modifications similar to those described above were made again, this time for longer-term operation.

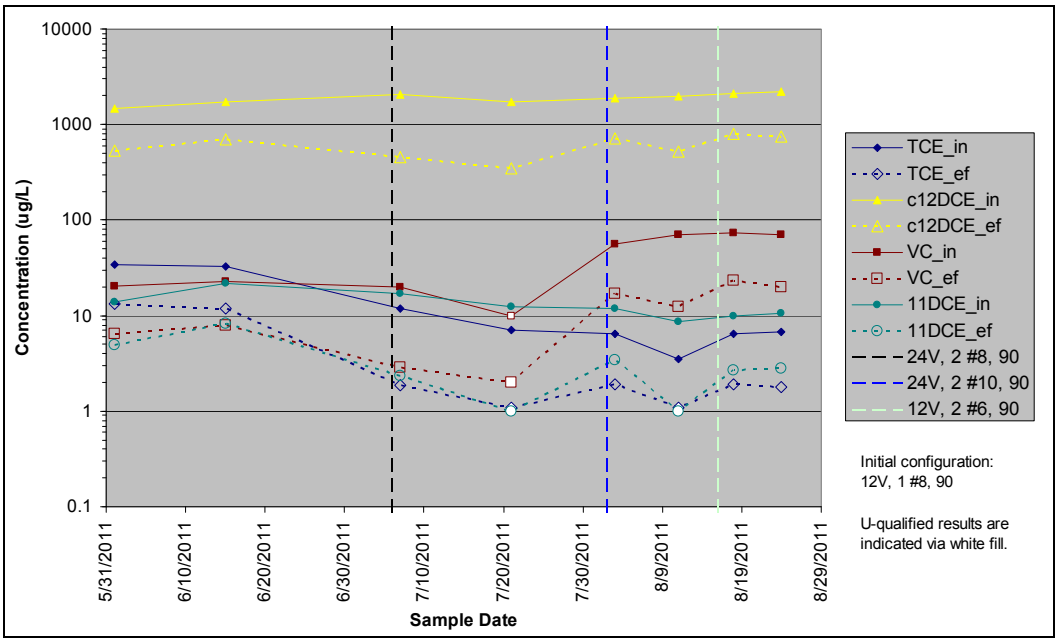
This second prototype consists of a submersible pump feeding water to a threaded tee to which one or two nozzles can be attached. (Additional connections can be made to increase the number of nozzles, but maintaining favorable spray patterns would require additional pump capacity.) The pump flow rate varies with the nozzle selection and operating voltage (12 or 24 volts DC) and can be determined by measuring the line pressure in the pipe feeding the nozzles. For this reason, a pressure gage was installed on the feed line.

Several more full-cone spiral nozzles were obtained with different spray patterns, orifice diameters, and optimal flow rates. Because the best nozzle for the intended application was not known and would be determined through optimization testing, the nozzles that were obtained represented a selection of those anticipated to be most appropriate for this application.

A small, stationary solar array providing approximately 0.85 kilowatts was installed to supply power to the air stripper. Given that significant testing and data collection were going to be necessary before the optimal configuration (e.g., pump rate, nozzle design, number of nozzles, relationship to influent flow rates) was known, the array was designed to support operation for only 12 hours per day. The concrete mounts for the solar array, however, were sized to accommodate additional panels in anticipation of eventually operating the stripper continuously.

If powered only by solar energy, the pump rate would vary widely through the day as the sun moves across the sky and is potentially blocked by clouds. This would represent an additional variable and would also limit the effectiveness of the air stripper during suboptimal solar conditions. Therefore, a battery bank was also installed to provide more consistent power and stabilize the pump rates over the timer-controlled 12-hour operating cycle. The pump is powered by deep-cycle 8D batteries, which are charged by the solar array. As with the array, the battery enclosure was also oversized in anticipation of an eventual conversion to full-time operation.

Since the prototype's installation at the end of March 2011, several tests have been run. Samples have been collected for VOC analysis during each test. Air-stripper parameters that have been tested included operating with one or two nozzles, operating with different nozzle designs, and operating with the pump set at 12 volts or 24 volts. In each of these tests, a set of samples was collected to represent manhole influent (i.e., ZVI-treated but not air-stripped water) and water exiting the air-stripper manhole. These efforts did not test extended (multiple-turnover) air stripping of the same water, such as was performed in tests of the first prototype. ZVI-treated water was allowed to enter and exit the manhole continuously as water was sprayed through the air stripper at flow rates exceeding the inflow/outflow rate. Comparing the spray rate against the flow rate into the manhole (which equals that out of the manhole) determines the turnover cycles; for example, a spray rate of 3 gpm and flow rate of 1 gpm corresponds to a turnover rate of 3. For each test, sampling was conducted at the same time each day so that the air stripper would have been operating for the same amount of time that day. Each configuration was tested twice, 1 week apart, to help smooth variations due to weather or other conditions. Figure 5 summarizes the testing results.



NOTES: Legend entries with the suffix "_in" represent samples of influent; entries with the suffix "_ef" represent samples of effluent. c12DCE = cis-1,2-DCE; VC = vinyl chloride. Dashed vertical lines provide information on when and how the pump and nozzle configuration was revised; see text for details. Note the logarithmic concentration scale. Units "ug/L" = micrograms per liter. Applicable standards [3]: TCE = 2.5 ug/L; cis-1,2-DCE = 70 ug/L; vinyl chloride = 0.2 ug/L; 1,1-DCE = 7 ug/L. Other data qualifiers are omitted for clarity.

Figure 5. Concentrations of Primary VOCs of Interest in Air Stripper Optimization Tests.

Approximate flow rates through the air stripper were determined using pressures documented during each of the sample dates (represented on Figure 5). Table 4 provides these flow rates.

Table 4. Approximate Flow Rates During Each Air-Stripper Configuration Tested.

Configuration	Date range	Approximate pump flow rate (gpm)
Pump operated at 12 volts; one #8 90-degree nozzle used	3/30/2011–7/5/2011	1.9
Pump operated at 24 volts; two #8 90-degree nozzles used	7/6/2011–8/1/2011	4.2
Pump operated at 24 volts; two #10 90-degree nozzles used	8/2/2011–8/15/2011	4.6
Pump operated at 24 volts; two #6 90-degree nozzles used	8/16/2011–end of this phase of testing	2.0

NOTES: Flow rates are per BETE catalog specifications for the listed nozzles at the measured pressures; each nozzle has an associated "K factor," and the flows in gpm are determined by multiplying the appropriate K factor by the square root of the pressure in pounds per square inch.

From these data, removal efficiencies were calculated for a selection of the VOCs (Table 5). The test results show that the most effective configuration was operating the pump at 24 volts and equipping the air stripper with two #8 90-degree spray nozzles. This first-cut determination of optimal pump/nozzle configuration was used in the next round of tests.

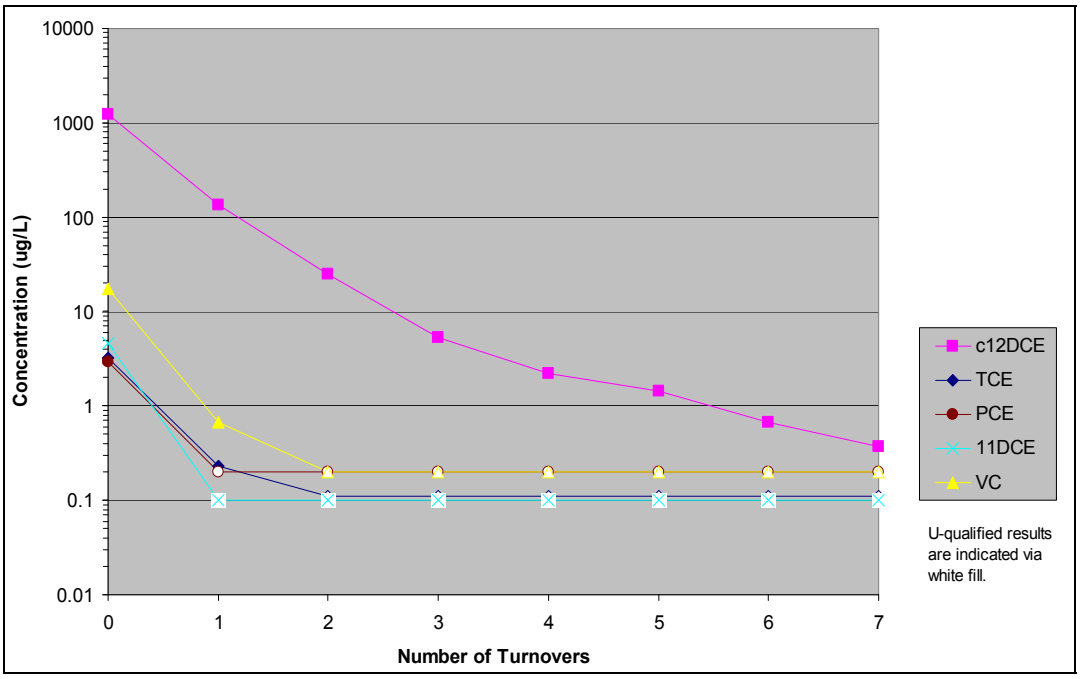
Table 5. Calculated Removal Efficiencies for Selected VOCs During Air-Stripper Optimization Testing.

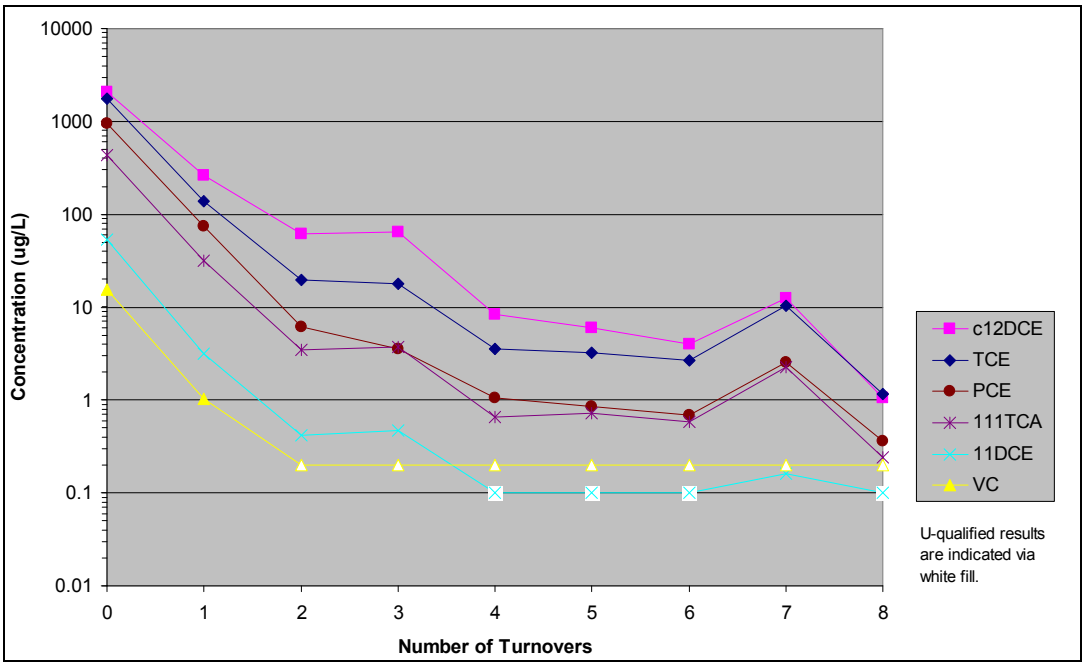
Analyte	Date Sampled	Removal Efficiency	Configuration
cis-1,2-DCE	6/1/2011	63.2	12-volt, 1 #8 90◦ spray nozzle
	6/15/2011	59.0	12-volt, 1 #8 90◦ spray nozzle
	7/7/2011	77.6	24-volt; 2 #8 90◦ spray nozzles
	7/21/2011	**79.5**	**24-volt; 2 #8 90◦ spray nozzles**
	8/3/2011	61.9	24-volt; 2 #10 90◦ spray nozzles
	8/11/2011	73.6	24-volt; 2 #10 90◦ spray nozzles
	8/18/2011	61.5	12-volt; 2 #6 90◦ spray nozzles
	8/24/2011	66.0	12-volt; 2 #6 90◦ spray nozzles
Trichloroethene	6/1/2011	60.9	12-volt, 1 #8 90◦ spray nozzle
	6/15/2011	63.7	12-volt, 1 #8 90◦ spray nozzle
	7/7/2011	84.3	24-volt; 2 #8 90◦ spray nozzles
	7/21/2011	**92.1**	**24-volt; 2 #8 90◦ spray nozzles**
	8/3/2011	70.8	24-volt; 2 #10 90◦ spray nozzles
	8/11/2011	84.3	24-volt; 2 #10 90◦ spray nozzles
	8/18/2011	70.8	12-volt; 2 #6 90◦ spray nozzles
	8/24/2011	73.3	12-volt; 2 #6 90◦ spray nozzles
Vinyl Chloride	6/1/2011	68.8	12-volt, 1 #8 90◦ spray nozzle
	6/15/2011	65.2	12-volt, 1 #8 90◦ spray nozzle
	7/7/2011	**85.6**	**24-volt; 2 #8 90◦ spray nozzles**
	7/21/2011	80.0	24-volt; 2 #8 90◦ spray nozzles
	8/3/2011	70.1	24-volt; 2 #10 90◦ spray nozzles
	8/11/2011	82.3	24-volt; 2 #10 90◦ spray nozzles
	8/18/2011	68.4	12-volt; 2 #6 90◦ spray nozzles
	8/24/2011	71.3	12-volt; 2 #6 90◦ spray nozzles

NOTES: All nozzles were BETE full-cone spiral cut nozzles. Highest estimated removal efficiencies are shown in bold.

The next tests were more extensive and explored extended air stripping of the same water. The lid to the manhole was kept closed and the test operated for seven exchanges with no new ZVI-treated water being introduced. An initial sample was collected, and subsequent samples were collected at the end of each exchange. The next day, the same process was followed for a test of raw influent—that is, water that had not been first routed through the ZVI cells—but this test was operated for eight exchanges. This latter test was performed to assess the potential for replacing the ZVI treatment method with larger-scale, solar-powered air strippers. The results of these tests are provided below.

Throughout both tests, the pump was set at 24 volts, and two #8 90-degree nozzles were used. Other data qualifiers are omitted for clarity





NOTES: The top graph shows the results of testing ZVI-treated MSPTS effluent; the bottom graph shows the results of testing raw, untreated MSPTS influent. Note logarithmic concentration scale. c12DCE = cis-1,2- DCE; 111TCA = 1,1,1-trichloroethane; 11DCE = 1,1-DCE; VC = vinyl chloride. Units “ug/L” = micrograms per liter. c12DCE standard = 70 ug/L; TCE standard = 2.5 ug/L; PCE standard = 1 ug/L; 111TCA standard = 200 ug/L; 11DCE standard = 7 ug/L; VC standard = 0.2 ug/L. Throughout both tests, the pump was set at 24 volts, and two #8 90-degree nozzles were used. Other data qualifiers are omitted for clarity.

Figure 6. Results of extended, multiple-turnover tests of MSPTS effluent and raw influent.

As suggested by the results for air-stripping raw influent water illustrated in Figure 6, even at the small scale of this prototype air stripper the desired degree of VOC removal is approached. Installing similarly-designed air strippers within the larger treatment cells and using pumps capable of higher flow rates would almost certainly provide adequate water treatment. The associated power and maintenance requirements remain to be determined, but will be better understood following the ongoing testing and optimization efforts.

The air stripper is inspected and maintained at least once weekly. As of late October 2011, minimal maintenance has been required over the roughly half year the air stripper has been operating. The pump intake, nozzles, and plumbing have been checked, and the manhole and flume have been inspected and cleaned at least once. The expected high quantity of iron oxides and related fouling, which was anticipated to be exacerbated and accompanied by biological fouling, has not yet posed any operational or maintenance difficulties. In fact, the pump intake screen and the nozzles have been easy to clean with a handheld spray bottle.

Further testing will be conducted in winter. Cooler temperatures will likely reduce the stripper's effectiveness. Even though the groundwater itself changes little in temperature in response to climate, its movement through the MSPTS will result in heat loss on colder days. Insulation has been added to MSPTS components to reduce heat loss. Keeping the water warmer is preferred for two reasons: freezing water would cause fouling and could damage air-stripper components, and VOCs are stripped more effectively in warm weather [4].

Following data collection over the winter, the potential for and requirements of a full-time air-stripper polishing component will be assessed, and replacing the ZVI treatment method with larger-scale air strippers will be considered.

REFERENCES

1. DOE 2006. Corrective Action Decision/Record of Decision for Rocky Flats Plant (USDOE) Peripheral Operable Unit and Central Operable Unit. September 29.
2. EPA (U.S. Environmental Protection Agency), 2000. *Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications*, EPA 542-R-00-008, U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response, July.
3. DOE (U.S. Department of Energy), 2007. *Rocky Flats Legacy Management Agreement*, U.S. Department of Energy Office of Legacy Management, March.
4. FRTR (Federal Remediation Technology Roundtable) 2002. *Remediation Technologies Screening Matrix and Reference Guide*, Version 4.0. Section 4.45, "Air Stripping," January. Available online at http://www.frtr.gov/matrix2/section4/4-46.html.